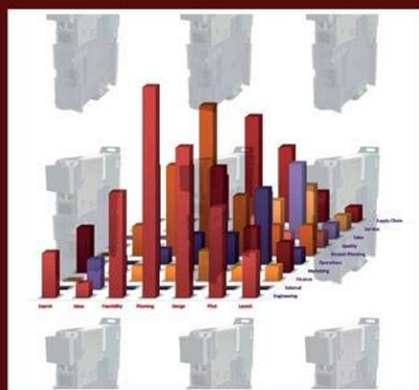




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An overview of enclosures, housings, and packages

1

1.1 A scenario from the world of enclosures

Imagine that you are immersed into the world of enclosures. In fact, imagine this—you're the Vice President of Engineering for a global original equipment manufacturer (OEM) called Better Electronics Incorporated also known by its acronym as BEI. Your company makes a fantastic gizmo. The only trouble is that like many electronics companies yours is full of electrical engineers, and as a result mechanical issues only bubble up to C-level once a problem hits the proverbial fan. Like today ...

You are still at the company headquarters despite that it is late on a cold Friday night in the middle of winter. You are sitting in a conference room waiting for the other executives to arrive, trying to look through the window and see if it has started snowing. The corridors are empty and most people have long since departed for their well-deserved weekend rest. You have promised your kids to get them up to Sugarloaf Mountains for a bit of family skiing. Your wife has called three times already and you are trying to dodge the argument that is surely to follow. You are way too late to drive up to Maine ...

Yet you have called an emergency meeting to fix this mess. Of course, your boss the CEO nudged you a bit and used a few words of encouragement that could not be printed. He pointed out that Red Lines is by far your biggest customers and they have already threatened to return all their current stock and withdraw all outstanding orders. Why? Because of a tiny problem with your gizmo. It stops working once it is left in the car in a cold winter night. You are thinking perhaps tonight you should test the device yourself. Maybe it's a simple case of an inappropriate material substitution. You remember that the VP of Procurement sent over one of his most obnoxious Director who was quizzing you about cutting cost by changing the PC/ABS in your gizmo to another grade. You have flatly refused at the time, but who knows that might have gone ahead and substituted it anyway. Should this be the problem?

After a bit of conference room linguistic tango, you have discovered that your hunch was right. Despite your objections, the material change was authorized while you were away on a family matter. Yeah, right you have buried your father and while you were away they overrode your objections. Wonderful! Now you must clean up this mess. You are trying to be patient and despite of the late hour suggest that you hop on a plane to the Far East on Monday and see if you can change back the material promptly. Procurement advises that the tool was already modified, specifically gate sizes were changed to accommodate the new resin. You try awful hard to not show your bitter disappointment. At this point, you look at the CEO and realize that he is in deep thought. You try to blame the supply chain; none of their members are present at this meeting.

Your exhausted CEO sighed and in a barely audible manner voiced his opinion “but the supply chain should have understood our requirements.” You think that perhaps, the supply chain should have performed better. Perhaps a more rigorous quality audit could have caught the hairline cracks on the housing, but the ultimate responsibility was still firmly placed in your domain. It was BEI’s responsibility to effectively control its supply chain. However, you remember that this was not an isolated incident for your company, and many of your competitors would struggle equally if asked about the many facets of enclosure design, development, testing, and manufacturing activities. Let alone properly orchestrating, monitoring, and indeed controlling such important activities, like rheology of the selected resin and making sure that no substitution is ever to be made without a written authorization from the Chief Engineer.

It’s very late now and finally the meeting is adjourned. You’re exhausted because this is not the only time there’s been a failure of an electronic enclosure. Gathering your belongings, you think of a pleasant day, a day that all this will be solved. Arriving to your office, you notice the Post-it Note stuck on your phone. Your assistant probably left it there. It says: call Frank, he will sort your enclosure problems for sure!

1.2 Definition

Many engineers associate the word “enclosure” with big shelters housing high-voltage equipment such as shown in [Fig. 1.1](#). However, the word “enclosure” is used here in a more general sense than utilized by [Tang and Joshi \(1999\)](#). *Electronic Enclosures, Housings and Packages* defines an enclosure in its most fundamental form, which is a volume containing electronics that is surrounded by a barrier. This barrier is the focus of this series of handbooks.

Electronic enclosures in the context of this series means the protective features built into the electrical and electronic elements of the product itself. Importantly, this label



Figure 1.1 A typical electrical shelter.

applies both to end-products and components. Therefore, an enclosure is a device that envelopes or incorporates an electronic circuitry but itself is an electrical insulator although it might potentially be a thermal conductor.

1.3 Introduction

Electrical and electronic equipment can be found in every aspect of modern life. Electronic enclosures are everywhere from toys and appliances to high-power computers and industrial or home automation including the latest electronic gadgets. Designing enclosures to satisfy and indeed to delight this wide range of potential users has become such a significant activity as to warrant a specialized collection of readily available references, data, and information that is constructive for both novices and advanced experts. Indeed, the whole supply chain will benefit by learning to apply proven tools and processes for the development of electronic enclosures, housings, and packages such as the one depicted in [Fig. 1.2](#).

This handbook was produced recognizing that an electronic enclosure provides a vital function for any encased system. Specifically, an enclosure protects enveloped electronics from adverse effects of the surrounding environment. Conversely, the same enclosure also protects the environment, most importantly people, from harmful effects of the encased equipment. Therefore, it is important to understand electronic enclosures, housings, and packages and their development.

1.4 The public facade

There are numerous examples where electronic enclosures worked unexpectedly well. Consider the example of Air France Flight 447. The flight according to [Faust \(2016\)](#)

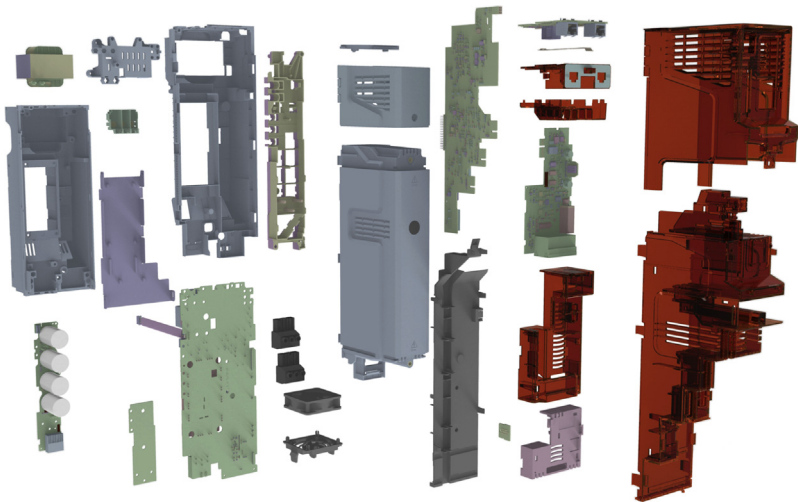


Figure 1.2 Exploded view of the main parts enveloped by an electronic enclosure.

was a scheduled passenger flight from Rio de Janeiro, Brazil to Paris, France, which crashed on 1 June 2009. The Airbus A330, operated by Air France, entered an aerodynamic stall from which it did not recover and crashed into the Atlantic Ocean at 02:14 UTC, killing all 228 passengers, aircrew and cabin crew aboard the aircraft.

After a sustained search the aircraft's black boxes were recovered. First, the flight data recorder chassis was found on April 26, 2011. However, its memory was only found a few days later on May 1, 2011. Finally, the cockpit voice recorder was located on May 2, 2011. These enclosures were all lifted from their grave sites nearly 2 years after the crash. [Stone et al. \(2011\)](#) assert that today the world knows what happened to Flight 447 primarily because of the excellent service performance of these enclosures.

But not every electronic enclosure is designed and manufactured so well. Let us turn to the Internet to explore an issue that all practicing enclosure engineers are painfully aware. That problem is fastener failure. This is not so much an issue of the fastener itself failing; but on many an occasion the wrong torque is applied, sometimes the wrong fastener is selected by the engineer, and the list goes on and on. But without further ado let's observe the pain of a mobile communication service technician:

If you've ever had to repair an iPhone, you'll know they have a ridiculous number of screws. Most companies standardize screws in their products, but since Apple doesn't expect you to fix a phone ...

You see, each of these screws is different, the red ones are 1.7 mm long, the yellow one, 1.3 mm, and the orange one, 1.2 mm. Guess what happens if you install either red or yellow screws into the orange spot, since your eyesight isn't good enough to notice a 0.1 mm difference? The screw will cut into the PCB and break several 50-micron traces" "causing a blue screen error on the phone.

One could feel the pain ... annoying, isn't it? The cost is also high according to [Corcoran \(2013\)](#). [Levin and Kalal \(2003\)](#) suggested that this example is, however, not unique at all to a manufacturer. It only underscores the fact that consumer electronics failures are very public indeed. The fact is that all other market segments have their own share of "battle stories" to tell and associated "wounds to lick." The important point to note is that fastener failures are as old of a problem as electronics itself according to [Golueke \(1958\)](#) and cause immense pain not only to enclosure engineers but also to senior corporate leaders. Therefore, a solution to the most frequent fastener problems will be provided in this handbook series.

Connector problems are another important failure mechanism in electronics. According to [Qi et al. \(2008\)](#) one of the rather annoying *no fault found* and *intermittent failure* diagnostic statements in electronics are frequent. They provide an example worth repeating here:

Connectors and other contacts can cause intermittent failures. A common example is a TV remote control. Sometimes the remote control doesn't work, but after you hit it several times, it works properly again. The problem is often a bad connection between the batteries and the contact. The bad connection can be caused by chemical factors

(e.g., an oxidation layer on the battery ends) or mechanical factors (e.g., improper positioning of the batteries). By hitting the remote control, the battery position is changed to displace the oxide layer or reseal the batteries correctly.

While this example is a very simple one, others are not so straightforward to understand or to correct. Connector-related problems will also be investigated in one of the handbooks.

Finally, let us consider a recent example of a thermal runaway. The BBC headline: “Samsung recalls Note 7 explosive batteries” can indicate the level of damage suffered by the manufacturer worldwide as noted by Yao and Sun (2014). According to the BBC report:

There was a tiny problem in the manufacturing process, so it was very difficult to figure out, the president of Samsung’s mobile business Koh Dong-Jin told reporters.

As a consequence, many airlines banned these phones (Wee, 2016) after images of the device fires were broadcast globally. How could this be? Is there a way to preserve corporate dignity by performing satisfactory enclosure engineering? Luckily, the answer is yes according to Klein and Dawar (2004). The first step in gaining insights into this fascinating area of technology is to understand its language, specifically terms applied to enclosure engineering.

1.5 Labels

Labels are important from a variety of aspects according to Punyakanok et al. (2008). They allow their users to perform an essential function. If markers are utilized in line with an accepted usage pattern, then a label becomes a fundamental trigger to activate a shortcut. The benefit is that users can bypass expending energy on thinking about a particular set of problems (Greca and Moreira, 2002). Previously found solutions can automatically be applied. Unfortunately, bypassing cognitive effort creates difficulties. All label users must be aware that their utility is somewhat diminished by misuse and misinterpretation.

A new field always struggles for descriptive labels, and one can detect a level of maturity in an industry that is capable of having its own language, one that is not universally understood by outsiders (Turner, 1971). This also applies within the enclosure field. Naturally, all languages were completely developed by the time electronics became commonplace, and as a result existing words were put into unusual contexts to describe items within the newly developed field.

These labels often were misused, for instance, the words “package” and “case” cannot be interpreted in their traditional sense (Woolsey, 1979). While a “package” must be undone to derive an item of use, this is of course not the situation with its electronics meaning where no one expects to unwrap a packaged device such as a micro-processor. The same argument holds for a “case.” Consider a guitar case or a suitcase.

A guitar cannot be played while in its case and a suit cannot be worn while tucked away for shipping purposes. Nevertheless, these words have found new meaning in electronics.

An engineer who designs the envelope around the semiconductor only is usually entitled as a packaging engineer. He would spend his days designing a very specific type of enclosure. This is important because his design assumptions, for instance, with regard to ambient temperature range selection, might not be valid or be invalidated by the thermal engineers (Ulrich and Brown, 2006).

Thermal engineers will spend their working hours developing a way to keep the various printed circuit board (PCB) components cool. They also worry about interconnections between PCBs forming subassemblies. For instance, there are many such connections in a modular system.

Unfortunately, engineers working on diverse levels view these problems from entirely different perspectives and might not readily inform each other about their fundamental assumptions. Especially if these engineers have never even heard of one another as often they are diffused throughout the long supply chain and also dispersed globally according to Reader (2006). Therefore, it would be helpful to standardize electronic enclosure labels. Until such time, this handbook will refer to all levels simply as *enclosures*.

Gumperz (1962) opined that linguists understand how members of a tribal group communicate. They create their own language. The enclosure engineering fraternity is no different. There is a language that needs to be mastered to enter the world of enclosures.

Psychologist Johnson-Laird (1983) studied mental model creation from a language perspective and created a method to gain insights from frequently utilized words. This is important with respect to enclosures since a uniform overall label is still to be developed.

Therefore, it is beneficial to anchor an understanding by reviewing first and foremost the associated labels. This will clarify what is an enclosure. There are many descriptors used in the context of enveloping an electrical or electronic assembly. These words all have different meanings, but they are generally used to describe enclosures applicable to the various packaging levels.

Boréus and Bergström (2017) have developed a system based on metaphor analysis. New product development (NPD) decisions could be facilitated within an electronic enclosure development process leveraging discourse analysis techniques (Gee and Handford, 2013). Basically, a record of all conceptual labels is prepared from cross-functional team meeting records. Subsequently, a transcription is made to allow a computer program to search for key phrases including ones that are listed in Table 1.1. Studying the context in which these phrases occurred allows emergence of a metal model. This mental model is then checked against a library of successful frameworks and an individualized NPD map is developed. This map contains a proper customized approach to the NPD program, and it is utilized to avoid shortcomings of commonly used programs such as the stage gate model (Grönlund et al., 2010). This approach also allows avoidance of many enclosure engineering—related failures. However, to appreciate this approach, a definition of enclosure is needed.

Table 1.1 Enclosure labels

Trigger word	Synonyms	Shared meaning
Barrier	Wall, obstruction, hurdle	A barrier might create issues for heat transfer.
Box	Package, container, envelope	Smaller enclosures often referred to as a box. This label precludes intellectual input and implies preference to a standardized enclosure.
Cabinet	Cupboard	Containing drawers and shelves often used to co-locate many devices with similar functions.
Case	Container, box, holder	Holds a few PCBs.
Chassis	Frame, skeleton	Provides strength to the enclosure.
Coating	Outside layer, covering, varnish, finish	Electronics often use various coatings such as conformal coatings to protect components and subassemblies. Larger assemblies and systems are usually protected by other methods, such as encapsulation or potting.
Compartment	Section, cubicle, booth	Connected electronic systems might be housed in one.
Container	Pot, bottle	Large systems might be housed in a shipping container—like enclosure. A PCB might be placed in a container to be potted.
Containment	Suppression, control, restraint	Mobile phone batteries, for instance, must be contained by the enclosure in the event of a thermal runaway. A fire is not an acceptable outcome.
Crate	Cage, pen, enclosure	A crate is a chassis with a specific functionality that is mounted in an electronics rack. There are four types of crate systems: CAMAC, FASTBUS, NIM, and VME.
Encapsulation	Enclosure	Usually used to describe a plastic completely enveloping the electronics as, for instance, in a transformer or coil encapsulation.
Enclosure	Enclosed space, pen	The most common denominator in all these labels. Therefore, it is used in combination with the profession such as enclosure engineering.
Envelope	Cover, surround, shroud	A potential overall designator, but it is seldom used to designate enclosure engineering activities.

Continued

Table 1.1 Continued

Trigger word	Synonyms	Shared meaning
Frame	Border, surround, enclose	Used to denote various subassemblies.
Housing	Accommodation, shelter, cover	An often-used synonym for enclosure usually also incorporating mechanical elements such as gears and levers.
Membrane	Casing, covering	Generally, denotes a flexible interface.
Pot	Pan, vessel, container, jar, tub	An important term denoting an entire subset of enclosure engineering along with encapsulations. Potting means placing a circuit board into a container and filling it with a material that will protect the electronics by excluding air and other potential contaminants. It might also provide heat transfer benefits.
Package	Wrap, box, tie-together, enclose	Denotes the method of covering the IC also known as the chip. This is the first enclosure level where overall heat management is influenced.
Rack	Stand, frame, bracket, holder, shelf	Provide shelf space for electronics.
Shed	Lean-to, auxiliary building	Denotes a small building especially erected to house electrical and electronic equipment.
Shelter	Protection, cover	Like shed in conception.
Skin	Coat, casing, covering, membrane	Denotes changeability of enclosures to suit the individual taste of a consumer.
Wrap	Enfold, cover, envelop	Like the meaning of skin but a wrap could be applied to a component or a subassembly within a system, for instance, to provide better heat transfer.

IC, integrated circuit; PCB, printed circuit board.

1.6 Discipline

Successful development of electronic enclosures demands integration of at least a basic knowledge of thermal, mechanical, and manufacturing engineering along with a working knowledge of electrical engineering. Such a holistic development is a

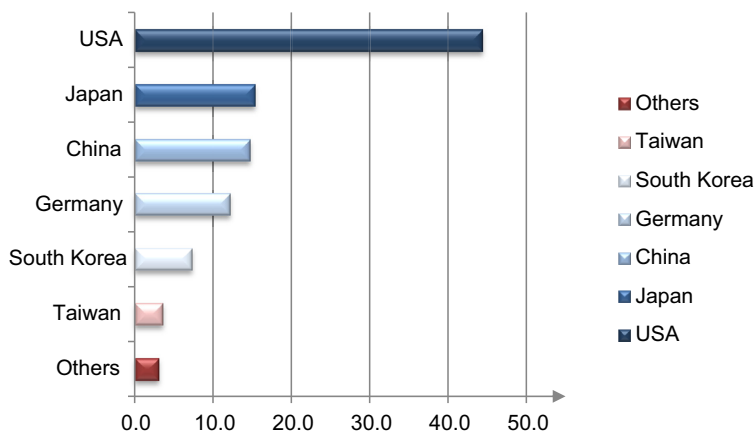


Figure 1.3 Electronics production.

prerequisite to excellent enclosure and housing development. Furthermore, electronic packaging is an engineering discipline often classified within electronics instead of mechanical engineering. Much difficulty ensues due to this apparent misclassification according to [Lu and Wong \(2009\)](#). Mechanical engineers receive the necessary training in heat transfer, dynamics, and bolted joint design. These important elements form the fundamental toolbox of the enclosure specialist. Of course, these skills could be learned by other engineers, hence the impetus for the birth of this book. It is proposed that a new integrated discipline of Enclosure Engineering be installed at principal tertiary institutions throughout the world especially in the leading countries shown in [Fig. 1.3](#). Until the first integrated program is finalized, this handbook provides a bridge between theory and practice of the various engineering disciplines. It is hoped that such a focused approach would allow better exploitation of the underlying opportunities.

1.7 The opportunity

There are three substantial reasons to study and master the art of electronic enclosures: low overall economic downturn, long-term profitability, and the creation of competitive advantage in niche market segments ([West et al., 2015](#)). A word of caution is in order: not understanding does make things worse. According to [Hahn and Hird \(1991\)](#) ignoring applicable regulations on occasion resulted in the loss of life not to mention corporate prestige. Therefore, following the rules, regulations, and generally accepted design practices is not only essential; it results in preservation of profitability and creation of a sustainable competitive advantage as well ([Porter, 1985](#)).

Electronic enclosures have morphed into today's industry by largely abandoning wood and using sheet metal and plastics instead. However, some time ago many enclosures utilized wood or wood-derived components. For instance, a TV set from

the 1970s often imitated household furniture by design according to [Wu and Vlosky \(2000\)](#). This enclosure strategy overcomes shoppers' reluctance to buy a product that was unused most of the time. It is hard to believe now that TV broadcasts were limited to certain hours of the day in most countries. [Bloch \(1995\)](#) believes that this is a prime example of how smart industrial design creates aesthetics that conceal some issues while highlighting perceived product advantages. Enclosures must be designed in a way as to provide confidence to the purchasing decision-maker about attributes that are neither easy to understand nor to confirm.

[Muccio \(1991\)](#) highlighted the fact that electrical enclosures provided the early thrust for the development of modern plastics. One of the major uses of plastics is still in the electrical and electronic applications and significantly in the enclosure segment. The principal reason is that plastics are inexpensive, easy to process into complex shapes, with desirable and controllable electrical properties. Plastics are dielectrics, in other words, good insulators, and for this reason their use in many cases becomes unavoidable. Plastics also behave as good heat insulators, so an avenue must be found to dissipate heat either through the enclosure by making plastics conduct heat better or by utilizing alternative methods.

Heat management has become a significant issue in packaging and thermal engineering. However, this is not a new phenomenon according to [Chu \(1986\)](#). Vacuum tubes had the same heat management issues and much could be learned from the practices developed shortly after WWII.

[Rosenberg and Frischtak \(1983\)](#) believed that while electronics tend to follow the economic cycles, enclosures seem to be more resistant to the ups and downs of the economy. This field is very robust and a rapidly growing one; there are many profit-making opportunities ([Martin, 1994](#)). Global trends can highlight niche market opportunities according to [Cavusgil and Knight \(2015\)](#). Understanding how different industries benefit from electronics enclosure knowledge will create a firm understanding on which to build a profitable enterprise.

Science contains a great variety of fields that are studied to advance knowledge. Many of these areas make a significant contribution not only to the advancement of science but also to provide better conditions for society. While this noble idea is certainly worthy of pursuit, businesses in general use a different criterion to establish the viability of a project. Ultimately, most projects must contribute to the profitability of the host organization ([Drucker, 2014](#)).

The electronic enclosures industry creates profits for both suppliers and buyers in the industrial supply chain. Suppliers profit by being able to manufacture an item that is important enough to afford a better profitability ([Stadtler, 2015](#)), provided principles in this book are adopted. An OEM is benefitting from an enclosure purchase by acquiring a functional device. The assumption is that this handbook's recommendations are fully implemented. If so, the OEM will improve its chances to gain an almost unassailable competitive advantage. Any OEM knows that such a position in the market place leads to sustained profitability improvements according to [Porter et al. \(1996\)](#).

1.8 Tech triangle

The technology triangle was devised to highlight the most urgent aspects of enclosure engineering. These topics are the backbone of any current enclosure design effort. Three random examples were provided at the beginning of this chapter to highlight their importance. [Walker and Dyck \(2014\)](#) assert that corporate reputation is at stake and with it the potential loss of customers and profitability. These three aspects of enclosure engineering if applied correctly can potentially save lives, but certainly enhance or if necessary rebuild corporate reputation.

1.8.1 Fasteners

The fact according to [Wagh et al. \(2016\)](#) is that very few electrical engineers have had exposure to the type of fastening problems faced by mining engineers. An ore crushing machine, for instance, must withstand tremendous vibration and therefore very special care is given when its fasteners are selected. The same could not universally be ascertained in electronics applications. Yet, electronics found its way to the ore crusher. In many instances without the knowledge of the engineer who was responsible for the enclosure design. Consequently, engineers find that their static connections fail due to loadings that are seldom properly understood ([Kounoudji et al., 2016](#)).

1.8.2 Connector problems

Connectivity has long been a fact of life for the enclosure engineer. Very few electronic devices are operated in isolation from others. While connectors are necessary, they are often overlooked and create reliability and hence customer satisfaction issues later ([Meier et al., 2015](#)). Connectors are designed to withstand dynamic use, but they do not seem to perform well under seemingly static, thermally induced micromovements.

1.8.3 Heat management introduction

Lack of proper heat management in accordance with [Lienhard \(2013\)](#) is one of the reasons executive attention is continually focused on electronic enclosures. All supply chain participants, therefore, must arm themselves with up to date and credible knowledge if to survive the senior executive muster.

Proper operation of an electronic device is a key aspect in the overall reliability of the system. The main purpose of an electronic component is to channel an electric current to perform a predetermined function. Every electronic device becomes a potential location for extreme heating. The reason for this is simple: as a current flows through a resistor, it is accompanied by heat generation. Most devices have associated resistance, so they become heat generators. Problems arise if this heat is not dissipated.

Continued miniaturization of electronics resulted in a spectacular increase in the quantity of heat generated per unit volume ([Cho and Goodson, 2015](#)). Unless properly managed, extreme rates of heat generation results in increasing operating temperatures

for electronics, which in turn jeopardizes the safety and reliability of these devices. Failure rates of electronic apparatus increases exponentially with increasing temperature (David et al., 2014).

According to Ani et al. (2015), one source of failure is the high thermal stresses imposed on the solder joints of components mounted on PCBs. These stresses are the direct result of temperature variations. High thermal stresses are one of the major causes of failure (Tang and Joshi, 1999). Therefore, heat management has become the most important factor in the design and operation of electronic enclosures (Moore and Shi, 2014).

1.9 Review

Enclosures are a vast business opportunity. Some enclosures are designed and made very well, while others could be improved. Enclosure-related labels were discussed to provide information about the language of the enclosure engineer and the supply chain. A definition of enclosure was provided to offer a fundamental building block of understanding. It was proposed that a new discipline Enclosure Engineering be instituted. Enclosures are a significant business opportunity and as such need to be systematically studied to understand their dynamics. Fastener- and connector-based issues were identified as significant improvement possibilities, as was heat management. These areas form the technology triangle. Potentially disruptive scientific advancements will be investigated in the next chapter.

1.10 Hot tips

Every chapter contains a few tips for the enclosure specialist including this first chapter that introduced an overview and a few fundamental topics.

- Learn the language of electronic enclosures for better understanding.
- Periodically check the state of potentially disruptive technologies.
- When in doubt, seek expert help.
- Study the technology triangle to master solving the most urgent problems in electronic enclosures.

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Technological innovation

2

2.1 Significance

Innovation is regarded by scholars and businesses alike as the most important source of profits (Drucker, 1993). Companies must innovate in order to remain competitive. The word *competition* was derived from the combination of two Latin words, *cum* and *petere*, which means to seek together (Girard, 1990).

According to Healy et al. (2014) companies hunt for profits; they in fact search for profits collectively with their competitors. When a member of the enclosure supply chain loses its competitive edge, it must innovate quickly in order to survive (Brondoni, 2014). However, innovation cannot be done so easily. Generally, there is neither money nor time available for true innovation. According to Deming and Edwards (1982) business leaders frequently reason like this:

If our competitors are more successful than we are, they must be doing something right. Practicality demands that we imitate them as exactly as we can.

In the first phase, imitation will be rigid and myopic (Goffin and Pfeiffer, 2002). Later, however, the element of novelty will be mastered and imitation will become more aggressive (Miner and Raghavan, 1999). According to Schumpeter (2000) in an innovative process, imitation and innovation cannot be truly separated. Sundbo (1998) argues that innovation waves happen regularly and a company that wants to remain competitive needs to understand where the next wave might come from or how it affects its business. In this respect, timing of research and development efforts is critical according to Hakansson (2015). Therefore, a familiarity with innovation periods provides an appreciation of the significance of innovation in the electronics enclosure context.

2.2 Innovation periods

Kondratieff (1979) posited that a new technological wave is created regularly, once in every 50–75 years. However, Kleinknecht (2016) criticizes Kondratieff's initial point as he starts counting his "waves" only from the beginning of the Industrial Revolution and ignores previous events. Nefiodow and Nefiodow (2014) argue that given the frequency of these cycles is such that a maximum of two cycles could be observed within a lifetime, it is not surprising that amplitude and frequency modulations were not observed as demonstrated in Fig. 2.1. This graph follows Kondratieff's observations but also provides a visual presentation of the size of the underlying effect. The vertical

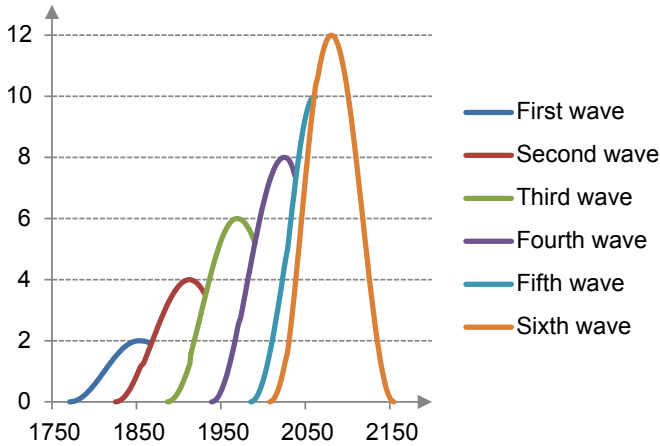


Figure 2.1 Kondratieff waves of innovations.

axis provides a quantitative display that subsequent waves are bigger than previous ones. This is primarily due to the underlying population growth. Bigger waves, however, also create bigger disruption (Gevorkyan, 2015).

Identifying the primary driver of the current sixth wave is not a simple matter. Some authors erroneously associate this wave with sustainability on the grounds of vanishing resources (Morone, 2016; Sachs, 2015; Van Den Bergh, 2013). While this observation sounds reasonable, it is derived from the underlying unchecked population growth that is responsible for the vanishing resources (Cairns, 2014; Nekola et al., 2013) and creates a confusion as to the technology that could rebalance the system. The sixth wave is the age of the minuscule (Grinin et al., 2016). Currently, nanotechnology is maturing very rapidly (Grinin and Grinin, 2014).

A contemporary of Kondratieff, Schumpeter's idea that innovation waves manifest themselves as innovative clusters strengthened Kondratieff's long cycle theory (Schumpeter, 1939). Others such as Goddard (2010) ignored both Schumpeter and Kondratieff and used a timeline that was strikingly similar but in many respect irreconcilable with the wave theory of innovations as Table 2.1 demonstrates.

Table 2.1 Comparison of innovation cycles

Time line	Kondratieff	Schumpeter	Goddard
1771-1800-1853	Textiles	Mechanization	The Industrial Revolution
1825-1853-1913	Railway	Steam power	The Age of Steam
1886-1913-1969	Electricity	Electricity	The Age of Electricity
1939-1969-2025	Computer	Nuclear	The Atomic Age
1997-2005-2061	Internet	Software	The Space Age
2007-2025-2081	Nanotech	Sustainability	The Modern World

A criticism leveled at Goddard is that while he reviewed the entire history of science he did not emphasize the perhaps most significant innovation of all times: the control and exploitation of fire (Mcpherson, 1984). This is probably due to fire's prolonged discovery that arguably took anywhere from 750,000 to a million years to master (Stratus, 1989; Raupach and Canadell, 2010; Goudsblom, 1987). Goddard (2010), however, did not attempt to use his timeline to develop a system or to gain a perception of trajectory. Therefore, Goddard's timeline cannot be utilized to charter enclosure development activities, but it can reinforce many aspects of both Kondratieff's and Schumpeter's theoretical predictive power.

The fundamentals of the long-cycle wave theory are no longer debated (Kleinknecht, 2016; Van Duijn, 2013; Tylecote, 2013; Bernard et al., 2014). This tool is useful in that it allows establishing an understanding how perceptions and technologies changed throughout the ages (Forrester, 2013) and to draw appropriate conclusions as to the potential changes facing the enclosure industry in the next decades.

2.2.1 Prehistoric

Kramer (1999) asserts that *Sahelanthropus tchadensis* reduced their relative energy cost of locomotion relying on bipedalism. Anthropologists believe that this happened about 7 million years ago (Senut, 2006; Cela-Conde and Ayala, 2003; Wong, 2003). Lovejoy (1988) and Napier (1967) argue that this was the greatest step forward in human evolution. In prehistorical time, fire was mastered. Glikson (2013) posits that attempts to control fire most likely provided the impetus to elevate early humanoids to the peak of the animal kingdom. Keeping the fire burning was no simple task and possibly provided speech among other social innovations according to Gentilucci and Corballis (2006). Today, every enclosure engineer is concerned with at least one manifestation of a fire-related issue: heat management.

2.2.2 Antiquity

Antiquity provided the invention of the wheel (Hooke, 2000), the first instances of purposeful use of inclined planes (Edwards, 2003), and its supreme manifestation, the screw (Koetsier and Blauwendraat, 2004). Mastering this simple device is still paramount in almost all electronic enclosure designs.

2.2.3 Middle Ages

The Middle Ages provide a very important lesson for technologists. Huebner (2005) argues that human development is not a linear process. Some technologies are almost continuously improved while the mass majority is quickly forgotten. Egyptian brain surgery, Greek organization, Roman building methods, and much other useful scientific and technological advancement have been left to waste (White, 1940). Recovery of such achievements is neither simple nor efficient. It is better to record the art and science while it is practiced well. Therefore, this handbook series attempts to create a permanent record of the state-of-the-art of electronics enclosures, housing, and packages.

2.2.4 First wave—mechanization

Goddard (2010) rightfully points out that the Industrial Revolution was preceded by the Scientific Revolution. This period afforded the foundations, for instance, for the discovery of electricity (Franklin, 1769). Therefore this period enabled to foster the right climate to create Kondratieff’s first wave of innovation displayed in Fig. 2.2. Giedion (1955) posits that this wave is characterized by mechanization as it is shown in Table 2.2. Mechanical Engineering and the creation of the fundamental understanding of what forms the essential toolbox of any enclosure engineer owes its very existence to this wave. Fig. 2.2 shows that this wave was well and truly over by the 1950s. This does not mean that mechanical engineering is no longer practiced or that its usefulness has diminished (Ernst, 1995). It means that economic features of the wave, the many opportunities, rapid growth potential, and extra profitability associated with the innovation waves are no longer applicable to this cluster (Schumpeter, 1939).

2.2.5 Second wave—steam

The second wave shown in Fig. 2.3 created steam power and with it the need to understand the fundamentals of thermodynamics and heat transfer. Today, heat management

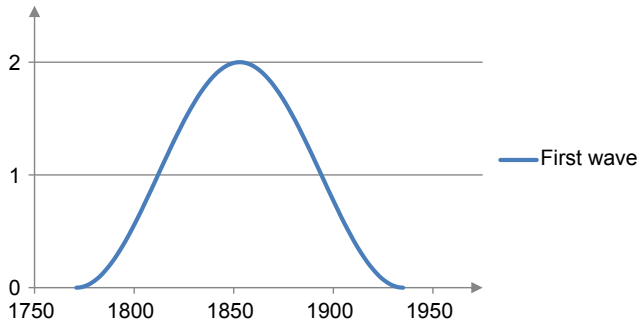


Figure 2.2 First innovation wave.

Table 2.2 First innovation wave

First innovation wave cluster: Mechanization
Textile machines
Farm machinery
Canal transportation, water power
Iron
Photography
Revolver
Morse code

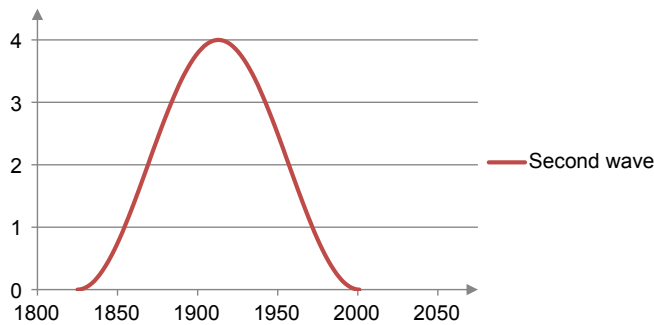


Figure 2.3 Second innovation wave.

Table 2.3 Second innovation wave

Second innovation wave cluster: Steam power
Railroad and steam ships
Steel
Cotton
Genetics
Submarines
The periodic table
Incandescent light bulb

of electronic enclosures is one of the most important considerations to assure adequate performance. Electronics cooling can therefore trace its origin to a time that was preceding the advent of electronics. This wave is characterized by the exploitation of steam as is shown in Table 2.3. Evaporative, two-phase cooling and other current cooling technologies are all leveraging knowledge that was established in this wave. The second innovation wave ended not long ago around the turn of the millennium. Contrary to technology scholars such as Nelson (1993), most economic scholars are only interested in the upswing of a long-cycle and not its full extent (Sterman, 1986), thereby fostering misunderstandings and lessening usefulness and predictive values associated with understanding innovation waves (Goldstein, 2006; Devezas, 2006).

2.2.6 Third wave—electricity

The next wave shown in Fig. 2.4 was characterized by electricity so much so that Goddard (2010) labels it as the Age of Electricity. This is a fundamentally important period for discovering properties of electricity and for the creation of electrical devices (Mckenzie, 2014). This knowledge leads to a search for, among other things, good insulators (Von Hippel, 1937).

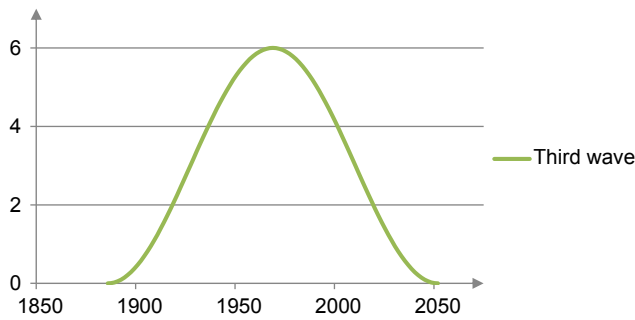


Figure 2.4 Third innovation wave.

Interestingly the birth of automobiles also happened in this innovation wave. Therefore, it would have been logical to power cars with electromotors. In fact, according to [Davis \(1926\)](#), this is exactly what happened. However, electric vehicles suffered from the same physics- and chemistry-related problems as their modern counterparts: insufficient energy storage and therefore, low range ([Emadi, 2014](#)). Inherent positive attributes such as superior acceleration, low noise, no pollution, and inexpensive operation were unable to overcome the fundamental problems ([Park et al., 2014](#)). Therefore, [Table 2.4](#) groups automobiles together with the invention of the internal combustion (IC) engine ([Pulkrabek, 2014](#)). This table, like all the others published on innovation wave clusters, makes no attempt to group innovations according to their proper technology cluster; rather it uses Schumpeter’s time period classification method ([Schumpeter, 1939](#)), which unfortunately presents an incorrect vantage point according to [Dassbach \(1999\)](#).

While the first and second waves have already completed their course, this wave is ongoing as displayed in [Fig. 2.4](#). It is in its rapid collapse phase. However, [Nelson \(1993\)](#) posits that its positive contribution is so minimal as to be unnoticed by economists and government bureaucrats by this time. Consider, for instance, the electric drive or electric traction industries ([Kirsch, 2000](#)).

Table 2.4 Third innovation wave

Third innovation wave cluster: Electricity
Electron
Radio
Blood groups
Automobiles and the internal combustion engine
Airship and airplane
Synthetic drugs
Machine gun

2.2.7 Fourth wave—computer

According to [Spear \(2006\)](#) the fourth wave shown in [Fig. 2.5](#) is not only the birth place of modern electronics but also affords the world with synthetic insulators that are in many respects superior to their natural counterparts ([Hall, 1993](#)). This step is extremely important in revolutionizing electronic enclosures ([Drury, 2001](#)).

The fourth wave will peak in 2025 as was observed by [Andergassen and Nardini \(2005\)](#). Therefore, growth in this cluster is already slowing, but there are many productive years left in this technology cluster. This is excellent news for electronic enclosures.

[Table 2.5](#) illustrates an ever-richer innovation wave cluster. This, however, might be due not only to the ever-increasing innovation wave amplitude but also to its shadow effect. This effect refers to the overlap between the various waves as was observed by [Rosenberg and Frischtak \(1984\)](#). Therefore, correct interpretation of the clustering effect becomes exceedingly difficult as was pointed out by [Silverberg and Verspagen \(2003\)](#).

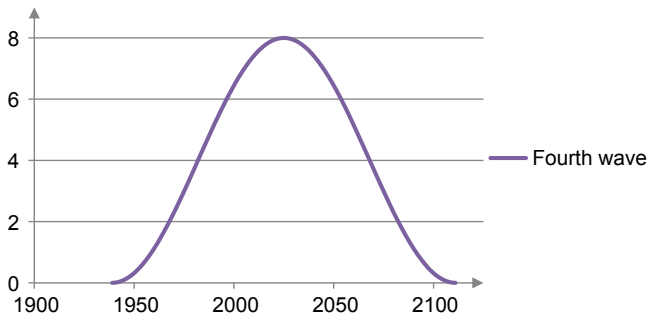


Figure 2.5 Fourth innovation wave.

Table 2.5 Fourth innovation wave

Fourth innovation wave cluster: Electronics		
Computer	Vitamins	Jet engine and rockets
Plastics	Subatomic particles	Nuclear magnetic resonance
Petrochemicals	Television	Nuclear fission
Electronics	Penicillin and antibiotics	
Aviation	Artificial fibers	
Space exploration	Helicopter	
Nuclear power and weapons	Radar	

2.2.8 Fifth wave—Internet

The fifth wave displayed in Fig. 2.6 brought important new customers. New innovations appeared in this new cluster as listed in Table 2.6. Electronic enclosures started serving communication device customers in addition to the already existing computer supply chain (Handfield and Nichols, 1999). Efficiency increases were achieved by deploying ever-more clever software solutions (Herring and Roy, 2007).

Yet, reliance on software-based codification is endangering the continued existence of enclosure engineering. Many argue that without classical understandings fundamental flaws will be repeated without a chance of remedy. According to Whitmeyer et al. (2010) the use of global positioning devices (called satellite navigation or Sat. Nav. in the United Kingdom), for instance, rendered maps obsolete. As a result, knowledge of cartography is rapidly disappearing.

Similarly, Turkle (2004) asserts that the reliance on computer code first replaced the slide rules, then calculators became unnecessary, and even equations started to become meaningless in an age where the average engineer manipulated computer aided design (CAD) data to analyze the geometry in a computer aided engineering (CAE) program. Often enough the fundamentals quickly get lost, and when a slightly unusual event

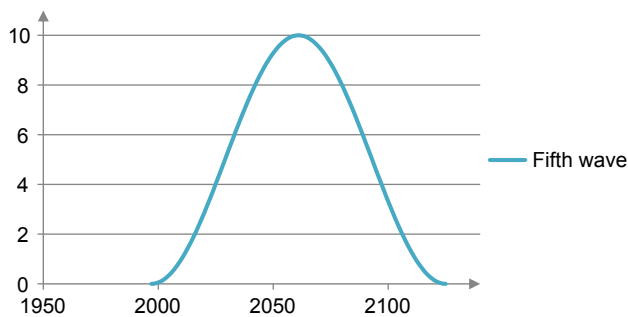


Figure 2.6 Fifth innovation wave.

Table 2.6 Fifth innovation wave

Fifth innovation wave cluster: Internet		
Digital networks	Pulsars	Internet
Biotechnology	Concorde and Tu-144	Superconductors
Software	Lasers	Satellite navigation
Hovercraft	Semiconductors	International space station
DNA double helix	Cell (mobile) phones	Search engines
Echolocation	Personal computer (PC)	Streaming videos
Radio telescopes	Space shuttle	Social networking

takes place, the entire development team is flabbergasted (Oppenheimer, 1997; Gatto, 2002; Baruh, 2012). This handbook series is desperately seeking to codify the existing knowledge base in accordance with Hall (2006) so that it could be utilized if such an event is about to take place.

Looking back at the last five waves of technological evolution allows us to appreciate that while new technologies emerge the old ones stay alive but in a much less emphasized format (Assous et al., 2016). Mechanization is still important. The Age of Steam has gone, but the steam cycle is as important today as it was at the time of its discovery. Consider the fact that most electricity still is generated by the steam cycle according to Mackay (2009), aided by the control of fire that is burning coal or gas. In addition, even nuclear power plants use the steam cycle (Kothare et al., 2000). According to Georgilakis and Hatzigargyriou (2013) the Age of Electricity still left us with its distribution ideas, for instance, reliance on alternating currents (AC). The first five innovation waves have created the Golden Age for Humanity as stipulated by Gordon (2016) and with it created unparalleled opportunities for the electronic enclosures industry.

2.2.9 Sixth wave—Nanotech

According to Nefiodow and Nefiodow (2014) the new technology wave, the sixth wave is fully visible by now and is shown in Fig. 2.7. Nanotechnology will challenge old design habits, much like the evolution of the computers and the Internet did.

A few elements of this emerging new cluster are listed in Table 2.7. Gerdtsri (2007) posits that an analytical approach is needed to create a successful roadmap in which to identify disruptive innovation hazards in this new wave.

2.3 Integration and reinterpretation

Each innovation wave created an opportunity for reinterpretation of previous efforts. This effect in addition to the underlying population growth increased the amplitude

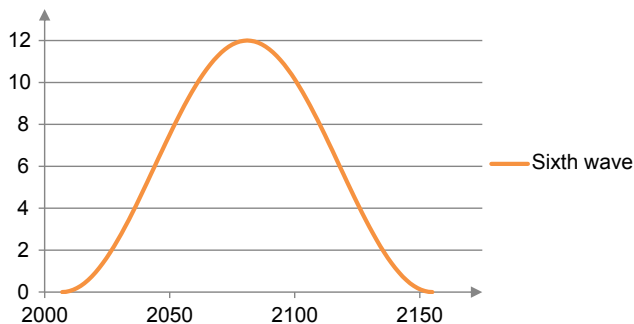


Figure 2.7 Sixth innovation wave.

Table 2.7 Sixth innovation wave

Sixth innovation wave cluster: Nanotechnology
Hubble space telescope
Cloning (animals)
Global warming
Nanotechnology
Sustainability
Renewable energy
The Human Genome Project

of subsequent waves as could be seen in [Fig. 2.1](#). Mechanization did not stay steady. It evolved with steam power, and thus machinery was redesigned to take advantage of the much easier energy distribution offered by the Age of Electricity. The innovation wave of electronics changed machineries again and so did the Internet Age as attested by the evolution of Industry 4.0 ([Lee et al., 2015](#)) also known as (a.k.a.) IoT ([Gubbi et al., 2013](#)). This effect cascades through all the innovation waves, and the fourth wave revolution in the area of electronics is no exception. Advancements created by this wave were reinterpreted by the Internet Age both in methods of communication and the ever-stronger prevalence of software according to [Alnaeli et al. \(2016\)](#). Importantly, the sixth and current wave is gathering speed in the form of nanotechnologies. This means that electronics once again will be reinterpreted. Therefore, new product development (NPD) efforts incorporating enclosures, housing, and packages need to be aware of this process.

Integration among the innovation drivers is desirable if greater efficiencies result. Professional practitioners of the mechanization age: mechanical engineers learned by integration. However, most engineers probably did not recognize the reason for such integration. Their curriculum included thermal engineering aspects from the second wave and they learned about electricity, electronics, and so on, basically highlighting the most important and relevant parts of each subsequent wave. This is primarily because of the reinterpretation effect ([Xiong et al., 2016](#)). However, one technology highlights current integration effects. According to [Tilli et al. \(2015\)](#) this technology is microelectromechanical systems (MEMSs). Therefore an entire section will be devoted to this important aspect of the sixth innovation wave.

2.4 Review method

A systematic review of the currently heralded technologies was performed in accordance with factors compiled by [Reagan \(2014\)](#). This process provided material and insights for this chapter. First, disruptive technological advances will be discussed, and their potential effects on the current state-of-the-art electronic enclosure design will be

indicated. Microelectromechanical systems (MEMS), a well-established and currently rapidly growing applied technology will be discussed to highlight technology adoption rates and discuss challenges to complete this review.

The review itself utilized secondary sources in accordance with [Rotolo et al. \(2015\)](#), that is, information already collated by other providers such as the World Economic Forum, or the Massachusetts Institute of Technology Review, a large number of industrial magazines, academic journals, patent reviews, and the Internet ([Hewson and Stewart, 2016](#)). Combining information created by these sources allowed focusing on a few important advancements in detail. Therefore, this review minimized possibility of disregarding an important major technological breakthrough.

Currently, a review of the potential advancements must include nonlinear optics (NLO; quantum computing), spintronics, and memristors as well as 2-D, organic, and modular electronics in addition to MEMSs. The most important promise of these sixth-wave nanoscale technologies is to further diminish size and weight of the system, increase reliability, and reduce manufacturing costs, therefore increase affordability ([Baird et al., 2004](#)) and market penetration ([Hirth, 2013](#)).

2.5 Disruptive technologies

Today the world is full of electronic devices. Their proliferation was unabated in the fourth wave. The fifth wave used electronics as a fundamental building block. It is probable that in the sixth wave electronics will be treated very much like other forgotten areas and only their efficient output will be important ([Grinin et al., 2016](#)). This quest for efficiency will be aided by the systematic approach of this dedicated handbook series. Therefore, a short review of the relevant technological advancements is provided beginning with a brief historical summary from electronics' perspective.

According to [Rogers et al. \(2010\)](#) it is important to note that integration of advances in material science and electronics will alter the fundamental perspective of enclosures. [Griffiths and Steyvers \(2004\)](#) also emphasize importance of integration across multiple science domains. This integration is necessary to miniaturize electronic circuits and to harness the potential of increased performance as was stated by [Moore \(1998\)](#).

The era of modern electronics began in Murray Hill, New Jersey, the United States, with the invention of the transistor in 1947 at Bell Laboratories and with that event the silicon-based semiconductor technology began ([Brinkman et al., 1997](#)). Performance of semiconductors has improved since 1947 according to [Rossi \(2005\)](#), primarily due to advancements in materials science, better understanding of the underlying physical phenomena, development of processing, and patterning technologies.

2.5.1 Nonlinear optics

Telecommunication networks utilize light for information transmission ([Cheffles, 2004](#)). The reason for this is simple according to [Keiser \(2003\)](#): a fiber optic cable is able to transmit 1000 times the information capacity of a copper wire. However,

computers among other electronics still use copper as the conductive medium. Therefore, the advantages of light-based communication have yet to improve computing performance. [Savage \(2002\)](#) pointed out that as computer speeds increase ultimately ability of the copper connections to carry information will be the ultimate limiting factor.

[Schaller \(1997\)](#) discussed Gordon Earle Moore's observation that the number of transistors in an integrated circuit doubles roughly every 2 years. This observation is commonly referred to as Moore's law ([Chien and Karamcheti, 2013](#)). This rule, however, is not a law at all, and scientists such as [Monroe \(2002\)](#) argued that this growth cannot continue unabated forever. Therefore, in the 1980s it was proposed that a new way of making computers might be possible. NLO was then what later became known as Quantum Computing ([O'brien, 2007](#)).

Fundamentally, according to [Gruska \(1999\)](#), using light is advantageous as the frequency spectrum of light is much higher than current electric communication signals'. Consequently, light can carry thousands of times as much information. In addition, the use of light-based signaling also surmounts another significant problem inherent with the use of electric communication signals. [Park et al. \(2009\)](#) have observed that as transistors are located closer together, the electrical signals passing through them start to create interference. This phenomenon is very much like radio stations broadcasting in close geographic locations at the same frequency ([Winters, 1984](#)).

Organic molecules were tried in the 1980s without a breakthrough success ([Yesodha et al., 2004](#)). Now silicon is investigated. However, turning silicon into a light emitter is not a simple matter ([Kane, 1998](#)). Despite the many and significant challenges, the University of California, Los Angeles, became the first to produce working silicon-based laser ([Andonian and Simakov, 2017](#)). This laser produced a pulsed beam. Intel scientists produced a continuous beam to facilitate data communications. According to [Rong et al. \(2005\)](#) a large and sophisticated infrastructure already exists for producing silicon chips, so silicon-based lasers might ultimately be cost-effective.

This handbook's author has worked on NLO for 4 years. Many dyes were analyzed in an effort to find the very best organic molecules ([Nalwa and Miyata, 1996](#)). Simultaneously, a novel way was developed to manufacture its elementary building block, the quantum gate. Super-injection-molding was developed as part of this effort at the R.L. Mitchell Technical Center in Summit, New Jersey, perhaps not so coincidentally only a few miles away from Murray Hill where the original transistor was developed.

[Krishnamoorthy et al. \(2009\)](#) posit that creation of a photonics-based chip-level interconnect is the first step in a viable development process. The ultimate objective is to facilitate light-wave communication between components. However, it must be stated that physicists are still busy developing the fundamentals and that this technology does not appear to be closer to producing a working computer, let alone replacing current electronic practices including electronic enclosures than it was in the early 1990s ([Brooks, 2012](#)). This technology needs to be monitored, but perhaps others will be more disruptive in the short to medium term.

2.5.2 *Spintronics*

Soviet scientists [Bychkov and Rashba \(1984\)](#) secretly established the theoretical foundations of spintronics during the Cold War. Experts argue that this field might displace conventional electronics ([Gomonay and Loktev, 2014](#)). This is because the technology of spintronics has the ability to compress data for computer memory.

The word spintronics is a combination of the words spin and electronics. This emerging field uses the fundamental property of particles known as electron spin for its operation ([Žutić et al., 2004](#)). Spintronic circuits are interesting because of the added computational dimension. Electron spin is a magnetic field phenomenon with one of two orientations: up and down. This fact adds two extra binary states to the conventional logic values: low and high. Information carrying capacity is drastically increased as both electron charge and spin are utilized. Spintronic devices promise speed, diversity, and functionality ([Gregg, 2007](#)).

Prototypes built on spintronic technology have been tested ([Awschalom and Flatté, 2007](#)). These include hard drives and new generation transistors. This technology alone or in conjunction with quantum computing might supplement or even entirely replace digital electronics ([Awschalom et al., 2013](#)). The crucial ability to manipulate four defined logic states will result in greater computing power, higher speed, and storage capacity according to [Eschrig \(2015\)](#).

Therefore, it is expected that spintronic devices will be smaller, more versatile, and more robust compared with their current silicon counterparts ([Han et al., 2014](#)). However, much like NLO a.k.a. quantum computing, this technology is still in its infancy. Consequently, it is unlikely that spintronics would disrupt electronics in the short term. As a result, the search must continue to locate a credible and ready technology that could affect enclosure design and development in the short to medium term.

2.5.3 *Memristors*

Leon Chua theorized in [1971](#) that the fourth fundamental electronic circuit board element would become the memristor, which would join the resistor, capacitor, and inductor as the fundamental building blocks of an electronic circuit. Chua called his new device the memristor: he combined the words memory and resistor.

Memristors have interesting and valuable properties that merit further investigation. Memristance takes place in nanoscale systems under certain conditions. Some believe that memristors could be the Kondratieff-waves-theory—predicted game changer and end electronics ([Ungerer et al., 2017](#)).

The working principle of memristors as explained by [Pazienza and Albo-Canals \(2011\)](#) is simple. A transistor functions by using the flow of electrons. Memristors, however, couple the electrons with ions, in other words, use electrically charged atoms. The significance of the operating principle is enormous. All information is lost if the power to a transistor is switched off and the flow of electrons is stopped. Conversely memristors retain information since they memorize the amount of charge throughput even after the power is switched off ([Jung et al., 2012](#)).

This discovery affords better information storage in accordance with [Kim et al. \(2011\)](#). Memristors allow the construction of safer, faster, and more efficient memory devices. Memristors also promise zero information loss. Memristor-enriched computer circuits allow instant rebooting, and hence immediate computational power availability. While this technology is promising, it is nowhere near mature enough to contemplate disrupting electronics in the short term. Therefore, the search must continue. The combination of 2-D, organic, and modular electronics holds great promise for disruption. Therefore, these technologies must be frequently evaluated.

2.5.4 2-D electronics

The 2010 Nobel Prize in Physics was awarded to Konstantin Novoselov and Andre Geim for their research of graphene ([Geim and Novoselov, 2007](#)). Interest in 2-D electronics started when graphene was discovered. Graphene like diamond is a structural variant of carbon ([Panchakarla et al., 2009](#)). Carbon atoms form a hexagonal 2-D lattice in graphene, unlike diamond that forms a three-dimensional structure. Importantly, graphene's two-dimensional lattice is only one atom thick. Therefore, graphene has high electrical and thermal conductivity, with adjoining mechanical flexibility and high tensile strength ([Balandin et al., 2008](#)).

According to [Schwierz \(2013\)](#) theoretical models predict that graphene transistors could be manufactured to perform 100 times faster than a silicon counterpart. According to [Rakheja et al. \(2013\)](#) MIT has already produced a graphene chip. The major issue in current chips is heat management. However, electrons travel through graphene with very little resistance ([Ju et al., 2014](#)), therefore generating lower heat losses. In addition, graphene is itself an excellent thermal conductor ([Fugallo et al., 2014](#)). This means fast heat dissipation and as a consequence improved performance. Therefore, graphene-based electronics should function at much greater speeds ([Zhang et al., 2013](#)). Right now, silicon is capable of the gigahertz frequency range, and it is doubtful if its speed can increase much further. Graphene, on the other hand, theoretically can do a terahertz—a 1000 times faster than silicon ([Sensale-Rodriguez et al., 2012](#)). In very special cases silicon has been able to meet this but not without excessive cooling and other accessories as was observed by [Krithivasan et al. \(2006\)](#).

According to [El-Kady and Kaner \(2014\)](#), graphene-based electronics could find use in communications and imaging technologies, where their inherent speed is a major advantage. High-frequency applications could be graphene's first successful applications. Graphene-based chips could also be made much smaller than its silicon counterparts perhaps smaller than a nanometer. Graphene, therefore, could be considered as the agent of further electronic miniaturization.

Initially, graphene research was focused on nanotubes ([Mittal et al., 2015](#)). These are essentially a graphene sheet rolled into a tiny cylinder. These tubes had excellent electrical properties. However, the problem with nanotubes is that they have to be positioned in order to produce practical circuits. [Jiao et al. \(2009\)](#) assert that this positioning has so far eluded graphene tube developers.

Single-atom thickness allotropes of phosphorus, silicon, and tin have a somewhat similar honeycomb-based structure. They were named phosphorene, silicone, and

stanene (Balendhran et al., 2015). They also have interesting properties. All four promises miniaturization, increased performance, and significant cost reduction. Experts believe that graphene-based technologies are close to be commercialized (Zurutuza and Marinelli, 2014). Will it disrupt electronics? This remains to be seen.

2.5.5 Organic electronics

The development of conducting polymers and their applications resulted in another Nobel prize, which was awarded in 2000 to Hideki Shirakawa, Alan G. MacDiarmid, and Alan J. Heeger. Their researches proved that plastic can conduct electricity (Shirakawa et al., 2003).

Organic electronic materials are constructed on a carbon-based backbone much like polymers. They are created by means of a chemical synthesis called polymerization. According to Wang et al. (2012) organic electronics, however, is not limited to conducting polymers. This class of materials includes other organic substances that could be used in electronics. These include dyes much like the materials used in NLO. Organic electronics promise advantages; low material and production costs are the most important among these. According to Heininger et al. (2004) mechanical flexibility is paramount in molded interconnect devices (MIDs) and hence a lot of interest in organic electronics. The synthesis processes are flexible enough to enable rapid growth of this technology. Biocompatibility makes organic electronics a desirable choice for in-vivo applications, so perhaps medical applications will also embrace this new technology (Irimia-Vladu et al., 2011).

Organic semiconductors are already incorporated into curved displays, like television and smartphone screens in the form of organic light-emitting diodes (OLEDs). OLED is an LED (light-emitting diode) that contains at least one layer of film composed of an organic semiconductor material. This material acts as an emissive electroluminescent layer (Dodabalapur, 1997). This organic semiconductor layer is situated between two electrodes and lights up in response to an electric current. One electrode is transparent so that light produced by the application of a current can be utilized as a pixel element in a digital display. One such application is an OLED TV. The major advantage of an OLED TV is its thinness and lightness. It reportedly uses less power than liquid crystal display (LCD) TVs while achieving a high contrast ratio to display deep black levels according to Yoon et al. (2013).

Other applications include portable solar cells and colored light sources. Consequently, organic electronics is considered to be the most mature technology, which was discussed so far. The organic electronics market is poised to grow quickly in the near future (Reynolds, 2006). Will it be fast enough? What will be organic electronics' market penetration within 5 years?

2.5.6 Molecular electronics

Currently, the paramount aim of electrical circuits is miniaturization. Molecular electronics is also known as single-molecule electronics (Tour, 2000). Avouris (2002) asserts that this field is considered to be a branch of nanotechnology. It supposedly uses

single molecules, although recently a collection of molecules were used as electronic building blocks. Molecular electronics is arguably in the position to create some of the smallest possible electronics. Imagine combining molecular electronics with organic electronics packaging. The small becomes miniscule. Molecular and organic electronics can complement each other and also have a lot in common. These two fields overlap in many aspects. While the organic electronics label means bulk applications, its twin brother the molecular electronics tags very small usually nanoscale and sometimes even single-molecule applications.

Feature sizes of electronic components have shrunk because of miniaturization. In molecular electronics, the bulk material used in conventional electronics is discarded and replaced by single molecules. Shrinking electronic components decreases power consumption while at the same time increasing sensitivity and performance of the device. Some molecular systems are self-assembling, that is, they create their own functional blocks according to [Klein and Shinoda \(2008\)](#). This is, however, not as simple a proposition as many commercial TV commentators hinted. Therefore, it is not expected that currently injection-molded products such as electronics enclosures would be made this way even if they are to take over all the electronics functionalities such as in MIDs. While several devices have been displayed in the scientific press like molecular wires ([Guldi et al., 2015](#)), transistors, and rectifiers yet, molecular electronics is still in the early research phase. It is worth remembering that none of these devices have left the industrial research laboratory.

However, large NLO's; spintronics'; memristors'; 2-D, organic, and molecular electronics' disruptive power MEMSs have already started changing electronics in a fundamental way. Therefore, an in-depth look is needed in order to understand the consequences of electronics enclosures, housings, and packages.

2.6 Microelectromechanical systems

MEMSs have been identified by [Walsh \(2004\)](#) as one of the most promising electronics adjacent disruptive technologies. Since then MEMS technology has proven the potential to revolutionize products ([Perlmutter and Breit, 2016](#)). Therefore, enclosures, housings, and packages all benefit from developments in this area. Hence this technology will be explicated in detail.

[Sarro \(2000\)](#) explains that MEMSs combine silicon-based electronics with applied mechanical engineering technologies. This technology then clearly falls into the integrated innovations category mentioned earlier. Microsystem-based devices have the unmitigated potential to disrupt current market segments and associated industries. MEMS also allows previous innovation waves such as electronics to be reinterpreted thereby fulfilling predictions made by [Tilli et al. \(2015\)](#) and [Xiong et al. \(2016\)](#).

MEMS is an acronym of a general technology trend that encompasses creation of miniscule and at the same time integrated devices, preferably entire systems or at least subsystems that combine both traditional electronics and mechanical features. [Madou \(2011\)](#) emphasizes that these devices are typically manufactured using traditional

integrated circuit (IC) fabrication processes. Typically, their size is comparable to IC chips. Therefore, some of their features might be measured in the nanometer scale. These systems generally have abilities like their larger cousins, that is, they are capable to control by sensing and actuating other macro-sized devices or creating effects that are useful and often observable on the human scale (Mcevoy and Correll, 2015).

Like with many new technological endeavors, labels are yet to be universally agreed upon as the MEMS acronym originated from the United States and is alternatively referred to as micromachines in Japan and termed as Microsystems Technology (MST) in most of Europe (Frank, 2000).

Generally, MEMS consists of electronics, mechanical structures, sensors, and actuators all purposefully integrated into a single package, assert Nguyen et al. (2002). As in macrodevices, sensors detect changes in the system's environment. Microsensors also measure magnetic, electric, mechanical, thermal, or chemical properties according to Zhuangde (2012). Localized electronics process this information, thereby improving reaction time of the system. Rebeiz (2004) elucidates that MEMSs condition an appropriate signal and trigger an on-board actuator to drive external changes.

MEMSs are often considered to be part of the newly emerging nanotechnology innovation wave as most of these devices are indeed very small, states Bhattacharyya (2015). Their components are usually measured in micrometers and their smallest components can indeed be measured on the nanoscale. Therefore, they are often truly microscopic. Many mechanical components such as hinges, pivots, levers, and gears were fabricated to prove viability of the MEMS scale. More complex systems such as pumps (Grzebyk et al., 2015) and motors (Balach et al., 2016) were also created.

MEMS technology has three distinct advantages according to Doerr et al. (2006). Firstly, MEMS is integrative and interdisciplinary at the same time. Usually electronics techniques are leveraged into another field such as mechanical engineering, but often hitherto unrelated fields such as biology and electronics are exploited together in a synergistic manner. Such integration produced a variety of new devices. Secondly, MEMS improves performance and reliability while at the same time reduces size, mass, and cost. Thirdly, MEMS also provides unique products that can only be made by micro-manufacturing methods. These three substantial factors make MEMS a disruptive technology, insist Tilli et al. (2015). Many argue that MEMS in fact is more disruptive than ICs were. However, there are many challenges that need to be solved before MEMS can achieve its potential, believes Mounier (2014). Many current obstacles are associated with miniaturization that an enclosure engineer focused on packaging technologies can successfully overcome.

2.6.1 *Developments*

Ho and Tai (1998) believe that the earliest known application of MEMS was in 1958. MEMS follows the usual technology adoption "S" curve as was indicated by Hall and Khan (2003). It started a slow progress in the late 1950s as it has made its slow progress out of research laboratories and into commercial products. In the mid-1990s noticeable progress was made; MEMS components began appearing in numerous products. The applications included accelerometers for control of airbag deployment

in automobiles and pressure sensors for medical device applications (Niarchos, 2003). Nevertheless, this technology was most successful in the inkjet printer head application, states Wijshoff (2010). Today, MEMS devices are proliferating according to Tilli et al. (2015).

They are found in unique applications such as retinal prosthesis (Lee and Ko, 2017) or in neural probes (Jeon et al., 2014). Generally, MEMS technology has been successfully applied in the following industries: aerospace, automotive, biomedical, chemical, communications, consumer products, fluidics, optics, and others such as industrial automation and process control acknowledge Tilli et al. (2015).

Saffo (1997) explains that the history of MEMS innovation is also useful to illustrate its adoption curve that mimics the normal S curve with limited success at the beginning and at some point, rapid proliferation. MEMS technology is currently in the rapid expansion phase as illustrated by Fig. 2.8. Therefore, it is essential for an enclosure engineer to become acquainted with this promising technology.

1950s

1958 According to Ikeda et al. (1990), silicon strain gauges were introduced, thereby heralding the new era of MEMS technology.

1959 “There’s Plenty of Room at the Bottom”—physicist Feynman (1960) speaks at the California Institute of Technology on December 29, 1959 in which he famously declares a public challenge by offering \$1000 to the creator of an electrical motor smaller than 1/64th of an inch (slightly less than 0.4 mm). However, according to Wanninayake (2015), it is important to note that Feynman’s talk went unnoticed at the time. Despite statements to the contrary it did nothing to inspire the conceptual beginnings of nanotechnology. Interestingly, his talk was only rediscovered and publicized as a seminal event in the field as late as the 1990s at the time when the technology adoption rate started to show promise. Perhaps a bit of a “smoke and mirrors” of who has truly accelerated the innovation adoption rates?

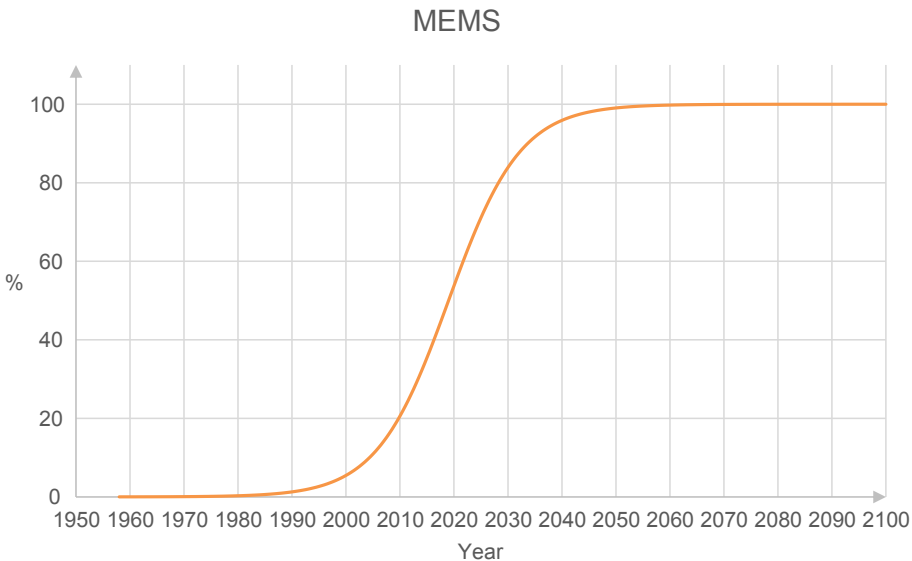


Figure 2.8 MEMS technology adoption curve.

1960s

1961 First silicon pressure sensor was manufactured (Bogue, 2007).

1967 Bustillo et al. (1998) state that surface micromachining was invented. Liu (2005) adds that Westinghouse introduced the first resonant gate field effect transistor (RGT) at the same time.

1970s

1970 First silicon accelerometer was shown to the public (Lynch et al., 2003).

1979 Fuller et al. (2002) assert that the first micromachined inkjet nozzle was prototyped.

1980s

1982 Disposable blood pressure transducer was created (Bryzek, 1996), which allowed MEMS technology to begin to colonialize medical device applications.

1982 Petersen (1982) published an important paper to the scientific and engineering community by providing material properties and etching data.

1982 LIGA process was invented according to Lorenz et al. (1998).

1988 First MEMS conference was held (Ameel et al., 1997).

1990s

1991 New methods of micromachining were created, which improved MEMS sensors according to Gad-El-Hak (2006).

1992 Markus et al. (1995) state that MCNC started the Multi-User MEMS Processes (MUMPs). This was supported by the Defense Advanced Research Projects Agency (DARPA).

1992 Xie et al. (2003) believe that the first micromachined hinge was created in 1992.

1993 First surface micromachined accelerometer was developed and marketed according to Lynch et al. (2003).

1994 Deep reactive ion etching was patented and this new technology was described by Klaassen et al. (1995).

1995 Tili et al. (2015) emphasize that a few BioMEMS applications were developed as early as the mid-1990s.

2000s

Proliferation phase of MEMS innovation adoption starts with the introduction of MEMS optical-networking components, declares Gad-El-Hak (2006) in his handbook. In addition, numerous other applications were developed at the same time.

2010s

Climbing on the “S” curve: MEMS technology was adopted rapidly by aerospace, automotive, biomedical, chemical, communications, consumer products, fluidics, industrial automation, optics, and process control according to Perlmutter and Breit (2016).

2.6.2 Definitions

The most numerous application of MEMS is in sensors and actuators (Bell et al., 2005). So, at this point it is important to define what a sensor and an actuator is.

A sensor is a device that receives input from its surrounds, measures this input, and provides an output signal proportional to the parameter being measured, assert [Henry and Clarke \(1993\)](#).

Applications for sensors include the following according to a list compiled by [Shipway et al. \(2000\)](#):

- Mechanical—acceleration, force, position, pressure, velocity, etc.
- Thermal—entropy, heat, heat flow, and temperature.
- Chemical—composition, concentration, and reaction rate.
- Radiant—intensity, phase, polarization, reflectance, refractive index, transmittance, wavelength, etc.
- Magnetic—field intensity, flux density, magnetic moment, and permeability.
- Electrical—capacitance, charge, current, polarization, resistance, and voltage.

[Hu and Lin \(2001\)](#) state that an actuator is a device that converts an electrical signal into a mechanical motion. An actuator can create a force to manipulate the system, other devices, or the neighboring environment to accomplish a useful function.

2.6.3 Applications

Currently the aerospace, automotive, biomedical, chemical, communications, consumer products, fluidics, industrial automation, optics, and process control industries utilize MEMS technology ([Perlmutter and Breit, 2016](#)). However, this list grows daily. Some of the applications are firmly established such as pressure sensors, while others are new like retinal prosthesis.

- The automotive industry uses a variety of sensors that are MEMs. These include airbag deployment, air conditioning compressor, brake force, fuel level, intelligent tires, internal navigation sensors, suspension control, and vapor pressure measurement applications.
- Communications-related applications include couplers, fiber-optic network components, filters, relays, splitters, switches, tunable lasers, and voltage controlled oscillators.
- Defense application consists of data storage, munitions guidance, remote control of equipment, and surveillance.
- Electronics applications include data storage, disk drive heads, earthquake sensors, inkjet printer heads, and pressure sensors.
- The medical device industry utilizes analytical instruments, blood and other pressure sensors, drug delivery systems, pacemakers, and prosthetics.

2.6.3.1 Automotive airbag sensor

Automotive airbag sensors were the first mass produced devices using MEMS technology, explain [Eddy and Sparks \(1998\)](#). These devices are ubiquitous today. Current airbag deployment is driven by a single chip. The system contains an accelerometer, which measures deceleration of a vehicle. During a crash the deceleration is so rapid that a threshold value is exceeded. The deceleration value is then transmitted as a change in voltage. The electronic control unit part conditions an appropriate signal to trigger airbag deployment and rapidly fill the airbag.

Airbag deployment was originally triggered by a purely mechanical “ball and tube” type accelerometer, explicate [O’reilly et al. \(2008\)](#). Such a device was not only complex

but also was heavy and costly. A “ball and tube” type device was typically located at the front section of the automobile. This mounting location necessitated the utilization of separate electronics controlling the airbag housed close to or within the steering column.

Zimmermann et al. (1995) highlight that MEMS has enabled equivalent functionality to be realized by integrating the accelerometer and the electronics into a single silicon chip. The resulting device is tiny and consequently can be located close to the airbag within the steering column, thus enabling faster deployment. This improvement also reduced the manufacturing costs drastically enabling rapid universal adoption.

The accelerometer part is essentially a miniscule pendulum incorporating a carefully sized mass as described by Lynch et al. (2003). As acceleration forces act on this mass, the micromachined capacitive or piezo-resistive membranes sense this change and provide an input signal into the controlling electronics component.

The airbag sensor application is fundamental to the overall success of MEMS technology (Gad-El-Hak, 2006). Over 100 million devices were sold and proved reliability and cost-effectiveness of MEMS technology, enabling rapid proliferation of automotive MEMS components.

Today a typical new car contains many MEMS devices in its active suspension, anti-lock braking system, appliance and navigation control system, fuel system sensors, noise reduction, rollover detection, seatbelt restraint tensioning, vibration monitoring, and other areas (Kraft and White, 2013). Consequently, the automotive industry has become the main driver for this technology.

However, the generic underlying fundamental component in the airbag sensor: an accelerometer is a device that has many potential applications. Some of the many likely uses for accelerometers include earthquake detection, pacemakers, video games, and weapon systems as stated by Kaajakari (2009).

2.6.3.2 *BioMEMS*

MEMS technology is applied to a diverse range of problems from DNA sequencing, drug discovery, to environmental and water quality monitoring in accordance with a review performed by Grayson et al. (2004). BioMEMSs integrate a microfluidic system with chemical testing. Emerging devices include chemical sensors, flow controllers, “lab-on-a-chip,” nozzles, and valves (Tay, 2002). A microfluidic system typically contains one or more pumps, chemical and flow sensors, explicates Saliterman (2006). BioMEMSs enable convenient and fast manipulation of miniscule amount of liquid volumes. Most often, these manipulations are done to ascertain properties of the fluid. Giouroudi et al. (2008) highlight that bioMEMS devices allow monitoring patients’ own conditions, including blood and urine analysis or pregnancy testing. Therefore, home-based medical applications are on the increase, presenting opportunities for packaging as well as housing experts.

Folch (2016) provides an example of a successful bioMEMS device that is displacing traditional test tubes from laboratories. Once again, this emerging technology has many labels such as the titerplate, microplate, microwell, or multiwell. Despite the numerous labels, they all mean the same thing, that is, a flat plate with multiple cavities

used as small test tubes. This device has become the standard tool in research and diagnostic laboratories. This is a simple MEMS product that contains small channels that utilize capillary action in their large number of cavities. These devices are classified as a “lab-on-a-chip” product (Ahn et al., 2004).

Oosterbroek and van den Berg (2003) assert that the evolution of a “lab-on-a-chip” might include implantable “pharmacy-on-a-chip” devices soon. These devices comply with a predetermined drug release profile according to Shawgo et al. (2002). Physicians no longer need to worry about overdosing or underdosing a patient, and these devices will one day eliminate the need for painful injections. Drug delivery of insulin is one target application (Ma et al., 2006). Polla (2001) points out that other applications include chemotherapy, hormones, and painkillers. A first-generation device releases its medication when an appropriate signal is received from an external hard-wired source. A second-generation device does the same thing but wirelessly. A third-generation bioMEMS chip interacts with MEMS sensors embedded in the human body and responds to internal signals according to Rousche et al. (2001).

Keloth et al. (2016) explain that one third-generation bioMEMS incorporates a structure that interacts with single cells. The device contains small silicon teeth that trap and release a single cell. The function of this device is to puncture cells and inject them with substances such as DNA, proteins, or pharmaceuticals. The purpose of this bioMEMS is to counter attacks, imbalances, and infections.

2.6.3.3 Inkjet printer head

According to Gardner et al. (2001) one of the most successful early MEMS applications was the inkjet printer head invented by Hewlett–Packard in 1979. At one time this was the largest volume MEMS manufactured (Tanner, 2009). There were more inkjet printer heads manufactured than automotive and medical pressure sensors combined.

Enclosures, housings, and packages can all benefit from 3D printing. Derby (2010) sees an opportunity in that HP’s technology is no longer protected by patents and a certain class of 3D printers utilize similar technology. Wijshoff (2010) explains that inkjet printers still use small nozzles to spray tiny drops of ink directly onto a substrate the printing medium. These droplets of ink are formed either piezoelectrically or thermally.

Thermal formation of droplets utilizes a microprocessor to issue brief pulses to a resistor that heats the ink, elucidate Singh et al. (2010). Ink flows over each resistor, which vaporize the ink to form a bubble, add Meinhart and Zhang (2000). As the bubble expands, some the ink is forced out of a nozzle. As the bubble ultimately collapses, a vacuum is created, which draws more ink into the head from the cartridge. A piezoelectric element can also be utilized for the same purpose (Wijshoff, 2010). In this case, a piezoelectric crystal element vibrates when a small electric charge is received. This vibration forces the ink out of the nozzle. In the crystal’s reverse stroke, it draws more ink from the cartridge. There are no moving parts in either system.

Printer heads evolved over time and the evolution was reviewed by Park et al. (2007). Early copies had only a dozen nozzles with resolution capability of 92 dpi.

Modern heads have 600 or more nozzles with a respective capability of at least 1200 dpi. It is possible that this technology will enable low-cost multimaterial, multi-color 3D printing (Derby, 2010). At least one injection molding machine manufacturer has developed such a system, explicates Berger (2015), but the technology has not yet caught the imagination of designers and manufacturing engineers. Nevertheless, this technology promises to be a game changer in small-volume, highly specialized enclosure, housing, or package development.

2.6.3.4 Medical pressure sensor

Hill et al. (2007) describe a miniature disposable pressure sensor that is used to monitor blood pressure in hospitals. These sensors are in fact MEMS based. The sensor connects to a patients' intravenous (IV) line and monitors the blood pressure via the IV solution. The sensor's cost is about 1%–2% of the previous non-MEMS variety. In addition, external blood pressure sensors had to be recalibrated and sterilized before each use. Patients also benefit from the newer MEMS technology as the previously painful needle jab is no longer needed. Therefore, a win–win situation can be credited for the huge success of this device.

The disposable sensor contains a piezo-resistive layer that is applied on a membrane surface to convert mechanical stress into an electrical voltage (Lynch et al., 2003). Measured pressure is proportional to deflection of the membrane and therefore voltage level. The sensing element is mounted on a base to fit into a manufacturer's housing.

According to Gad-El-Hak (2006) pressure sensors are the largest-volume mass produced medical MEMS application. Accelerometer MEMS, however, are gaining acceptance, writes Kaajakari (2009). A pacemaker design described by Tashiro et al. (2002) includes a MEMS accelerometer that measures the patient's activity levels. This technology has some similarity with airbag sensors. The accelerometer allows the patient's activity level and actual motion to be monitored. The MEMS conditions the relevant signals and sends it to the pacemaker to carry out the necessary adjustments.

2.6.3.5 Microoptical-electromechanical systems

Rai-Choudhury (2000) observes that microoptical-electromechanical systems or MOEMSs are important, as optical communications provide the only practical means to “big data” and IoT. In other words, MOEMSs address the network scaling issues created by the exponential growth in data traffic. Traditional routing technology slows the data flow by performing an optical to electronic to optical transformation. Keeping information in an all optical data flow provides superior throughput capabilities.

The MOEMS include attenuators, cross-connects, detectors, equalizers, filters, modulators, multiplexers, optical switches, and waveguides, lists Leondes (2007). Lapisa et al. (2011) believe that MOEMSs provide an inherent advantage in accuracy, batch processing, cost, mechanical durability, power consumption, size, and switching density. As such they appear to be a perfect solution to the issues currently facing large networks, states Motamedi (2005). While a typical optical switch can cost over \$1000,

their MOEMS counterpart provides the same functionality for less than a dollar. Therefore, not surprisingly MOEMS technology was adopted remarkably rapidly.

2.6.3.6 Overhead projection display

MEMS technology's maturity is demonstrated by the fact that one of its early application that is of the overhead projection display is fading rapidly. This application the Digital Micromirror Device (DMD) was developed by Texas Instruments ([Bloom and Tanner, 2007](#)). The device contained over a million tiny pixel-mirrors each measuring $16\text{ }\mu\text{m}$ by $16\text{ }\mu\text{m}$ and was capable of 20° rotation over 1000 times a second, explicates [Greivenkamp \(2004\)](#). While the original application is no longer commercially viable, alternative uses such as directed energy applications might rejuvenate this aspect of MEMS technology according to [Kanskar et al. \(2017\)](#).

2.6.3.7 Radio frequency microelectromechanical system

This is a growth area in MEMS production, state [Goggin et al. \(2015\)](#). RF MEMSs are designed specifically for cellular phones and other wireless communication applications. The introduction of RF MEMS has increased functionality, performance, and reliability while lowering associated costs and minimizing size. The RF MEMSs incorporate circuit tuning elements such as capacitors, filters, inductors, resonators, microphones, and switches. Low-loss small size position RF MEMS to replace traditional RF elements and allow creation of entirely new RF devices. It is projected that RF MEMS components continue to replace classic components in mobile phones, allowing cellular phones to shrink and decrease power consumption, assert [Carty et al. \(2016\)](#).

2.6.4 Miniaturization issues

MEMS is about the miniscule; it is a technology to create tiny integrated microsystems using IC fabrication techniques according to [Leondes \(2007\)](#). However, [Tilli et al. \(2015\)](#) insist that miniaturization is about shrinking existing devices and their costs. It is also about affording a complete rethink of the underlying structure of the entire system.

Major miniaturization issues of MEMS currently include the following:

- Cost was extensively studied by [Lawes \(2014\)](#): spectacular cost minimization is expected from every MEMS device. Many believe that acceptable cost minimization can only be achieved by IC batch fabrication methods. Yet other mass production methods might be relevant such as injection molding. No one, however, argues the necessity of high-volume production.
- [St-Gelais et al. \(2015\)](#) focused on heat transfer: heat dissipation is increased while heat storage decreased. Therefore, heat transfer could be improved, provided great expertise is applied.
- Integration issues were highlighted by [Zhuang and El-Sheimy \(2016\)](#): It is complex interdisciplinary and device specific. X-on-a chip system components may not scale down as expected without additional research.

- [Kim et al. \(2014\)](#) explicate material properties: material selection and analysis based on classical data might lead to unacceptable errors. Grain structure, Poisson's ratio, Young's modulus, and other elements of mechanical theory such as fatigue, residual stress, and wear might be size dependent at the nanoscale.
- Physical properties such as friction might be greater than inertia and atomic, capillary, electrostatic, and static friction at a nanolevel can be significant design drivers, advise [Hoang et al. \(2017\)](#).
- Testing issues are covered by [Osten \(2016\)](#) and he explains that miniaturized device packaging and testing is not straightforward. Packaging a large portion of the device costs sometimes greater than 70% ([Ge et al., 2017](#); [Uzunlar and Kohl, 2014](#); [Phillips and Kohl, 2015](#)). Testing is not rapid and is also expensive in comparison with conventional IC techniques.
- Transport properties: fluidic and mass transport properties are design critical. Miniscule flow spaces are blockage prone yet can precisely regulate fluid movement if designed appropriately warns [Chan et al. \(2015\)](#).

2.6.5 Industry challenges

All parts of the enclosure, housing, and packages industry face considerable challenge. Therefore, it is not surprising that the MEMS part of the industry also faces challenges. These include education and training; design, simulation, and modeling; packaging and testing; standardization; and manufacturing issues, list [Grace et al. \(2015\)](#).

2.6.5.1 Education and training

The integrative and interdisciplinary nature of MEMS creates a level of complexity that demands highly educated and extremely well-trained scientists and expert engineers from a diverse array of experiences and backgrounds, assert [Villanueva et al. \(2016\)](#). Qualified MEMS-specific, enclosure, housing, and packages engineering personnel is small and does not meet industry demand. Education at graduate level is a necessity. Expert external supervision is highly advisable to increase quality of graduates and lower costs.

2.6.5.2 Design, simulation, and modeling

[Shoaib et al. \(2016\)](#) imply that increased innovation and reduction of unnecessary "time-to-market" costs can only be achieved with an updated NPD model. Successful device development mandates modeling and simulation to be integrated with the NPD cycle, observe [Gmelin and Seuring \(2014\)](#). It is also important that MEMS designers have access not only to adequate analytical tools but also have the expertise to drive them in a way that creates value to the entire NPD process.

2.6.5.3 Packaging and testing

Packaging and testing of devices is a great challenge facing the MEMS industry, write [Shoaib et al. \(2016\)](#). MEMS packaging presents unique and significant problems compared to IC packaging in that a MEMS package must provide protection from an operating environment as well as enable access to it. Traditional housing engineers

are very familiar with this conundrum. This is one of the many justifications to integrate enclosure, housing, and package design and development. Consequently, packaging is the most expensive fabrication step and often makes up 70% while some manufacturers report as high as 90% of the final cost of a MEMS device (Ge et al., 2017).

2.6.5.4 *Standardization*

Due to MEMS technology's current position on the "S" curve (see Fig. 2.8), standardization has been very difficult, observe Grace et al. (2015). Therefore, reasonable quality control and standardization are generally only found at facilities with very large investment. Networking of small to medium-sized enterprises (SMEs) is important and necessary to lay an acceptable foundation for a global standardization system.

2.6.5.5 *Manufacturing*

Many MEMS companies have limited access to fabrication facilities for either prototype or device manufacture, explain Tilli et al. (2015). Most organizations expected to benefit from MEMS technology do not have capabilities and competencies to support successful MEMS fabrication. Affordable and cooperative access to fabrication facilities is crucial for the successful commercial exploitation of MEMS technology.

2.6.6 *The future*

The market for MEMS devices is currently undergoing an explosive growth phase according to Marek et al. (2016). MEMS is an enabling technology for the development and production of new industrial and consumer products. MEMS is also a successful disruptive technology in that it differs significantly from existing technology (Walsh, 2004). Thereby, MEMS is requiring a different approach, skill sets, capabilities, and competencies for successful exploitation (Tilli et al., 2015). Scaling, packaging, and testing issues of MEMS are significant (Shoaib et al., 2016). Like all disruptive technologies, MEMS faces challenges associated with rapidly developing processes that no longer fit established methods and personnel who often lack the necessary level of experience and expertise (Grace et al., 2015).

2.7 Technology review

In summary, the current global trend is to get ever-more power into an ever-smaller space in electronics. Cho and Goodson (2015) posit that this fact will have extremely serious consequences and as such deserves to be discussed in its very own chapter under heat management. There is also a remarkable long-term trend to integrate. In this context it meant along electrical elements, but now it also means to integrate between the active circuitry and its substrates. Siengchin et al. (2016) underline that this is the driving factor behind MIDs, which will be discussed in detail in the last book of this

handbook series. Electronics innovation waves were investigated and their effect on the electronic enclosure industry was explicated. Six emerging technologies and their potential disruptive influences were analyzed. It was found that NLO, spintronics, and memristors while being interesting concepts present no short- to medium-term disruptive power in the area of electronic enclosures. However, 2-D, organic, and molecular electronics present exciting potentials for the short and medium term. In addition, MEMS technology was reviewed as it represents one of the first nanotechnologies that have already progressed to the rapid innovation adoption phase. It is proposed that all technologies be monitored to prevent future surprises. Electronics innovation waves were investigated so that market based activities could be accounted for. Therefore, it is important to explore all active enclosure market segments in the next chapter.

2.8 Hot tips

A few tips could make all the difference between success and the lack of in the field of electronic enclosures:

- Innovation waves display trends that are important for the success of the electronic enclosures industry.
- Emerging technologies need to be monitored periodically.
- Technology review must be based on real information rather than hype.

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3.1 Introduction

It is important to consider how each industry benefits from a better understanding of electronic enclosures in line with the ideas advocated by [Masanet and Horvath \(2007\)](#). Specific themes emerge as each industry is studied ([Barnes et al., 2002](#)). However, there are also elements that are contained in every one of them. This handbook is focused on the similarities because collectively they provide a general platform for success in the field of electronic enclosures.

Enclosures found in diverse industries utilize different types of packaging design criteria ([Ulrich and Brown, 2006](#)). Industrial forms of electronic enclosures are usually labeled as electrical enclosures and protect the enveloped equipment from industrial conditions. Various industries use specialized enclosures to protect their equipment. Frequently chosen materials provide high impact resistance and medium-range heat tolerance as explained by [Ashby and Johnson \(2013\)](#). Transportation, energy, power, food and beverages industries have benefitted in the past from this standardized choice. Predetermined material selection created an opportunity for enclosure manufacturers to design cost-effective, standardized, and customized electrical enclosures for these industries. An example is provided by [Beutel et al. \(2009\)](#) in the field of instrumentation.

Several factors drive growth of the enclosures market. Foremost among these is the continued and accelerating trend of automation ([Ford, 2009](#)). Most visible is home and automation according to [Gomez and Paradells \(2010\)](#). [Claudel and Ratti \(2015\)](#) think that the future of automotive automation is also bright. Industry, however, is the driving factor of low-quantity but high-profitability enclosure production, and it absorbs these devices in its general and process automation markets ([Jämsä-Jounela, 2007](#)). Additional momentum is created by evermore stringent safety legislations. Global growth of both residential and industrial infrastructure also helps to create a stable almost noncyclic enclosure supply chain.

However, there are major impediments for maximizing growth of the electronic enclosure market. Chief among these is the high price of standard enclosures. According to [Rosato and Rosato \(2012\)](#) this is due to as much of the amortization of tooling, particularly injection molding tools, but also contributing factor is the ability of profit taking. Currently, the electronic enclosures market is highly fragmented with a few large global participants and many small to medium-sized enterprises participating. Global original equipment manufacturers (OEMs) play an important role in driving the supply chain of enclosure products. The result of the perceived needs of these large OEMs is that custom enclosures with high level of customization are in great demand ([Salim et al., 2017](#)). Distinctive project requirements such as the assurance of great

levels of modularity advocated by Ulrich (1994) provide opportunities not only for growth of the entire market but also for the very few competent knowledge providers.

Growing residential and industrial infrastructure in addition to the noticeable expansion in the energy transmission and distribution (T&D) network are significant driving factors for the growth of the global electrical enclosure market. This segment of the enclosure market is expected to reach \$6B by 2020, at a compound annual growth rate of 7% between 2015 and 2020. The true size of the electronic enclosures market is hidden as OEMs capture and drive almost all the input from the supply chain. While number of units shipped can be estimated, their value is much harder to ascertain as was stated by Rosen (1974). The growth rate is estimated to be greater than the electrical counterparts and assumed to be around 8%–10% in accordance with the method utilized by Bodie (2013). The electronic enclosure market is often estimated to be several times larger than the electrical enclosures market. The total market is estimated to reach at least \$50B by 2020.

3.2 Aerospace and defense

This category was created by economists (Rodríguez-Segura et al., 2016). From the electronic packaging point of view there are significant differences between aviation-related, space explorations, and defense applications. While the first two, for instance, put a premium on minimizing mass (Liem et al., 2014), the latter one focuses on robustness and field serviceability (Goertz, 1989).

3.2.1 Avionics

According to Jones and Gross (2014) avionics has strict size, weight, and power consumption requirements. It also must deliver adequate heat dissipation while meeting relevant aerospace and defense standards. Increased capability means more power consumption and hence larger heat loads. Heat management challenges are made even more difficult by the remote locations and temperature extremes. Despite of these challenges avionics must operate reliably and without fail (Li et al., 2015).

3.2.2 Unmanned aerial vehicles

Unmanned aerial vehicles (UAVs) are also known as drones (Tsach et al., 2010). These are variously sized aircrafts that may be remotely controlled or can fly autonomously. Autonomous flight of drones is controlled by sensors, global positioning systems (GPS), and embedded systems according to Valavanis and Vachtsevanos (2014).

Low-cost and at the same time high-quality consumer drones have created a new category of products according to Anderson and Gaston (2013). These have massive appetite for the right electronic enclosures. Goerzen et al. (2009) posit that they integrate aerospace engineering and consumer electronics practices. The future seems to be bright for the enclosure specialist in this market segment. However, there is huge

pressure to contain risks associated with the use of drones. Zoldi et al. (2015) assert that there seems to be an agreement that new regulations are needed.

The new regulations should balance security, safety, and privacy aspects. The Federal Aviation Administration (FAA) is developing new rules to govern UAV use. According to Marshall (2016) rules will include where and how drones could be flown. However, other experts argue that overregulation will have a negative effect on the UAV market segment (Matiteyahu, 2014).

3.2.3 Defense applications

Moore and Shi (2014) emphasize that as additional electronic components are packaged into ever smaller space, there is an associated increase in thermal density. In addition to the thermal density challenge, the operating environments demand specialized solutions. Schelling et al. (2005) warn that ambient temperatures can reach well over 55°C, which require special considerations and unique thermal designs. Operational requirements also include prevention of sand, dust, water, and other elements. These in turn require a sealed solution to make heat management an even greater challenge. Primary objective of a good defense enclosure is to increase service life and operational range by incorporating proper cooling and protection strategies.

3.2.4 Space applications

Scott (1991) implied that space exploration was a major driving force for the development of electronics. Even today, projects like the International Space Station pay for the emergence of new design techniques. For example, few realize that the Space Race afforded the impetus for creation of the integrated circuit (Dawson, 2017). Today these once high-tech components are incorporated into various consumer electronics. The Space Race is relegated into history books, and as a result there are only a few electronics producers who remain to serve this field. As a result, a technology gap now exists between space and commercial components.

Electronics designed for space applications experience one of the harshest environmental conditions possible (Navarro et al., 2014). A rocket launch imposes severe vibrations on electronics and this is only for starters. Space electronics must also endure extreme temperature variations. Only radiation heat transfer is applicable due to vacuum. A satellite on earth orbit experiences a temperature difference of 270°C as the temperature into the sun is 120°C while in the shadow it is -150°C. The most common electronics cooling method is simply not possible, once again due to vacuum. Therefore, electronic enclosures are designed to channel heat from the sun facing to the shadow side. Panels on the shadow side radiate heat out to space. In addition, space enclosures must not release vapors that would interfere with operation of other equipment. Space-qualified electronics must not outgas and as a result the enclosure must be made of ceramic materials. This requirement prevents use of commercial components utilizing plastic packaging according to Label and Sampson (2016). In addition, space electronic enclosures must withstand high levels of radiation. Extreme vibrations, temperature differentials, material restrictions, and radiation levels all create unique

requirements. Consequentially, electronics development today is no longer fueled by space exploration (Dawson, 2017). Instead consumer electronics provide this momentum (Wei, 2014). Meanwhile continued space applications demand enclosures that are safe and reliable.

3.3 Automotive

The range of transportation modes: road, rail, shipping, and air all use electronic enclosures. Aerospace and aviation has rapidly evolved and their use of electronics could be considered somewhat mature (Hanssen et al., 2017). However, the automotive industry is overdue for a paradigm shift based on Kondratieff-waves-theory (Kondratieff, 1979). Not surprisingly, even if somewhat belatedly, in-vehicle electronics are bringing a shift to the world of cars, trucks, and buses according to Fleming (2015). Liu et al. (2016) believe that the current trend is toward automation and connectivity. This means that automotive is a segment where the use of electronic enclosures will grow exponentially.

It would be an oversimplification to state that nothing is changing on the mechanical side of the automotive industry. After all internal combustion engines and the relatively recently “rediscovered” electric motors have been around for a long time as was observed by Kumar and Jain (2014). Yet, these major components now attracted many electronic accessories. Furthermore, these components are more and more integrated into their hosts presenting new opportunities for the well-prepared electronic package designers.

Consider a not so distant future in which drivers merely position themselves in their cars as computers perform the drudgery of driving (Car, 2014). Of course, not everyone is at peace with this idea. Machines taking over control of road-going vehicles still sound slightly futuristic. However, driverless cars have almost arrived.

3.3.1 In-vehicle systems

In-vehicle electronics permit the auto industry to provide its end-users with greater functionality. Reliance on electronics increased safety levels, decreased fuel consumption, and introduced new levels of in-vehicle information and connectivity (Zeng et al., 2016).

As a result, in-vehicle systems offer an excellent opportunity to the electronic enclosure supply chain. OEMs utilize vehicle electronics to achieve environmental and safety compliance. Siano et al. (2017) state that electronics sometimes assist in the subversion of compliance by mimicking sought after vehicle behavior, for instance, in emission controls. However, most applications are benign and developed to advance compliance and other functions. As a result, this segment is expected to expand rapidly.

Currently, according to Hank et al. (2013) an average vehicle contains more than 50 microprocessors. More than 100 sensors provide information to be processed by the microprocessors connected by over a kilometer-long wiring. Industry experts estimate

that in-vehicle electronics amount to 40%–50% of the total cost of an average vehicle. This fact seems to underscore that this market demands ever-increasing applied enclosure knowledge especially when rapid growth is also factored in.

The main components of in-vehicle electronics are the actuators, controllers, displays, microprocessors, instrumentation panels, and sensors (Patsakis et al., 2014). These specialized components need customized enclosures in the various systems such as chassis control, communications, diagnostics, emissions monitoring, engine management, entertainment, measurement, navigation, and safety systems.

A design challenge is to provide an operational life of 20 years or more according to Zhang and Liu (2002). Enclosures must defend the electronics from extreme temperatures, weather conditions, variety of loads experienced during congested city driving or long-distance cross-country trips, and even from the occasional off-road adventures. The combination of these conditions makes designing proper enclosures challenging.

Converged vehicles combine automated and connected technologies (Lee et al., 2014). Their many benefits include enhancement to safety, potentially increased road capacity, and the reduction of congestion, thereby lowering overall fuel consumption. A converged vehicle uses a myriad of sensors and wireless communication to collect data and process this information to make navigational decisions. Such a vehicle transmits its own data to the environment allowing other road users to capture and harness this information. Therefore, converged vehicles provide proof of a new wave existing according to Kleinknecht (2016).

3.3.2 Automated vehicle technologies

The current speed of technological advancement in the area of automated vehicle technologies is amazing according to Denaro et al. (2014). Nearly all major OEMs started their research and development activities. Tier 1 suppliers such as Bosch, Delphi, TRW, and others are developing many of the advanced technologies. Initially, automated vehicle technologies were developed to aid the driver. According to Khachane and Shrivastav (2016) these included antilock brakes and electronic stability control, which through use of sensors and microprocessors were able to provide an interpretation of driver's intention and engage the appropriate braking system to improve vehicle operation. Newer technologies are designed to correct driver's error. Future technologies will automate vehicle movements. Experts such as Flemisch et al. (2014) believe that a fully automated vehicle is within reach in a decade.

Active parking assistance has been offered as an option on some vehicles (Swan, 2015). This system provides driver feedback through cameras and sensors. Current automated parking systems still require a driver to apply the brakes while the system only provides steering action. It is expected that soon drivers will be able to choose a potential parking spot, immediately leave their car, and permit the car to maneuver into the chosen location. Such an advanced system would also allow achievement of greater parking densities. Miller and Valasek (2015) question how such an overzealous exploitation of parking spaces would affect drivers of conventional cars and warn that this issue, among many others, remain to be resolved.

The ultimate aim of automated vehicle technology developers according to [McGehee et al. \(2016\)](#) is to achieve automated operation in densely populated cities and highways. Congested roads can be puzzling for drivers. Development of an automated vehicle to master such a complex environment is complicated and could take much longer than currently expected ([Denaro et al., 2014](#)). Yet automated vehicle technologies offer an exceptional platform for the electronic enclosure specialist.

3.3.3 Connected vehicle technologies

Car owners can already locate and start their vehicle remotely. [Narla \(2013\)](#) posits that this is only the first step of a revolution promised by connected vehicle technologies. Connected vehicles could share information, which could be utilized by other applications. Such an application could improve safety and mobility and reduce pollution and fuel consumption ([Bock et al., 2016](#)).

Applications leveraging vehicle connectivity sourced information can prevent collisions, optimize navigation decisions, and issue road condition warnings ([Guler et al., 2014](#); [Zha et al., 2016](#)). Vehicle safety applications might use a variety of ways to alert drivers to various threat levels. Advanced connected vehicle systems allow cars to actively avoid threats, by automatic application of the brake system.

The European proof-of-concept project, SARTRE, allows the formation of road trains ([Dávila and Nombela, 2010](#)). In the SARTRE system, the lead vehicle is driven by an operator. However, all other vehicles can be driverless. Connected vehicle technology is used by the cars to enter or exit a road train and follow the lead vehicle. SARTRE is harnessing information provided by cameras, lasers, and radars.

A wide array of communications technologies is available for connected vehicle communications. These include 5.9 GHz dedicated short-range communications (DSRC), third-generation (3G) and fourth-generation (4G) cellular communications, Wi-Fi, and Bluetooth, to name a few. Experts note that DSRC will be required for safety applications. Cellular communications might be enlisted to support additional applications.

Connected vehicle technology consists of several types of communication devices ([Guler et al., 2014](#)). Each in turn needs their own enclosure design. These include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-device communications.

- V2V refers to communication directly between vehicles. These might be adjacent or near-field communications.
- V2I systems link vehicles with the roadway, traffic signals, and other infrastructure elements, such as bridges.
- Vehicle-to-device communications allow cars to link with devices such as mobile phones or pedestrian transmitters. These systems allow cars to process additional information about their operational environments.

Many safety applications require V2V links. Such a connected vehicle system can provide blind spot warnings, can orchestrate multivehicle cruise controls, inform collision avoidance systems, activate brake lights, and issue lane change, road condition,

and emergency vehicle warnings. These applications utilize sensor-based solutions. They harvest information from cameras, radars, and lasers.

V2I applications leverage the cloud and robotics. V2I applications could announce warnings for various road conditions such as approaching curve speed, school, and construction zones. They can duplicate relevant road signs and display it within the vehicle. V2I can also improve intersection safety and alert drivers of a stop sign or other traffic signal. V2I allows drivers to optimize driving speed.

Vehicle-to-device technology could use mobile communications or specialized DSRC transponders to include other road users. Pedestrian applications could issue warnings to drivers if a pedestrian is about to cross the road. Such a feature could be very useful in darkness, sun glare, or in other weather-induced low-visibility. It is possible that public transport passengers could have access to real-time data on arrival and departure times and to optimize their travel during multimodal transport.

If test results of current research projects are positive, new vehicles may start to be equipped with connected vehicle systems. As connected vehicles increase, road transportation becomes safer and more efficient according to [Kamalanathsharma and Rakha \(2016\)](#), thereby accelerating market penetration of these devices. Hence, it is expected that enclosure specialization will continue to grow within the automotive sector.

3.4 Built environment (HVAC and vertical transport)

Smart buildings according to [Snoonian \(2003\)](#) deliver a built environment that makes occupants feel good or at least neutral and therefore more productive. The underlying concept is to reach this state potentially at lowest cost and minimizing environmental impact over the building's entire lifecycle. Achieving smart buildings categorization primarily requires the ability to execute intelligent design decisions. The concept of smart buildings is generally discussed with respect to commercial buildings. However, recent development indicates that most of these concepts rapidly gain traction in the private home markets, first in the multidwelling environment, for example, fire safety, and then gradually in the single-family home environment.

Smart buildings use advanced information technology during operation to integrate subsystems, which in the past have typically operated independently and without reference to each other ([Weng and Agarwal, 2012](#)). These systems now share relevant information to optimize building performance.

[Sinopoli \(2009\)](#) posits that smart buildings collect information beyond the building envelope. Systems are interconnected and interact with operators and occupants. This provides a new level of visibility, information, and performance. Generally, smart buildings consist of automation, control and monitoring, efficiency, elevators and escalators, energy, HVAC, lighting, networks including wireless, security, and smart meters. Most aspects of automation, control and monitoring, and networks are no different than in other applications. Security and smart meters have interesting enclosure aspects that are highly specialized and therefore beyond the scope of this handbook. Efficiency and energy aspects sometimes overlap other areas. It is better to approach these concepts through a focused discussion on lighting, HVAC, and elevators.

The built environment is generally more conscious of recent developments in lighting technology in the forms of light-emitting diodes (LEDs). In addition, heating, ventilation, and air conditioning (HVAC) has always utilized control modules housed in electronic enclosures. Improvements have allowed first a much greater interconnection in the form of building management systems and recently to network such environments. Today, a building supervisor might be located on the other side of the globe due to such networking abilities afforded by, for instance, chiller controls in an HVAC system (Tiwana, 2000).

Building owners know according to Arkin and Paciuk (1997) that two things repulse most tenants: badly performing air conditioning and unpredictable, slow elevators (lifts outside of North America). Elevators and escalators are the core products of the vertical transport industry. From the electronic packaging point of view LED, HVAC, and vertical transport have much in common as they all serve the same destination: the built environment.

3.4.1 Light-emitting diodes

LEDs initially claimed to produce no heat and never needed to be replaced as they somewhat magically possessed infinite life (Christensen and Graham, 2009). Once the hype died down, it was found that the first successful deployment was in various indicators, and in these applications, LEDs have appeared to produce no or rather negligible amounts of heat. Burned out LEDs soon invalidated the second sales argument. Conversely, these failures were blamed on heat management issues.

For a long time white light was the Achilles' heel of LED technology (Reineke et al., 2009). The introduction of high brilliance LEDs with white and monochromatic lights have opened the way for general illumination. Universal illumination introduced increased currents to the LEDs. This in turn highlighted heat management issues (Christensen and Graham, 2009). Although LEDs are much more efficient than the incandescent light bulb, thermal management became the key design aspect for both package and system level. Therefore, more attention was focused on thermal paths in LED enclosures.

3.4.2 Heating, ventilation, and air conditioning

Modern heating HVAC systems interface to the building automation system (BAS). Such systems afford control over heating and cooling units. Facility managers can monitor the BAS and devise corrective action as a response to alarms generated by the system. This activity could be done locally or remotely. Various schedules could be implemented based on planned and actual occupancy according to Agarwal et al. (2010). Alkar and Buhur (2005) state that there are numerous gateways that link advanced HVAC systems with either a home automation system or a BMS (building management system). The BAS or BMS directly controls HVAC components in a smart building scenario. Depending on the actual BAS type, different interfaces are used and consequently a great variety of enclosures are needed.

3.4.3 Elevators

According to [Halpern and Pike \(1998\)](#) microprocessors first appeared on elevators in 1979. Even the first system controlled all aspects of elevator operation. Passengers are presented with a simple push button interface. The system, however, relies on information collected by a myriad of sensors. Controllers provide a predetermined sequence of operation. In an ideal case, real-time calculations are performed in line with proprietary algorithms that try to successfully balance passenger demand with car availability ([Yu et al., 2011](#)).

Sensors supply data on actual car loads and positions, moving direction, door status, all calls, and alarms. Programmable logic controllers are utilized for a single or multiple car configurations and/or sized by number of stops and interfaces ([Yang et al., 2008](#)). The controller is also expected to function in testing mode. System test is done without a complete shutdown of the elevator in a smart building. Controllers are compact and consume less power than previous generation relay-based controllers. However, heat management is an issue like in all electronic enclosures.

Efficiency is important. A single cabinet offers the same functionality as multiple cabinets of relays and associated equipment according to [Sachs \(2005\)](#). Microprocessor-based controllers allow the elevator motor room to become smaller or replaced altogether in a machine-room-less design ([Sachs, 2005](#)). This in turn is one of driving force of elevator refurbishments. Elevator refurbishments offer excellent long-term electronic enclosure opportunities.

3.4.4 Smart home

According to [Chan et al. \(2008\)](#) technologies already utilized by the commercial building sector are becoming available for the home. Comfort levels of users are increasing. This is great news for the enclosures industry as these features utilize a great many devices all needing their separate enclosures.

3.5 Chemicals and explosive environments

The chemical industry presents a special challenge to enclosures in the form of material selection especially for exposed areas. Explosive environments are even more severe and need special focus both from the design and manufacturing point of view. A latter chapter dealing with environmental consideration will discuss this important area.

3.6 Consumer electronics

Consumer electronics is a huge and growing market as displayed in [Table 3.1](#); it was \$287B in 2016 and contains exceptional enclosures opportunities. It is, however, the fastest moving segments and consequentially development times are the shortest. Aesthetics are paramount considerations in addition to safety, efficiency, and excellent heat management aspects according to [Chandler et al. \(2009\)](#).

Table 3.1 Consumer electronics market size

Year	Market size (in \$ Billions)
2012	206
2013	203
2014	211
2015	285
2016	287

Recent incidents underlined vulnerability of enclosures and the importance of thermal runaways (Wilke et al., 2017). These incidents emphasized the need for a better and more holistic approach affording special attention to consumer electronics components with a negative temperature coefficient (Gupta and Gupta, 2015).

3.6.1 Displays

According to Muccini and Toffanin (2016) there are five display trends that are worth following from the electronic enclosure point of view. These are 3DTV, 4k and 8k TV, OLED TV, and head-mounted displays. OLED TV technology was also discussed from the organic electronics point of view. This is by far the most promising segment from the enclosure perspective.

3.6.2 Head-mounted displays

A head-mounted display is a device worn on the head (Melzer, 2014). It may be designed in a monocular form that covers only one eye. Another design is a binocular form that covers both eyes and forms one image.

3.6.3 Augmented reality

Augmented reality (AR) is one user of head-mounted displays according to Kress and Starner (2013). The AR label was created by Caudell and Mizell (1992) who were Boeing researchers at the time. Therefore, AR is another technology that found its way from aerospace applications into industrial and then consumer markets. Stanimirovic et al. (2014) state that a large automotive company recently developed an application utilizing AR for its service technicians. A globally recognized earthmoving equipment OEM also enlisted AR for very similar purposes. The Google Glass started the interest in wearable AR in the consumer market (Lv et al., 2014). Now

smartphones and tablets are also employing this technology. AR drives development of new devices that can be very beneficial for the growth of the enclosure industry.

3.7 Electrical

Electrical enclosures are the best examples on which to sharpen novices' design skills according to [Hughes and Drury \(2013\)](#). They are highly customized and afford repetition and fine-tuning of design processes. Therefore, electrical enclosures could drive advances within much of the total enclosures new product development segment. Yet, this segment of the industry also suffers from many problems ([Neitzel, 2016](#)). Specifically, a significant skill gap exists between available talent and minimum staffing requirements.

3.8 Energy offshore (oil and gas)

For a long time, this segment was the darling of the enclosures market. The environmental requirements set it apart from all other segments. This resulted in the development of specialist providers. As oil price plummeted, most of these companies struggled to find new outlets for their skill sets ([Smith et al., 2015](#)).

3.9 Food, beverage, and tobacco

Hosing down and other regulations make this segment special ([Moerman, 2016](#)). In general, these requirements translate into a difficult heat management environment. Full encapsulation of components is often necessary to withstand the demand of this environment. Innovative designs often appear as an afterthought of the more common applications.

3.10 Instruments

The instrument market is an exciting segment where low volumes often translate to judicious use of standard enclosures. Yet, instruments are often placed into hostile environments, where standard enclosures become a liability ([Greeff, 2015](#)).

3.11 Material handling

Material handling is a significant market segment with relatively mild requirements according to [Joe et al. \(2014\)](#). However, there are exceptions to this rule of thumb. Enclosures might be exposed to extreme temperatures in mining, foundries, and

other areas. In addition, severe vibration environments might also be encountered. Even mild applications, such as fully loaded container handlers might present challenges to the unwary enclosure designers.

3.12 Medical device

Consumers are interested in quantitative information. Currently, every facet of a person's life could be captured and information could then be analyzed. This possibility is propelling the acceptance of wearable health trackers (Goyal et al., 2016). These are either smartphone applications or wearable and connected devices. Specialist devices allow people to track different health-related data. Much information could now be tracked over time such as general activity levels and mood, blood pressure and heart rate, sleep patterns, food and drink consumption, and smoking. The information is usually transmitted wirelessly to allow data emergence of a quantitative pattern.

A large and growing segment of the electronic enclosure market is focused on medical device development. There are special requirements enclosure designers need to be aware of contained in the IEC 60601 standards. IEC 60601 requirements are very different from consumer electronics standards. According to Nistor and Tucker (2015) adhering to IEC 60601 standards allows an enclosure to become "601" compliant. In addition, there are specialized standards for specific devices in this set. IEC has produced over 60 of these special standards.

These requirements are mostly due to patient care regulations. Importantly, medical device users seldom acquire training that includes dangers of electrical equipment. Armstrong (2014) emphasizes the importance of medical device testing for electromagnetic compatibility. All medical devices must continue to work throughout testing without any deterioration in performance. For example, false alarms or faulty patient information are not allowed. Medical devices must keep on working reliably and accurately despite of environmental issues. This means that medical devices need specialized enclosures.

There are many manufacturing rules according to Ghadimi and Heavey (2014) that are associated with source materials traceability and procedures. Reliability is of paramount importance. Yet, it is rarely that medical devices would be placed in truly harsh environments when compared to space applications, for instance. Therefore, this segment was recognized as a very profitable one provided special industry-specific knowledge is applied to medical electronic enclosures.

3.13 Off-road, tracked, and other transport applications

This very large segment has many unique requirements. Dynamic loading of the enclosure by vibration and shock is common as are unforeseen abuse conditions. Unless a better use temperature range is established -60 to 70°C should be taken for granted, thereby challenging most commonly used enclosure materials. It is for this reason that this segment might eventually be better served by specialist companies.

3.14 Pharmaceuticals

According to [Greene et al. \(2016\)](#) the pharmaceuticals market segment is in many respects similar to the food, beverage, and tobacco segments. However, it is much more driven by very specific regulations. Therefore, it demands very specific enclosures in order to successfully compete.

3.15 Robotics

Engineers are advancing toward developing machines that mimic humans ([Stroud and Augusma, 2015](#)). A robot is defined as a mechanism that can sense its environment, formulate a decision primarily based on sensory information, and execute a physical process as a direct consequence of its decision. Therefore, robots are machines that respond to environmental stimuli. However, robots differ from each other significantly.

The first real robots were not like humans ([Boubekri et al., 1991](#)). They performed very simple tasks. Many consisted of only one arm that continually moved objects from one location to another. Slowly, robots were developed to take on more complex tasks, such as assembling and welding ([Liu and Zhang, 2015](#)). These robots, however, serviced only industrial applications. Currently, industrial robots have much improved versatility, but they are certainly not humanoid in presence ([Hägele et al., 2016](#)).

Despite appearances, robots are now targeting consumer households ([Nguyen et al., 2013](#)). It is likely that the next wave of consumer-type robots will perform only dedicated tasks. However, according to [Ding et al. \(2015\)](#) as the costs of components will fall and capabilities increase, robots will become more versatile. This is an area where electronic enclosures will have a significant part to play. Well-designed enclosures will satisfy aesthetics, safety, reliability, and other requirements.

3.16 Review

This chapter has reviewed the various market segments for electronic enclosures. Segments such as the chemicals, explosive environments, energy and offshore, food, beverage, tobacco, material handling, off-road, and pharmaceuticals require very specialized expertise. These segments can of course be learned from this handbook but supplementary materials will be needed to successfully address their industry-specific challenges. Other industries such as aerospace and defense, automotive, built environment, consumer electronics, electrical, instruments, medical device, and robotics will find this handbook very helpful. It was found that automotive, the built environment, consumer electronics, electrical, instruments, medical device, and robotics offer the highest growth market segments at present.

3.17 Hot tips

Every industrial segment has its own rules and regulations. There are, however, similarities across all markets. The following tips could make any electronic enclosure projects more successful:

- Check for the specific industry standards before starting a new electronic enclosure project.
- If possible, focus on a more rapidly growing market segment.
- Check periodically to make sure that the segment is not in relative decline compared to other opportunities.

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Enclosure requirements

4

4.1 Introduction

This chapter will work toward developing a functional requirement specification (FRS) from generally available information (Loucopoulos and Karakostas, 1995; Van Lamsweerde, 2009; Dick et al., 2017). An example of the relevant text will be displayed in each section to facilitate understanding and development of general enclosure design practice in accordance with Jamnia (2016). There are many requirements that drive development of any new products as was observed by Schuh et al. (2016). Stark (2015) argues that some of these requirements are unique, but there are many general criteria that most development projects will encounter.

Selection of an enclosure or other packaging for an electrical or electronic product affords the designer with a range of choices as is displayed in Table 4.1. Most criteria are directed by the nature of the application (Drury, 2001). Packaging of an electronic system must insulate users from electric shock and afford protection to the enveloped circuitry from a variety of sources. Generally, enclosure selectors develop a set of requirements that the enclosure must meet based on the proposed application. A comprehensive set of requirements also includes potential abuse conditions. However, creating a complete set of requirements is often not a simple matter, especially if disposal is also must be factored in (Irimia-Vladu, 2014). Geographic location often determines the applicable standards regime that a device must meet while security and safety requirements are application driven.

The environment a device will be subjected to either in shipping or after installation needs to be carefully considered. According to Bloch (2009) the degree of ingress protection (IP) required will also determine certain minimum characteristics of the enclosure as is the inherent risk of physical damage coupled with internal accessibility requirements. Exposure to various chemicals might also be an important element in the decision matrix, states Wypych (2016). There are other important factors that also need to be considered, warns Stark (2015). For instance, an enclosure must offer adequate levels of protection against mechanical damage. Lall et al. (2007) demonstrated that such damage might arise from excessive vibration, shock, or impact stresses. Traditionally, cooling of solid-state electronics was not considered at the beginning of the new product development (NPD) process as was observed by Moran (2001). Sah (1991) points out that this was due to the fact that at the time solid-state electronics replaced vacuum tubes it was believed to produce no heat at all. This clearly was at least an oversimplification or marketing-driven institutional exaggeration. Since the 1980s cooling has become once again an important aspect (Yeh, 1995; Riffat and Ma, 2003; Chu et al., 2004; Zhao and Tan, 2014). Fig. 4.1 shows that increasing operating temperatures reduce electronics reliability and are regularly

Table 4.1 General requirements

General requirements	General meaning	Further information	Common FRS headings
What will be the first impression based on aesthetics of this product?	Look and feel	Book 2 Design	Industrial Design
What will the risk of physical damage be?	Safety	Book 2 Design	Overview
What accessories and user modules will be necessary and available?	Modularity	Book 2 Design	Construction
What will be the forces acting on the enclosure, housing, or package?	Strength	Book 2 Design	Structural Robustness
How will the operating temperature be controlled?	Thermal management	Book 2 Part 1 Thermal	Thermal Management
What materials can be selected?	Materials	Book 2 Part 2 Materials	Materials
What will be the weight of the internal assemblies, components, and equipment?	CG	Book 2 Part 3 Mechanical	Structural Robustness
What will be the maintenance requirements?	Maintenance	Book 3	Design for Maintenance
What type of environment will the product be experiencing?	Environment	Environmental Considerations	Operating Conditions
What degree of ingress protection will be required?	Ingress protection	Environmental Considerations	Product Safety
Will there be internal accessibility requirements?	Environment	Environmental Considerations	Mechanical End Use Requirement

What will be the security requirements?	Security	Environmental Considerations	Product Safety
What will be the minimum safety requirements?	Safety	Environmental Considerations	Product Safety
How will the product be developed?	New product development	NPD	Design Compliance
Where will the product be installed?	Location	Requirements	Overview
What will the product be used for?	Application	Requirements	Introduction
How will the product be mounted?	Mounting	Requirements	Construction
What will be the electromagnetic compatibility (EMC) or others like electrostatic protection requirements?	Shielding	Shielding	Product Safety
Which standards will apply?	Standards	Standards	Product Safety
Which harmful substances does legislation need to be complied with?	Sustainability	Sustainability	Harmful Substance Compliance

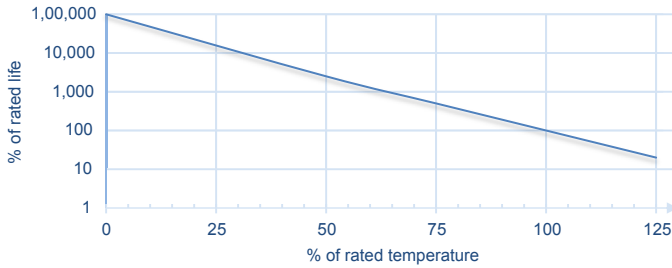


Figure 4.1 Life versus Temperature.

identified as causing most field failures (Wang et al., 2014a). Controlling the operating temperature is ever-more critical as power density of electronics is increased according to Khazaka et al. (2015).

The unintentional production, propagation, or reception of electromagnetic energy may cause unwanted effects and for this reason must be considered carefully, asserts Paul (2006). Limiting radio frequency noise emission is also a function of the enclosure (Lienig and Bruemmer, 2017) as is protection from electrostatic discharge (Gao et al., 2003). Furthermore, enclosure engineers must think of maintenance issues, user requirements, and total cost of the product, add Saaksvuori and Immonen (2008).

Total mass and position of the center of gravity (CG) of the enveloped electronics and other equipment are critical to note for many calculations including vibrations, declares Thomson (1996). Mounting position is critical for certain types of enclosures to function as was intended. Maintenance requirements, like replacing a fan shown in Fig. 4.2, might drive certain design choices and initial concepts, highlight Petroski et al. (2010).

It is fundamental that housings protect electronic and electrical components from the environment. From a design perspective, an enclosure is also a useful framework

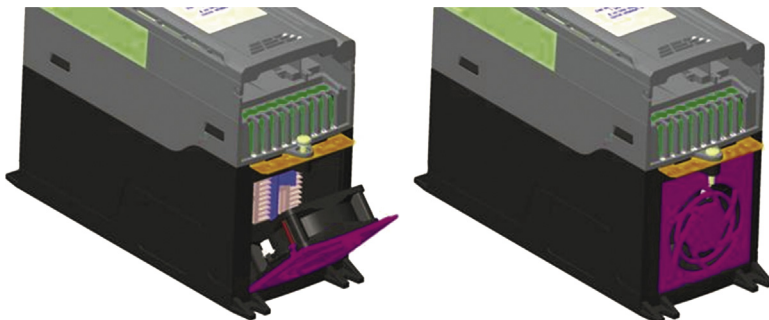


Figure 4.2 Easy replacement of the fan.

for developing a systematic arrangement of the numerous modules (Dick et al., 2017). An enclosure also must maintain reliable connections between the various subsystems and external inputs and outputs.

Last but not least aesthetics are supreme not only in consumer but ever more frequently even in industrial applications (Gemser and Leenders, 2001). Styling is important, but its effects are far reaching including a strong influence on cost, functionality, tooling, and manufacturing requirements. Aesthetics requirements often dictate the choice of a custom-developed enclosure as in Fig. 4.3.

Yet, standard general-purpose enclosures are also available, emphasize Horowitz and Hill (1989). Enclosure engineers utilize various strategies for products made in small quantities. General-purpose boxes or off-the-rack card cages may be used as these could be cost-effective in low-production runs. They normally range in size from around 10 mm (smallest dimension of the box) to a maximum dimension of more than 2 m. Therefore, it should be relatively easy to locate an enclosure to fit even the most demanding application (Hughes and Drury, 2013). However, optimizations of these enclosures are cumbersome and often lead to development of a custom-designed enclosure.

In addition, mass manufactured devices demand specialized packaging to increase visual appeal and develop a competitive advantage for the original equipment manufacturer (OEM). Trott (2008) posits that the same or slightly modified electronic system may be repackaged in different formats allowing successful market segmentations and profit maximization practices.

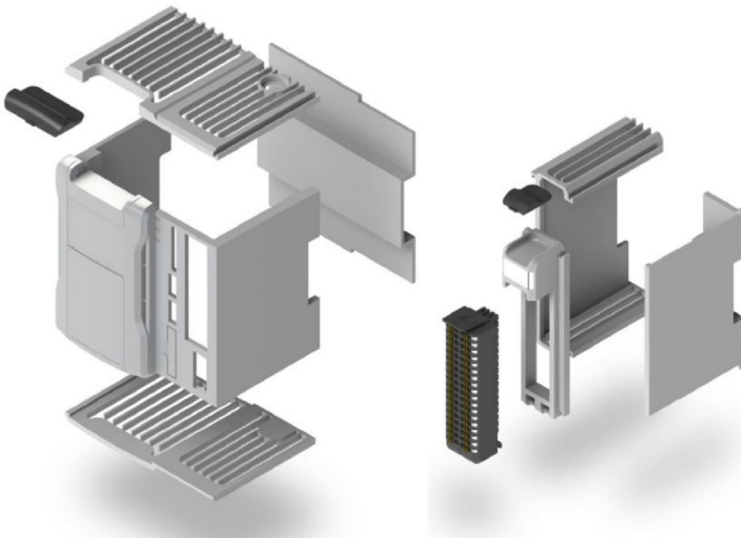


Figure 4.3 Industrial design for aesthetics.

4.2 Creating a functional requirement specification

Tympas (2008) believes that user requirements specification (URS) is compiled by the marketing department representatives in any large organization. Studies by Fatima et al. (2017) have shown that compilation of this critical information has a lot to do with applied psychology and as such is beyond the scope of this book. Yet it is worthy of pointing out in accordance with Anu et al. (2016) that many major errors happen at this stage, partly due to marketing's general inability to connect with their customers and partly due to the fact that many users and their requirements are simply invisible to the OEM as was discovered by Dick et al. (2017). This could happen due to their remoteness in the supply chain or simply because the end user is unknown. Therefore, marketing will fill in the information based on guess work and hunches rather than real-life data, a reproach made by Armstrong et al. (2015). Another reason is that marketing itself is often removed from the customer's and end user's reality and shielded from these realities by the sales team, observe Arnett and Wittmann (2014). La Rocca et al. (2016) explain that sales teams collate the relevant NPD data in their customer relationship management software commonly referred to as CRM. However, sales managers are forced to sell first and do all else second even if corporate management does pay lip service to completing CRM data, state Cui and Wu (2016). As a consequence, most organizations find themselves in a woefully inadequate position when it comes time to harness CRM data and convert it to a usable URS. Therefore, any good NPD executive needs to manage this process very carefully and often with a level of alarm that is not attached to the more mundane engineering aspects of the NPD process, assert Gmelin and Seuring (2014).

Hooks (1994) suggests that the best way to demonstrate the critical step of converting the URS to FRS is to develop a realistic FRS and to provide additional guidance on its fundamental elements. In this chapter the imaginary product will be a typical housing (unimaginatively labeled ZZ1, ZZ2, and ZZ3), which the OEM named Better Enclosures (BE) decided to make in three different sizes (hence progression of the numerical extension). This section needs careful attention to absorb the many perhaps slightly unfamiliar expressions, acronyms, and the like. The overarching purpose of this exercise is to guide any would-be FRS compiler to a much better future by enhancing this critical step in the NPD cycle. The following will be a step-by-step development of the ZZ NPD FRS.

4.3 Introduction of the functional requirement specification

The introduction section should be brief, according to Mcphee (2003), and state the purpose of the FRS and who its intended audience is, which will always be very similar to the following example. It should also indicate revision control measures (Tichy, 1982).

It is beneficial to include procedures and administration information into the introduction, opine [Grönlund et al. \(2010\)](#). This subsection's purpose is to orient all participants in the NPD and instill productive work habits up front. It is worth making sure that all directions are clear, are unambiguous, and point in the right direction, including embedded links to repositories and the like. Frustrated team members due to misdirection seldom become star NPD performers, observe [Gmelin and Seuring \(2014\)](#).

4.4 ZZ introduction example

The purpose of this document is to specify the mechanical requirements for the ZZ family of products. This document should be used as a reference for NPD engineers to ensure they are designing to achieve this specification and should be considered the master document for all enclosure features. As such this document will be continually updated throughout the conceptual phases of the development; all changes following initial release must be detailed in the Revision History on the front page.

4.4.1 *Engineering procedures and administration*

The process of specifying, designing, and initial manufacturing of BE products must follow the BE NPD process. Most the design work is carried out in the scoping and engineering phases, which is facilitated by the BE Module Design Process (BE-MDP). All documents relating to the NPD process and development are to be located and found on the Central BE Depository (under folder NPD Process, Procedures and Standards).

Any testing or engineering decisions made during the design phase must be documented, reviewed, and stored correctly to allow traceability and demonstrate due diligence in the design process, including the following:

- Design meeting presentations and minutes; detailing any decisions and relevant reasoning
- Results of computer-aided engineering (CAE) studies
- Decisions and testing relating to material choices
- Testing of prototypes and concepts
- In-house testing to meet the requirements of the relevant standards
- Third-party testing and approvals
- Test reports and certificates to demonstrate conformance to all the items listed in the Test Dashboard

All documents for the ZZ project must be stored on Central BE Depository in the appropriate locations.

4.5 Functional requirement specification overview

The overview serves as a continuation of the introduction, but instead of continuing the process orientation it is focused on the product itself ([Veryzer, 1998](#)). As such it

presents the first real challenge to converting the information gained in the URS compilation into a comprehensive and motivating FRS document. [Mayntz and Hughes \(1988\)](#) suggest that it is appropriate to direct readers to internal technical standards (TS). This topic will be discussed in the Standards chapter of this handbook.

[Brown and Eisenhardt \(1995\)](#) observe that the first major challenge is the provision of direction on cost. An example is furnished here with the recognition that it might demotivate many members of the NPD team, which is a major concern to [Sethi et al. \(2001\)](#), stifle creativity not to mention innovativeness according to [Eppler and Sukowski \(2000\)](#). Burying this information into the overview might also not be advisable, yet it is a start, but a start that must be made very cautiously as it has wide-ranging effects on how NPD process will be carried out ([Leonard-Barton, 1992](#)). Unintentional effects are rather difficult to address at a later stage.

4.6 Product overview example

The ZZ product family will be the next-generation servo drives, succeeding the existing servo drives manufactured by BE.

4.6.1 Frame and enclosure sizes

The ZZ range will be split into three physical frame sizes (frames 01, 02, 03) and four power ratings. The input voltages range from 200 to 400 VAC.

4.6.2 Levels of functionality

There will be several levels of functionality available for ZZ as is displayed in [Table 4.2](#). These levels of functionality must be configurable at the factory during the customize to order (CTO) process in an efficient and robust manner.

Table 4.2 An example of various functionality levels

Levels
Value
Network Slave
Intelligent Network
Indexer and Network Master
Advanced Motion and Network Master

Table 4.3 An example of target dimensions

Frame	Height (mm)	Height w/Conn (mm)	Width (mm)	Width w/option (mm)	Depth (mm)
1a	228	238	40	63	Fit in 200 mm cabinet
1b	228	238	40	63	Fit in 200 mm cabinet
2	268	278	40	63	Fit in 200 mm cabinet
3	308	318	40	63	Fit in 200 mm cabinet

4.6.3 Cost

Target costs for ZZ are detailed in the cost tracking tool. The cost of the mechanical structural components must be kept as low as possible while maintaining the functional requirements. Parts count should be kept to a minimum (TS 1-000-00*-*-*).

4.6.4 Multisourcing

The targets for multisourcing of components must be met to protect the company from supply and pricing issues. See Multi Source documents for full details (TC 1-000-00*-*-*).

4.6.5 Target dimensions

Target dimensions are shown in Table 4.3. Depth dimension includes connectors, options, and cable bend radii. See specification for intended minimum cubicle size.

4.6.6 Projected annual volumes

Quotations and design decisions must be based on the projected annual volumes (PAV) detailed in Table 4.4. Also see development of a volume model (TC 1-000-00*-*--) for more information.

Table 4.4 An example of projected annual volumes (PAV)

Frame	Volume (PAV)
1a	50,000
1b	50,000
2	25,000
3	25,000

4.7 Operating conditions

Determining reasonable operating conditions is critical for a well-written FRS. Operating conditions will drive the entire NPD process according to [Yap and Souder \(1994\)](#), and most design decisions will trace their roots back to this simple set of criteria. Consider for instance materials used for the enclosure ([Ashby and Johnson, 2013](#)). A temperature difference will be produced by the device, which must be added to the operating temperature. If the selected temperature maximum of the range is too high, the material costs and processes will carry a premium, while if the selected range is low, many potential applications will not be covered, thereby inducing sales and marketing disapprovals for the project. As a result, the operating conditions must be evaluated without any pressure as these form the very foundation of any successful enclosure NPD, emphasize [Keeble and Wever \(2016\)](#).

4.8 Operating conditions example

This example contains instructions and information on the temperature ranges, rated altitude, humidity, noise, vibration, and robustness criteria.

4.8.1 *Operating ambient temperature range*

Operating ambient temperature range is provided with and without derating and power-up condition.

- -20°C to $+40^{\circ}\text{C}$ without derating
- Up to $+60^{\circ}\text{C}$ operation with derating (if required)
- 20°C power up

4.8.2 *Storage ambient temperature range*

Storage temperatures are important as the ZZ product range will be shipped and stored anywhere in the world. Therefore, long-term storage of up to 2 years of -40°C to $+25^{\circ}\text{C}$ must be met. Short-term storage temperature range is from -40°C to a maximum of $+60^{\circ}\text{C}$.

4.8.3 *Rated altitude*

It is desirable that an enclosure should require no derate at or below an altitude of 1000 m at 40°C ; 2000 m at 30°C ; 3000 m at 20°C . Consequently, thermal simulations should be carried out at altitude equivalents so that the product could be virtually tested prior to physical testing. All physical testing should consider altitude requirements. Maximum operating altitude of the enclosure is 30,000 m with derate. There are significant implications for creepage and clearance values with increased altitude.

4.8.4 Humidity

Different levels apply during transport, storage, and use conditions. The maximum relative humidity for class 3K3 operation is 85% noncondensing in accordance with EN 61800-2 and EN 60721-3-3 standards.

4.8.5 Audible noise

Major portion of audible noise will be generated by the fans. Therefore, in an effort to limit the amount of noise generated, variable fan speeds matching thermal conditions of the enclosed device derived from analytical thermal models, at a minimum of three available fan speeds.

- Target audible noise level when fan is operating at minimum speed: 50 dBA (measured at 1 m)
- Target audible noise level when fan is operating at maximum speed: 65 dBA (measured at 1 m)
- Testing of single and multiple enclosures carried out to assess total system noise levels

4.8.6 Vibration and robustness

Test must be performed as per standard BE shock and vibration requirements 7022-0154 at prototype (P1) stage and early production stage to verify production parts.

4.9 Customization

Mass customization has been established as a desirable goal of NPD ([Wakoya and Bayiley, 2015](#); [Tseng and Hu, 2014](#); [Pollard et al., 2016](#)). [Modrak et al. \(2015\)](#) believe that modularity is a way to accomplish it. Most enclosures and housings need to be optimized for this type of design and manufacturing process. [Gualandris and Kalchschmidt \(2013\)](#) warn that flexibility demands careful planning from the beginning of the process and as such influences the development of the FRS. It is paramount to note that both housings and enclosures will need to be approved and customization efforts present special challenges in this context ([Wang et al., 2016](#)).

Design notes could be utilized to highlight an issue or concept according to [Brown and Chandrasekaran \(2014\)](#). These should be numbered so that their use could easily be controlled and references could be made for instance during negotiations with potential subcontractors ([Kunda, 2009](#)). Importantly, design notes are often the only information that is read in a long FRS document. Therefore, their use should be encouraged. There is one inserted at the end of the next section to serve as a guide.

4.10 Customization example

4.10.1 General description

The ZZ product will be a “basic drive module” (BDM) and will meet the specification for an “open-type module.” Therefore, it must be mounted inside a cabinet along with a feeding section and other auxiliaries to form a “complete drive module.” The product enclosure must maintain safe operation and comply with the minimum enclosure standards required for each country it is sold. Suitable mounting points must be incorporated into the product to fit standard and custom enclosures (standard enclosure suppliers’ name might be inserted here to offer some guidance to the readers, but it must be carefully managed not to push but to only provide a helpful “nudge” in the right direction and to provide clarification).

A key requirement is to achieve the smallest possible size for each ZZ servo drive frame size. Customers demanded that the product must fit in 200-mm-deep cabinets including cables, connectors, and backplane approximately and additional 25 mm. Critical dimensions were identified and these are width and depth. These two dimensions must be minimized and kept consistent across all frame sizes. Dimension of length is flexible.

As these products are often assembled into cubicles before being transported to their final location, they must be robust enough to withstand transportation when mounted.

ZZ products will have an internal electromagnetic compatibility (EMC) filter that could be disconnected by the user.

4.10.2 Enclosure definition (drive standard IEC61800-5-1)

The following definition of the drive applies to the electrical enclosure for all ZZ products. When referring to definitions in UL61800-5-1, the drive type is considered a BDM (open type). For an open-type BDM according to UL 61800-5-1 4.3.3.3 “Protection by means of enclosures and barriers”: live parts that are likely to be touched when making adjustments shall be protected to at least IPXXB.

4.10.3 Customer options and kits

The following options and kits will require substantial design input: brackets and mounting kits; connector kits; EMC filters; user option modules; external brake resistors; and ducting kits.

4.10.4 Factory-fit module

There must be configurable levels of functionality through use of a standard module, which can easily and reliably be fitted to the ZZ products during the CTO phase. These must not be user removable and should blend in with the overall design. The connection method between the factory-fit module (FFM) and the main drive must be selected carefully to provide a reliable connection, which can easily and robustly be assembled during the CTO process. The same FFM modules must fit all frame sizes, voltages, and power ratings. Connections must be designed in accordance with [Table 4.5](#).

Table 4.5 Design Note 1

Item	Note
Factory Fit Connections	Where pin headers or similar connectors are used, it must be possible to inspect the connection after assembly to ensure that no pins are bent and that full engagement is achieved. This requirement also applies to any user connections.

4.11 Aesthetics

An initial impression cannot be made twice ([Carlston, 2014](#)). Psychologists have discovered that product purchase decisions are made very quickly according to [Mittal \(1989\)](#). [Crilly et al. \(2004\)](#) posit that the look and feel of any product is a critical success factor. Therefore, even the most mundane enclosure or housing will benefit from expert industrial design ([Uemura et al., 2015](#)). Not surprisingly, the FRS also contains instructions for this important activity.

4.12 Industrial design example

The next redesign of the ZZ product range will not begin within a decade. Therefore, aesthetics must remain fresh for this period. Industrial design must consider different target global markets in terms of styling, colors, and other factors. An appearance which reflects quality as perceived by the customer must be targeted. The ZZ product must look and feel robust to the user. Functionality must not be compromised by aesthetic considerations. User removable covers or option modules should be easy to fit or remove and maintain a sense of quality when used. Ease of installation through cable management and physical mounting should be considered in the industrial design phase. The ZZ product design must be developed to fit into the family of BE products by using design cues and features of recent product designs. Colors displayed in [Table 4.6](#) should be considered for the design. These are as recommended by the BE Industrial Design team.

Table 4.6 Colors

Color	Pantone	Comments	RAL
Cool gray	4 C	Silk Gray	7044
Gray	425 C	Basalt Gray	7012
Black	Black C	Traffic black	9017
Orange	137 C	Melon yellow	1028

4.13 Product safety

Ward and Sobek Ii (2014) assert that product safety is a critical aspect of any NPD effort. The specific areas that must be addressed as a minimum include conformance to various and relevant standards (Solanki and Chapman, 2012), desired IP rating (Bloch, 2009), pollution degree requirements (Grasshoff and Hellsdorfer, 2013), protection from live parts (Mohla et al., 1999), creepage and clearance calculation guidance (Day and Stonard, 1977), flammability requirements if the enclosure contains polymers (Apte, 2006), safety labels and markings (Bluff, 2014), and earthing requirements (Desmedt et al., 2001).

Lee (1971) instructs that all metal parts should be bonded and then earthed in the interests of electrical safety. Traditionally, this rule has applied to doors, panels, mounting, and gland plates. Facilities for the connection of an earth conductor must be provided on these components as well as on the main body of the housing or enclosure. Dedicated earth points must be positioned such that attachment to the primary body can be achieved utilizing short conductors. These reduce a probability of damaged conductor by snagging (Prasad and Sharma, 2013).

Protection against electric shock can also be achieved by total insulation against indirect contact. In such a case, the housing or enclosure must be made of insulating material and carry the Symbol 417 in accordance with IEC 5172 and be visible externally to indicate a “double insulation” (Davies et al., 1998).

4.14 Product safety example

The reference file for all safety-related requirements is the conformance specification, which should be considered as the master. The following points are extracted from the conformance specification to help clarify and expand on enclosure design-related items. For further information please see Conformance Specification TS 1-000-021-789.

4.14.1 Conformance to standards

The enclosures shall be designed to ensure that safe installation and operation is possible and to meet or exceed the applicable standards. Safe operation of the product takes precedence over all other issues. At all times the relevant IEC and UL standards are to be followed. Conform to at least UL61800-5-1 open class rating and to IEC61800-5-1 enclosure requirements.

The following standards should be referred to throughout the enclosure design:

- IEC61800-5-1 IEC standard
- UL61800-5-1 Power Conversion Equipment
- UL94 Tests for Flammability of Plastic Materials for Parts in Devices and Appliances
- UL746B Polymeric Materials—Long Term Property Evaluations
- UL746C Polymeric Materials—Use in Electrical Equipment Evaluations
- BS EN60529 Specification for degrees of protection provided by enclosures (IP rating)

4.14.2 Ingress protection rating

IP ratings shall be IPXXB and IP20.

“Live parts that are likely to be touched when making adjustments shall be protected to at least IPXXB.”

IP20B should be the target IP rating for the ZZ enclosures. This rating implies IPXXB is met (protection of persons is met and ingress of solids to protect from installation debris). For further information please see Conformance Specification TS 1-000-021-789 Section 6.1.

4.14.3 Pollution degree

Pollution degree 2 must be met—nonconductive dust in operation and temporary conductive condensation when unpowered is possible. The design of the drive should maximize reliability and take into consideration lessons learnt from previous BE products. Pollution Degree 3/3C3 to be considered as an option.

Creepage and clearance distances must be measured in accordance with UL61800-5-1 Annex C at the appropriate pollution degree level. For further information please see Conformance Specification TS 1-000-021-789 Section 3.2.3.

4.14.4 Protection from contact with live parts

The distances from any live part to the user are detailed in IEC/UL61800-5-1 and EN60529. A tool has been created to detail requirements for each frame size and voltage rating. Consideration of unused connections must be made to maintain safety (e.g., unused brake and DC bus connection accessibility). For further information please see Creepage & Clearance Document TS 1-000-021-790.

4.14.5 Creepage and clearance

Creepage and clearance rules are documented in TS 1-000-021-790. Compliance to this document is compulsory. Enclosure design must account for electrical creepage and clearance requirements between parts of different potential, safety circuits, and earthed parts.

Insulation materials utilized must have sufficient Comparative Tracking Index (CTI) values to comply with UL746C requirements. Different materials will affect creepage distances required. Use the “creepage and clearance tool” to perform any related analysis.

Variations due to manufacturing tolerances and assembly processes should be considered. A minimum addition of 0.5 – 1.0 mm should be added to all creepage and clearance values calculated in the analysis tool. The amount of tolerance must be based on engineering calculations. For instance, potential movement of two relevant objects during vibration must be taken into consideration. Measurement of creepage and clearance must be done in accordance with [Table 4.7](#). For further information please see Creepage & Clearance Document TS 1-000-021-790.

Table 4.7 Design Note 2

Item	Note
Measurement of Creepage and Clearance	Creepage and clearance measurements must be made in accordance with UL61800-5-1 Annex C. Specifically, some small features like gaps, grooves, and others may not be taken into count as per Table C1 of the same standard. In addition, materials, assembly methods, and manufacturing tolerances must also be considered in the evaluation. Field wiring terminals must be assessed in accordance with UL61800-5-1 Annex DVF.

4.14.6 Polymeric flammability requirement

The ZZ products will be classified under the UL open-type category. It is probable that part or all the enclosure will be polymeric. In addition, internal parts might also use polymers. Therefore, flammability requirements, safety of the user, and the installation environment must be paramount considerations in design decision-making. UL94-V0 Flammability rated materials are suitable for plastic parts exposed to the user and internal parts. All polymer-based materials must adhere to the nominal wall thicknesses as specified in the UL yellow card for the material at a given flammability rating. Any polymeric material used to support live parts must have a suitable temperature rating to cope with the expected temperatures in service—also accounting for any risk of impact and suitable strength to support the part in accordance with UL61800-5-1 Table 14. Any polymeric material used must have suitable electrical ratings if utilized for insulation purposes. Where polymeric materials are used to support or provide a barrier between the user and dangerous voltages, the Deformation Testing detailed in Section 9 of the standard must be carried out.

4.14.7 Safety labels and markings

Suitable safety markings must be applied to the product to at least meet minimum requirements of UL61800-5-1 Table 28. Aside from meeting all applicable standards, consideration must also be made to ensure that the product can be installed safely, easily, and quickly. Displaying screw tightening torques, cable sizes, location of disconnects, etc. should all be considered for inclusion on the product. The design must be considered from the point of view of the installer and the environment in which the product will be used. All safety labels and markings must be as per Fig. 4.4, that is, clear, safe, and simple to ensure comprehension and compliance.



Figure 4.4 Labels and markings.

4.14.8 Earth requirements

Earth requirements include protective earth and EMC earthing and screening.

Protective earth is a mandatory component of the ZZ product and any conductive parts exposed to the user must be bonded to it. An external connection to the protective earth must be suitably sized and robust for the intended application. For instance, if a formed thread in sheet steel is used, it must be tested for overtorque resistance and repeated use. There must be a dedicated protective earth connection point close to the incoming electricity supply. Minimum cross-sectional area requirements must be complied with. It should be possible to connect the earth across multiple enclosures without any difficulty, compromising safety or robustness. Choice of materials and plating must be approved by the Chief Engineer due to repeated corrosion resistance issues experienced on previous products both chemical and galvanic in nature as per Table 4.8. For further information please see Conformance Specification TS 1-000-021-789.

Earth screening points are required for motor cable, encoder cable, and external brake resistor. The motor screen should be as well connected as possible to the back plane of the product to give optimum EMC performance. It is paramount to minimize number of components in the current path, maximize cross-sectional area of conductor, and keep distance to the minimum.

A robust earth connection from the power input to the motor connection is required; this may be formed as part of the enclosure if sheet metal is used. Consideration in the design should be given to bend radius of cables, especially motor cables as they can be quite stiff, and brackets to support the cables, and screening must be robust and easy to fit and configure. All motor cables should be kept away from the incoming AC cables. Speed of installation is important as well as a robust construction. Cable tie points must be provided to secure cables to the enclosure in a location that was analytically proven to carry all the relevant loads and tested to prove compliance in accordance with Table 4.8.

Table 4.8 Design Note 3

Item	Note
Plating of Steel Parts	Plating of steel parts must conform to TS 7022-0044. Special requirements or acceptable nonconformance must be authorized in writing by the Chief Engineer.
Durability of Threads and Fixing Points	Minimum testing requirement is 150% of the recommended torque contained in the User Guide, repeated no less than 50 times without damage or deformation to the thread form or surrounding material.

4.15 Construction

Meller and Deshazo (2001) underline that there are many differing types of enclosure and housing constructions. This section will explore design-related issues, welding, bolted joints, casting, vacuum forming, extruding and molding issues. After these issues have been covered, an example will be presented.

Construction instruction of an FRS is a difficult area as enough instructions should be provided to facilitate design, but not too much to stifle innovation according to Trott (2008). Therefore, this area needs executive attention to avoid undesirable and possibly even catastrophic consequences according to Sethi et al. (2001).

4.15.1 Design

As with many design problems strength of the modern enclosure or housing comes more from the attention the NPD team have paid to the design than from simply material thickness, asserts Ashby (2000). Most wall- and floor-mounted metal enclosures and cabinets available today are produced from a sheet steel of 0.75–2 mm thickness with folding and welding techniques utilized to provide rigidity and strength. As a rule of thumb, the thicker the sheet steel, the more expensive the enclosure. In addition, many manufacturing difficulties like making cutouts or holes increases with thickness. Rosato and Rosato (2012) warn that this rule does not hold for injection-molded plastic enclosures, which follow casting rule of thumbs instead.

Mounting plates are thicker to allow for drilling and tapping holes for components, but with every new hole, strength is reduced. As a result, an engineer should sign off on every modification, however trivial it might be, instructs Den Hartog (2014). Enclosures are also available with various mounting systems to preserve strength and eliminate necessity of the engineering review.

Other design features accommodate the environment for which the enclosure is designed for. An example would be the addition of gutters to manage precipitation and to ensure any water runs away from gasketed features.

Enclosures and housings are almost always manufactured using more than just one manufacturing or assembly technique. Just to illustrate this point, an enclosure could have a rolled frame, folded and perhaps welded doors, and side panels, in addition to die cast hinges and many fixing parts. Injection-molded thermoplastic covers could complement extruded aluminum profiles to provide an aesthetically pleasing modern style of an enclosure or housing.

4.15.2 Welding

Hounshell (1985) argues that one of the most common small batch manufacturing method of construction is to cut the basic components of the enclosure or housing from sheet steel and form the parts into the desired shapes prior to permanent assembly: welding. Dependent on the specification of the enclosure, various types of welding methods can be utilized.

An enclosure or housing with a need to achieve only a very low IP rating could possibly be produced utilizing spot welding techniques (Cho and Rhee, 2000). However, a much more common approach currently, as more tightly sealed enclosures are demanded, is to seam weld all the sections together. Asahi et al. (2004) declare that this method produces an enclosure or housing without any penetration risk between the various components. The downside is a much higher price due to additional labor, materials, time, and energy.

4.15.3 Self-assembly and bolted construction

Large enclosures offer modular self-assembly systems (Loffink, 2008). Establishing the true cost of these systems is not simple as they transfer the assembly process and associated costs from the manufacturer to the customer. They, however, offer quick delivery of standard enclosures and busbar systems. The equipment is delivered in a “flat packed” kit form with some savings usually attributed to delivery and storage costs (Gershenfeld, 2012). It is important to confirm that adequate training and support is available from the OEM to guarantee correct and efficient system assembly. Self-assembled bolted construction will allow significant modifications to panel layouts, while keeping costs relatively low and associated delays to a minimum.

4.15.4 Casting

A large number of materials are suitable for either casting or die-casting. Kaye and Street (2016) assert that die-casting is only used for certain materials if there is a reasonable mass production volume guaranteed. On the other end of the casting spectrum, a sand casting can be used for a single part according to Chougule and Ravi (2006). Casting can integrate design features into the enclosure such as a fitting while eliminating associated assembly costs.

4.15.5 Vacuum forming

Throne (2003) elucidates that vacuum forming is utilized for plastic materials or very thin metals. The material is stretched over a molding form, vacuum is applied, and the sheet is drawn into the cavity to provide the finished shape. The tools are much cheaper than, for instance, for injection molding as the applied pressures are lower and only one side of the tool is needed to be made.

4.15.6 Extruding

Plastics (Nakajima, 1997) and metals such as aluminum (Saha, 2000) and magnesium (Friedrich and Mordike, 2006) can be extruded to net shape. The raw material is heated to a molten or semimolten state and is then pushed through a die to give the desired shape of the component. Relatively large production quantities are required. Carneiro et al. (2001) state that the cost of the die is very much lower than, for instance, in

injection molding; hence there is a great incentive to always consider this process prior to deciding on a much more capital-intensive injection molding.

4.15.7 Glass fiber molding

Mallick (2007) points out that enclosures and large housings can be manufactured on a one off and prototype basis by hand “lay-up” of the fiber mats. However, this is a slow process and as a result expensive. Therefore, it is usual for large quantities to be manufactured by a more cost-effective process, the hot press method. This method uses heated materials and a form of a die or alternatively a vacuum forming technique.

4.15.8 Injection molding

Understanding the process of injection molding from the enclosures, housings, packaging standpoint is critical according to Meyer (1987). The process of injection molding enclosures and housings involves the conversion of plastics granules, called pellets, into a net-shaped molded form (Soh and Chung, 2002). The material is heated to its molten state and injected, under pressure, into the forming tool. This process is suitable for both thermoplastic and thermo-setting materials and a substantial part of Book 2 and Book 3 will be devoted to this important process.

4.16 Construction example

This example follows the previously selected ZZ product line. A proper construction example cannot be provided without specifics. However, these specifics will change with every NPD process within the enclosure industry. Thus, this example will only serve to provide a “flavor” rather than to create a basis for a “cut and paste” form.

4.16.1 General construction overview

The ZZ enclosure products will use a modular build system to allow late configuration (CTO) of the electronic product, to minimize stocked part numbers, and to decrease lead times to the customer.

Base product (Power Stages) and FFM's will be built at a subcontract manufacturer and shipped to local hubs. Upon receipt of an order the end-product will be assembled, configured, and tested at the hub, and packaged and sent to the customer.

There will be one FFM on the product that must be designed to be easily fitted by a production operator using no special tools. The FFM must look integrated into the product and not be easily removed by the customer.

It should be considered to use the board area of FFM module on the control printed circuit board (PCB) to save cost by populating with value components and circuitry. On occasions when building other variants, it will not be populated and broken off during assembly.

The value base unit may not be subjected to the assembly process at a hub and will be stocked as a finished good direct from the manufacturer. The design of the housing for the FFM must work with all variants.

The general construction of the ZZ enclosure will likely be a mixture of sheet metal and molded plastic and fastened using molded and formed clips or as last resort standard fasteners.

4.16.2 Material topology

It is critical to avoid silicone and silver as per [Table 4.9](#) for materials selected for the product enclosure and the final product. Construction materials should be selected based on the following aspects (in no particular order):

- UL flammability rating and wall thickness requirements
- Mechanical properties
- CTI of material (to keep creepage distances small)
- Thermal compliance
- Aesthetic properties
- Accuracy
- Cost
- Manufacturability
- Supplier suitability and location

4.16.3 Reuse of parts

All members of the design team should aim to reuse external and internal parts where possible on different frame sizes. This is to improve economy of parts and reduce inventory. Reuse of parts from other BE products should also be considered where possible, especially with regard to fasteners, connectors, and electrical components.

4.16.4 Mounting arrangements

Mounting arrangements include consideration of panel and DIN rail mounting, standard cabinets and maintenance, addition or removal of devices. Mounting

Table 4.9 Design Note 4

Item	Note
Use of Silicone	The use of silicone- or silicone-based products should be avoided as it is an issue to a few industries, such as paint shops. Therefore, it is a major advantage to be able to declare a product silicone free. All silicone use must be authorized in writing by the Chief Engineer.
Use of Silver	The use of silver in contact materials like carbon ink must be avoided to prevent issues relating to migration of materials and dendrite growth.

arrangements often utilize fasteners and therefore considered to be part of the technology triangle. Thus, extreme caution must be exercised when the FRS is providing instructions in this important area. Best is to avoid mechanical fasteners if possible.

4.16.4.1 Panel mount

It must be possible to panel mount devices as a standalone or in a system utilizing multiple ZZ products. Screw fixing points of appropriate size must be provided at the top and bottom of the drive—the number of fixings required should be minimized to keep installation time to a minimum.

4.16.4.2 DIN rail mount

A design to mount all product sizes directly to standard DIN rail as per long-standing customer demands is required. Therefore, a DIN rail mount solution must be incorporated into either the product enclosure or the mounting bracket. The solution must allow for the products to be mounted side by side without a gap between them, with the assumption that such an arrangement is feasible from the thermal management point of view. DIN rail mount is for permanent positioning of all devices, and thus screws must not be required to achieve a permanent fastening. DIN rail mount must be positioned at the same position relative to the top surface of the devices on all sizes to create a professional looking alignment among the variously sized devices.

4.16.4.3 Standard cabinets

The ZZ products will typically be mounted in standard industrial cabinets. The mounting solutions designed should take this into account to make installation and commissioning as straightforward as possible. Target depth is 200 mm minimum including low-profile connectors. Typical enclosure materials are polymeric and formed sheet steel. There is typically a removable backplane to which the devices will be mounted. This is usually offset from 10 to 30 mm from the back wall of the enclosure.

4.16.4.4 Maintenance, addition, or removal of devices

It should be as simple and quick as possible to remove and replace a device from a system. Therefore, minimal disturbance to wiring and mounting arrangements is desired. Minimum number of fasteners and items requiring a tool during the removal process would create a competitive advantage. A design allowing easy replacement and connection of a new device into an existing position is desired. Replacement of an existing device with any other member of the enclosure family without any issues but disallowing replacement with a competitor's product is essential.

4.16.5 Connectors

Connectors are one of the top issues and one member of the enclosure technology triangle. Therefore, [Table 4.10](#) incorporates top priorities for design and selection of connectors. These are size, pitch, type, cost, EMC, board-to-board connections, reliability, verifiability of connection integrity, and lubrication.

4.16.5.1 Printed circuit board interconnects

A connector is needed to pass signals between various PCBs. The reliability of this connection is critical to proper operation of the ZZ product. Design and selection of this connector requires careful consideration of mechanical robustness of the connection, suitable number of ways and plating for control signals, specification of contact plating, incorporating features into the design to prevent damage to contacts during manufacturing. PCB interconnects are likely to be in the cooling airflow and therefore contamination and blockage of the airflow must be considered.

4.16.5.2 Factory-fit module connectors

A critical part of the design is the connection between the FFM and the enclosure. Therefore, careful consideration should be given to mechanical robustness of the

Table 4.10 Design Note 5

Item	Note
Size	All connectors must be the smallest possible size, while taking current capacity, signal type, and usability into consideration.
Pitch	The finest pitch should be selected, balancing this requirement against usability and capacity.
Type	User connection should be pluggable to ensure installations are quick and simple.
Cost	The lowest-cost connectors, which meet all technical and safety requirements from approved vendors, should be selected.
EMC	Connector design and shielding characteristics must be considered to minimize electromagnetic compatibility (EMC) issues.
Board to Board Connections	Soldered connection should be avoided to simplify assembly and minimize manufacturing-related quality issues.
Reliability	Plating materials and thicknesses must conform to relevant BE internal standards.
Visibility in Manufacturing	All interconnects must be visible postassembly and allow verification of connection integrity.
Pluggable Connector Lubrication	Lubrication must be applied to tin-based sliding connections to avoid micromotion-related reliability issues.

connection, suitable number of ways and plating for control signals, specification of contact plating, incorporating features into the design to prevent damage to contacts during manufacturing, and ease of verification of connection integrity as per [Table 4.10](#).

Critical factors in the selection of a connector design for the FFM that is fitted later: quick and reliable connection to the device in a production environment, ease of connection integrity verification, and provision of appropriate protection to avoid connector damage during manufacture or transport.

4.16.5.3 *User option modules interface*

ZZ devices will incorporate provisions to allow for the connection of up to two user option modules, which use a 36-way PCI card edge connector for the interface. Two interface PCB’s with gold fingers will need to be connected to the ZZ Control PCB assembly. These PCBs will need to be connected at right angles to the control PCB. Good mechanical support of the interface PCBs will need to be achieved. The physical configuration and size of the interface PCB assembly must be carefully considered to maintain the critical 40 mm device width requirement. A low-cost solution is desired, but reliability must be ensured and tested in accordance with [Table 4.11](#).

4.16.5.4 *Power connectors*

Supply and motor power connections need to be pluggable, power socket soldered to the power PCB, and mating plug fitted by the end user.

It is preferable that these connections either be located on the top or bottom surfaces as close as possible to the front face of the device or to be located on the front face of the device. Supply and motor power connectors must be rated to meet maximum system rating requirements.

To reduce risk of accidental contact of stray strands with live connectors the maximum wire stripped length should be specified on the device, possibly molded into the adjacent plastic component. Please refer to power connector certification information contained in [Table 4.12](#) to determine maximum allowable length.

4.16.5.5 *Power cable sizes*

Power cable sizes are displayed in [Table 4.13](#).

Table 4.11 Design Note 6

Item	Note
PCI Express PCB Connector	All connections to the PCI Express interface should be designed and made in accordance with TS 7005-0327 and ECAD guidelines with regard to solder resist and plating connections. Straddle mount PCI Express connectors must be avoided.

Table 4.12 Power Connector certification requirements

IEC Certification	UL Certification	CSA Certification
IEC 61800-5-1 “Terminals” Clause or IEC 60947-7-1 or IEC 60947-7-2 as appropriate	UL 61800-5-1 Clause 4.3.8.8 and IEC 60947-7-1, or IEC 60947-7-2 UL 1059 as appropriate	C22.2 No. 274 Clauses 4.13.4 and 4.13.35

4.16.5.6 Terminal marking

Each terminal position to have terminal identity molded into adjacent plastic if possible or provided on an additional label near to or on the terminal itself. The terminal identifier should be clear from the front of the product and must not be obstructed by cables or connections not associated with the terminal it marks.

For pluggable connectors provided with the product, it is required that the terminal markings be both molded into adjacent plastic and marked on plug connector.

The following terminals will require marking:

- L1, L2, L3
- BR, DC+
- U, V, W
- Safety earth (for supply and motor)
- Encoder
- I/O numbered
- Communications connections
- DC bus (DC–, DC+)
- 24V bus (24V+, 0V)
- EMC cap disconnect

4.16.6 User options

See Table 35 of product specification for full details (TC 1-000-00*-*-*).

Table 4.13 Power cable sizes

Product size	Max. Cable size (input and output)	
	200 VAC	400 VAC
1a	4 mm ² /12 AWG	4 mm ² /12 AWG
1b	4 mm ² /12 AWG	4 mm ² /12 AWG
2	4 mm ² /12 AWG	4 mm ² /12 AWG
3	6 mm ² /8 AWG	6 mm ² /8 AWG

4.16.6.1 Connector kit

Depending upon the final design, it may be necessary to offer kits to the customer with alternative connectors for special installation conditions, for instance, low-profile right angle pluggable connectors.

4.16.6.2 Bracket and mounting kits

It may be necessary to supply additional cable management brackets for the alternative mounting arrangements:

- Mounting of multiple rows of devices above each other
- Combining the cable management bracket for multiple device installations
- Routing cables in alternative directions
- Special customer requirements to manage, terminate, and strain relieve cables

4.16.6.3 Electromagnetic compatibility filters

Design points regarding EMC Filters:

- Depth of the devices must remain unchanged with filter fitted for the multiaxis connections and minimizing depth of installation.
- The DIN Rail mounting must remain functional with an EMC filter fitted.

4.16.6.4 User option modules

The user option modules are individually purchased I/O, communications or control feedback interfaces for the device. They allow a customer to add extra connections or control interfaces to increase functionality or connectivity of the core device platform. A customer should be able to easily fit and remove user modules as they require.

- There should be provision for two User Option Modules on the ZZ devices.
- Electrical connections must be made to the front face of the options; they should be located appropriately.
- The options are cooled by natural convection through venting on the top surface; this must not be blocked.
- Additional parts may be required to fit user option modules to the drive to avoid increasing the width of the base product. In other words, not to penalize devices with no option modules fitted.

4.16.6.5 Brake resistor

A brake resistor is a customer fit option which will be sold as a separate item. When fitted to the device it should adhere to the following requirements:

- The brake resistor is likely to get hot; mounting and marking needs to accommodate this.
- The brake resistor plus device must fit within the previously prescribed design envelope.
- Mechanical fixing should not need special tools.

- Mounting options must be available to the installer to configure as required, so brake resistor could be located on either side of the device.
- Depth of the devices must remain unchanged with brake fitted for the multi-axis connections and minimizing depth of installation.
- Wire routing for brake must remain within the volume of the drive enclosure.
- Must be possible to fit the brake resistor with user option modules also fitted.

4.16.6.6 Earth screening bracket

A user-fit earth screening and cable management bracket must be supplied with a device. This will fit near to the motor connections and provide a means to connect the screen from the motor and encoder cables to the earth bracket and provide strain relief for the cables.

- Provided with every ZZ device.
- Provision for cable ties must be given.
- There must be space for the encoder, motor, and control cable connections.
- Allow device to be fit in a 200-mm-deep cabinet when bracket is installed.

4.16.6.7 Additional busbar parts

Replacement and additional parts must be available as follows:

- It must be possible to purchase additional or replacement DC bus connection parts.
- It must be possible to purchase additional or replacement 24 V bus connection parts.
- Spare screws, ring terminals and other parts should be available if required.

4.16.6.8 User memory card

Secure digital memory cards (SD cards) will be supported on ZZ devices to store user programs. However, no other type of memory cards will be supported.

4.16.6.9 Ducting kit

A solution to exhaust heated air from the devices through the backplane and enclosure is desirable to reduce internal temperatures. Mounting the ZZ devices in multiple rows in the same cabinet would require this feature. The aim should be for this kit not to affect product rating; testing should be conducted to determine if derate required and the solution optimized. Thermal simulation should be used to optimize this solution prior to the P1 stage. This is a customer-fit option which will be sold as a separate item. The following points list the relevant requirements:

- Ducting solution must be simple and easy to install for a system of drives.
- Size of the ducting needs to be optimized to take the smallest amount of panel space when implemented.
- Must be robust and of low cost.
- Use of standard tools to install the kit is a must.

4.16.6.10 Competitor adaptor brackets

It is necessary to consider designing customized brackets to allow migration from a competitor product to ZZ.

4.16.6.11 Retrofit kit

There is a significant installed base of previous generation devices for which ZZ device is intended to be a drop-in replacement.

- Customer fit retrofit mounting bracket which will be sold as a separate item.
- Fit within the space envelope of previous products.
- Mounting hole use to be eliminated as all devices to be mounted via DIN rail.
- Must be robust and of low cost.

4.16.7 Multiaxis systems

Multiaxis systems require many devices to be mounted side by side and connected together for control of a multimotor system. A motor is connected to each drive but the input power, low voltage supply, and control signals may be shared across the multiple devices. A chain of devices could be supplied by either a DC supply or an AC supply with the top priority design criteria emphasized in [Table 4.14](#).

4.16.7.1 General notes

The following notes indicate priorities for design of the multiaxis system along with [Table 4.15](#):

- The installation of the device to device connections must be easy, quick, reliable, and safe.
- Keying of connections may be necessary to prevent misconnections.
- The multiaxis system must consider the inclusion of user option modules, which will vary the width of devices.
- It must be possible to connect devices together, which are not mounted touching side by side, either through standard hardware or through additional components.
- There will be a maximum number of devices able to be connected in a multiaxis manner; see product specification for details. The numbers will be limited by fuse rating, input power, ambient temperature, and other factors.
- In an AC-fed multiaxis system only one device can have the AC connection; the remainder will be powered via the DC bus connections device to device.
- Consideration for rows of devices mounted above each other using the rear ducting solution must be made, with regard to cable management and connector positions.

Table 4.14 Design criteria

Simple	Robust	Reliable	Easy to use	Safe

Table 4.15 Design note 7

Item	Note
Cable Management	Cabling is an important part of any multiaxis system. Therefore, consideration must be made for cable entry directions, cable types, and typical connection arrangements.
Connector Types and Positions	Initial customer case studies have shown that the ability to fit as many devices into a cabinet as possible is important. Therefore, minimizing the distance between rows of devices is a key success factor. Connector types and positions are also critical.

4.16.7.2 Safety

Safety is the number one priority:

- Protection of the end user is of utmost importance.
- Solution must comply with all applicable safety requirements of ZZ Device Conformance Specification.
- Creepage and clearance requirements must be met in all cases.
- All required safety and terminal markings must be correctly displayed.
- If the DC bus is accidentally disconnected, the end user must remain protected.
- When the multiaxis connections are not used, they must be suitably protected with covers, creepage and clearance, breakouts, and other ways.

4.16.7.3 DC multiaxis connections

The DC bus must be able to be shared in a simple and cost-effective way across multiple devices.

- The DC busbar must be able to carry an 80 A current with acceptable temperature rise.
- Bus voltage: 800 V Max.
- The conductor and any supporting part materials must be selected appropriately.
- The simplicity and number of fixings must be optimized.
- The covers and parts should be tool removable.
- It must be possible to make an external cable or busbar connection to the DC busbar.

4.16.7.4 24 V multiaxis connections

The 24 V supply for control must be able to be shared in a simple and cost-effective way across multiple devices.

- The 24 V busbar must be able to carry a 30 A DC current,
- Bus voltage: 32 V Max.
- The conductor and any supporting part materials must be selected appropriately.
- The simplicity and number of fixings must be optimized.
- The covers and parts should be tool removable.
- It must be possible to make an external cable connection to the 24 V busbar.

4.16.7.5 Communications

The communication connection must share across multiple devices in a simple and cost-effective way.

- Two shielded RJ45 ports on the front of the drive.
- Communication ports to be arranged to allow daisy chaining of drives together with simple jumper cable assembly or standard patch cables.
- The connection must be robust and simple to use.
- An external connection to the communications ports must be possible.

4.16.7.6 Earth busbar

The earth busbar connection must be able to be shared in a simple and cost-effective way across multiple drives.

- The earth busbar must be able to carry the required current.
- The earth busbar should be connected by a screw to a dedicated mounting point on the drive.

4.16.8 Safety circuits (safe torque off)

The safety circuit should be mechanically isolated from the rest of the control electronics through the means of a physical isolation barrier.

- The barrier should be created using insulating material of appropriate thermal and electrical properties for the environment.
- The barrier could be formed from the main enclosure or another part of the construction like an internal air duct.

4.16.9 User interface and display

This section will provide guidance for light-emitting diodes (LEDs), display, remote keypad connection, and reset button.

4.16.9.1 Light-emitting diodes

An LED must be visible on the front face of the product to display status.

- Red LED.
- Located on front of the device.
- Clearly visible by eye from 10 m to assess drive status.
- Can be part of the FFM or the control PCB.

4.16.9.2 Display

An optional display should be designed to provide basic status and parameters and error codes for the user.

- Single-digit seven-element LED display may be sufficient such as red LEDs.
- This display should mount to the front surface of the product and be able to withstand the standard shock and vibration levels specified.

4.16.9.3 Remote keypad connection

Provision for a connection to a remote keypad should be made as an option, connected in the same position as the simple display described previously.

- User fitted and removable without use of any tools.
- Provide an RJ45 socket for connection of a cable to the remote keypad.

4.16.9.4 Reset button

A tool operable device reset switch must be located on the front of the ZZ device and remain accessible on a fully configured and wired device.

4.17 Internal fittings

An enclosure provides a protected space for equipment. Normally, enclosures are constructed for safety, security, and environmental protection reasons. Many fittings may be incorporated within the enclosure design, primarily to assist in the mounting of the equipment, including plates, studs and inserts, rails, racking, brackets, and other accessories.

4.17.1 Plates

Mounting plates are usually take the form of plated or painted sheet steel. These plates sometimes folded along two or more edges to give extra rigidity. They are attached to the enclosure with a variety of fasteners, such as nuts and bolts, studs or fixing rails. The fixing rail method normally allows the greatest flexibility. The mounting plate position can be adjusted between the front and rear of the enclosure.

Mounting plates could be manufactured from many different materials such as aluminum and stainless steel mostly dependent on the application. Standardized pre-punched mounting plates are also available that allow captive nuts to be fitted to hold equipment. These plates save installation time by avoiding additional operations such as drilling and tapping. On very large enclosures partial height mounting systems are available.

4.17.2 Studs and inserts

Mounting studs and inserts are normally used with wall-mounted enclosures. Non-metallic enclosures and housings also extensively utilize this method. Mounting studs and

inserts are traditionally positioned in a way to accommodate a manufacturer's standard line of accessories.

4.17.3 Rails

Mounting rails are a common and highly coveted feature in Europe. These systems are readily available and take the form of various standard lengths of top hat-shaped profiles that are called DIN rails. The system also contains brackets that allow equipment to be fitted anywhere within the enclosures. DIN rail systems are fitted mostly as accessories. Therefore, they tend to pick up their main fixing positions from the mounting plates. These rails may also be fitted to the doors of the enclosures.

4.17.4 Racking

19-inch rack enclosures have been designed specifically for the electronics industry. Racks allow prepacked modules such as servers, routers, and others to be fitted effortlessly and rapidly. The width between front fixing holes has been standardized at 482.6 mm, which is a converted measurement from the original 19-in. distance, hence the name for this racking system. Other dimensions such as 515 mm stipulated by IEC 60917 Series and 600 mm are also utilized. New standards such as ETSI and metric modular are becoming more accepted by the industry.

Racks have many options including drawers, sliding rails, and trays. Normal rack systems are designed without ingress protection. This is often due to the perception of the benign environment in which they are supposedly installed. Enclosure OEMs have designed accessories to allow racks to be installed in an IP product. The simplest manifestation is a two-vertical rail system. This is fitted to a 600-mm-wide enclosure and thus offers the 482.6 mm, 19-inch front fixing option. Many variants to the basic system exist. Some include variable depth versions, while others are incorporating partial height rails and even swing frames. Swing frames are nothing more than a simple frame with two vertical rails to provide the 482.6 mm, 19-inch spacings.

4.17.5 Brackets

Many OEMs offer various specialized brackets to help with the installation of equipment. These cover a large range. Some are simple angled brackets for fitting profile rails for terminals. Others support monitors and various other equipment.

4.17.6 Accessories

Many other useful accessories are available. These include drawing pockets, earth bars and cables, lighting, various panels, switches, door stays, and cable retaining rail systems.

4.18 Locks and hinges

Enclosures and housings are fitted with locks and hinges for two main reasons. These are on the one hand to enable easy access to the interior and on the other to prevent unauthorized access. Balancing these two criteria is never simple and needs careful analysis to assist decision-making. It is important to realize that tampering, vandalism, and unauthorized use of equipment are on the rise. Therefore, there is a significant need to incorporate more sophisticated security measures into newly developed products.

There are many options. The simplest form is probably an insert lock. Such a lock is operated by a key and rotates a simple cam or tab to make the engagement within the enclosure body. Various lock inserts can be installed to increase security measures. The locking mechanism while primarily secures the door often performs other functions as well. For instance, a gasket may be fitted to provide a seal to comply with IP requirements.

Unauthorized access is not the only reason for the provision of sophisticated locking systems. Many enclosures contain high-voltage electrical equipment. In such cases it is essential that the equipment is isolated prior to gaining access. Such access doors utilize interlocking systems, which isolate the supply before the door can be opened.

Much of the previous information relates to larger enclosures. There is also a need for smaller, but no less secure, locking systems in the electronics industry. In this segment a range of push and slide action and quarter turn fasteners, pawl latches, and similar methods have been used successfully.

Importantly, a lock must ensure that doors mate correctly with their gaskets, so hinge design also becomes critical. A simple piano hinge design seldom can perform as was intended. A hinge design that squeezes the gasket must be used. Care must be taken to guarantee that the hinge does not allow or cause unwanted distortion. Therefore, locks and hinges are essential parts of the enclosure and housing system. It is paramount that these devices are designed properly.

4.19 Lifting arrangements

Properly designed and executed lifting arrangements are an important feature of any large enclosure. These arrangements allow these large devices to be lifted and transported.

4.19.1 Eyebolts

The most common method of lifting large and heavy equipment is by providing eyebolts. The eyebolts are most commonly screwed to the top surface of the enclosure. Eyebolts can be fixed onto the enclosure in a variety of ways. The most common is a collar and nut combination in an appropriately strengthened top section of the enclosure's underside.

Certified eyebolts manufactured in accordance with relevant standards must be utilized, where the thread diameter dictates the safe work load (SWL). These are listed in tables in the various standards. An eyebolt must not be heat treated inadvertently or otherwise after it has been tested and stamped. Grinding, sanding, and other processes could anneal the metal, thereby reducing its strength.

Safe working loads are provided with the general assumption of a vertical lift on the eyebolt. Slings with links and shackles attached to the fixed eyebolts make it possible to lift from a single hook. While this is often desirable, the sling angle reduces the safe working load of the eyebolt often by as much as 75%.

4.19.2 Practical advice

Personnel performing lifting operations must be suitably qualified, trained, and familiar with all the relevant standards. They must also be aware of their responsibilities under the local health and safety legislation.

It is important to reduce the risk of the load becoming unstable while being lifted. Therefore, the weight distribution must be even. Low CG is desirable. It could be accomplished by positioning heavy items lower in the enclosure.

4.19.3 Thermal management

[Nakayama \(2004\)](#) asserts that electronics cooling is critical. Therefore, this part of the FRS is critical as well.

4.19.4 Thermal management example

This example displays information on thermal analysis, system integration, fan requirements, considerations for heat sinks, and PCB cooling.

4.19.4.1 Thermal analysis

Each size must be analyzed to verify and optimize the cooling solution during the early development phases and peer reviewed before prototyping. Thermal design and development plan (DDP) should be used as master reference for all losses and component selection. Worst case motoring conditions (see thermal DDP) must be simulated. All profile conditions need to be simulated to verify heat sink sizing and cooling performance. Overload calculations and software-based simulations must be made to allow thermal headroom calculations. The simulation should be carried out considering the rated altitude detailed previously. A thermal report must be written detailing all calculations and simulation steps taken and provide a detailed review of the final design prior to physical prototyping. The report should include the following minimum information:

- Fan selection data
- Heat sink sizing and positions
- Internal ducting details

- Venting details
- Ducting solution
- Device junction and core operating temperatures and margins to limits
- Internal ambient and airflow values around critical components

4.19.5 System integration

A ducting solution needs to be designed to accommodate thermal integration of systems containing multiple devices. Ducting should be considered to provide a solution whereby the hot air flow exiting multiple devices is channeled to exit the cabinet. Ducting allows reduced cabinet size and decrease ambient temperatures inside the cabinet, thereby increasing reliability of the devices.

- This solution could ventilate through the top surface and then through an adaptor duct to guide the air through the back panel or vent directly out of the rear of the device.
- An additional kit may be required for this option.
- The aim should be to achieve this without a derate, but simulation and testing should determine the applicable derate level if one is required.

4.19.6 Fan requirements

Fan selection specifications include electrical and mechanical requirements. In addition, speed, cost, dimension, coating, fan connector, leads, and heat shrink tubing information are also provided to facilitate design and selection of an appropriate fan or fans in the largest device size.

4.19.6.1 Electrical

The following electrical requirements assist proper fan selection for the ZZ devices:

- Rated voltage: 12 VDC
- Motor protection: polarity protected and locked rotor protected

4.19.6.2 Mechanical

The following mechanical requirements assist proper fan selection for the ZZ devices:

- Replaceable and pluggable by user; tool removable from drive
- Material: UL 94 V0 compliant
- RoHS and WEEE compliant
- UL compliant fan
- Operating temperature: -10 to 70°C
- Storage temperature:
 - Long term: -40 to $+50^{\circ}\text{C}$
 - Short term -40 to $+70^{\circ}\text{C}$
- Bearing type: $2 \times$ ball bearing

- Life time requirements:
 - L10 @ 40°C 60,000 h
 - L10 @ 50°C 35,000 h
 - L10 @ 60°C 17,000 h
- End of life = Current exceeds 15% of initial value or speed is less than 85% of original value.

4.19.6.3 Speed

To minimize audible noise and maximize fan life, the lowest nominal speed fan to provide acceptable cooling performance should be selected. The speed of the fan will be variable with a minimum of three available speeds by the control circuitry to provide quieter operation during periods of lower thermal demand.

4.19.6.4 Cost

Cost is a primary factor in the fan selection, once technical and functional requirements have been met.

4.19.6.5 Dimensions

The fan dimensions are listed in [Table 4.16](#) to guide the design effort.

4.19.6.6 Coating

PCB and bearings protected from dust and water in accordance with BS EN 60529 IP54 must be provided or the PCB should be conformal coated with an agent that is approved in writing by the Chief Engineer.

4.19.6.7 Connector

The following connector examples are provided to assist proper fan selection for the ZZ devices:

- Molex terminal crimp (2off) part# 08-70-1039 Series 5263
- Molex housing 2-way (2off) part# 50-37-5023 Series 5264

Or

- JWT A2501 series terminal crimp—(2 off) part # A2501 TOP-2
- JWT A2501 series housing (two way) part # A2501 H03-2P

Or other equivalent that is approved in writing by the Chief Engineer.

Table 4.16 Fan dimensions

Frame size	Fan dimensions
1	$38 \times 38 \times 28/40 \times 40 \times 28$
2	$38 \times 28 \times 28/40 \times 40 \times 28$
3	$(38 \times 28 \times 28/40 \times 40 \times 28) \times 2$

4.19.6.8 Leads

The following lead criteria are provided to assist proper fan selection for the ZZ devices:

- Insulation rating: min 10 M Ω at 500 V d.c. UL Class A
- Lead wire: 1007-F-26 AWG
- Cable: 1 off red (+) and 1 off black (–)
- Polarity:
- Pin 1 = red (+ve)
- Pin 2 = black (–ve)

4.19.6.9 Heat shrink tubing

The following heat shrink tubing criteria are provided to assist proper fan selection for the ZZ devices:

- Insulation rating: 600Vrms 125°C UL rated.
- Minimum wall thickness after shrinkage is 0.44 mm.
- Insulation must cover the entire lead with a maximum of 15 mm from the exit of the fan hub, 10 mm from the Molex connector or tinned end.

4.19.7 Heat sinks

This NPD effort shall utilize an extruded heat sink design. All heat sinks must comply with the following specifications:

- 7022-0025—Metal parts
- 7022-0045—Extruded heat sinks
- 7022-0071—RoHS and REACH

4.19.7.1 Material

Heat sink material must be selected as follows:

- Extruded aluminum 6063- T5: UNS A96063; ISO AlMg0.5Si; AA6063-T5.
- Mass of material used should be minimized to save weight and cost.
- Number of different heat sink profiles and lengths used should be minimized if possible.

4.19.7.2 Heat transfer surfaces

Heat sink heat transfer surface criteria are as follows:

- Surface texture 1.6 Ra
- Surface flatness 50 μ m
- Not concave
- No burrs on holes
- Special requirements may be required if using thermal tape or other attachment methods

4.19.7.3 Non-heat transfer surfaces

Heat sink non-heat transfer surface criteria are as follows:

- Side face should be finished flat to standard BE drawing tolerances.
- No burrs or sharp edges on holes, cut ends, or accessible corners.
- All surfaces to be cleaned and degreased.

4.19.7.4 Heat sink holes

Specific hole requirements, square bottom, through hole, countersunk, or others, must be specified on the part drawings; additional operations should be avoided where possible to keep costs low. If using an extruded profile part holes for screw fixings, testing must be conducted to verify strength and suitability of the screw engagement.

4.19.7.5 Heat sink anodizing

Not required as standard. However, if required it must comply to specification 7022-0095. Standard finish should be a clean and possibly a basic chemical oxidization process to prevent uncontrolled oxidization of the surface in the product. Heat sink anodizing must be finalized with potential suppliers during prototyping phase and evaluated against thermal and environmental requirements.

4.19.7.6 Heat sink sizing

The heat sink sizing information is listed in [Table 4.17](#) to guide the design effort.

4.19.8 Printed circuit board cooling

Areas of high loss on the PCBs must be identified and suitable cooling to be considered in these areas. Air should not be blown over fine pitch components where possible to avoid contamination as indicated in [Table 4.18](#).

Table 4.17 Heat sink sizing

Size	Base thickness (mm)	Number of internal Fins	Maximum height to gap Ratio	Fin thickness (mm)
1	3.5	10–20	20:1	1.1
2	3.5	10–20	20:1	1.1
3	3.5	10–20	20:1	1.1

Table 4.18 Design Note 8

Item	Note
Contaminants Carried by the Airflow	Small surface mount components should be mounted out of the airflow where possible if minimal cooling is required. Air should be guided over heat sinks by ducting or a similar design and kept off component legs to prevent contamination buildup leading to short circuits. Areas of stagnation should be identified and eliminated to prevent buildup of contaminants over the long term. Provision of drainage for condensate should be considered, especially around high current connector pins. Conformal coating should be applied where possible to protect components.

4.20 Structural robustness

Many enclosures and housings have failed in the past (Maidique and Zirger, 1984). Part of the myriad of reasons is that very little was done in the way of appropriate engineering calculations and analysis. The structural robustness example consists of information about requirements for polymeric enclosures (Bryce, 1997), impact resistance (Cantwell and Morton, 1991; Shyr and Pan, 2003; Chamis et al., 1972), shock and vibration testing (Harris and Piersol, 2002; Bert, 1973; Ibrahim, 1978), calculations and analysis (Strang and Fix, 1973; Zienkiewicz et al., 1977; Hughes, 2012), and packaging (Clement, 2007).

4.21 Structural robustness example

The ZZ devices are to be UL open-type rating and must meet the requirements of UL61800-5-1 and internal BE specifications. The design must be robust and ensure user and system safety; some of the tests below are above and beyond what is required to meet the standard but will ensure confidence in the design.

4.21.1 Polymeric enclosure

All enclosures need to conform to Enclosure Integrity Test 5.2.2.4 of UL61800-5-1. This is to verify that the ZZ product meets the IP rating specified. The enclosure must also be tested to IEC 60529 to IPXXB/IP20.

4.21.2 Impact resistance

For open-type enclosures, there is no specific impact test. However, UL 61800-5-1 Deformation Tests 5.2.2.5 should be applied. Technically this only applies to the

cabinet in which the device is located. However, this test can be used as a measure of the robustness of the design and an indication that it is fit for purpose.

- Deflection Test 5.2.2.5.2—this test should be carried out on any metallic part of the product casing.
- Impact Test 5.2.2.5.3—this test should be carried out on any polymeric part of the product casing.

These tests can be carried out in house or externally, but results must be recorded and a report filed in the master NPD journal.

4.21.3 Shock and vibration

Part of the robustness measures should be that the drive passes the shock and vibration testing to BE Specification 7022-0154.

- Prototype testing should be carried out at P1 or P2 stage to identify weaknesses in the design early on.
- Testing of final tooled parts by a third-party test house with suitable accreditation must be completed to provide evidence of this conformance.
- The testing should encompass all possible variants and configurations of product, including the interconnection methods for multiaxis systems and available user options.

4.21.4 Calculations and analysis

All final calculations must be kept in the permanent NPD record. If a calculation or analysis could not be located, the design deemed to have been failed and must be withdrawn from production.

4.21.4.1 Static simulation

Structural analysis should be utilized where appropriate to ensure robustness and suitability of materials and individual parts and assemblies. Topology must be optimized. Features such as snap fits and flexible members must be simulated prior to prototyping to ensure robustness and suitability of features and materials. Reports must be filed with the Office of the Chief Engineer's. All structural analysis must be presented at the appropriate Design Review.

4.21.4.2 Dynamic simulation

Dynamic simulation must also be used early in the NPD process. Simulation and virtual prototyping must be utilized to identify issues prior to physical prototyping.

- Simulation of the shock and vibration testing could be carried out to identify maximum stresses on certain components of the assembly like PCBs, capacitors, connectors and other components.
- Impact simulation on external parts could be used to identify areas of concern and to select materials.

4.21.5 Packaging

The packaging should be designed to the Packaging Specification TS 1-000-021-739, which includes a template for recording details of individual product size packaging requirements.

4.22 Materials

Material selection is a complex issue according to [Ashby and Cebon \(1993\)](#) and an entire Part of the follow-up handbook will be devoted to its vagaries. However, some of the more important issues will be addressed in any well-written FRS. Hence, an example is provided here.

4.23 Materials example

This FRS example on materials contains information on material selection, polymeric material requirements, polymeric enclosures and external parts, polymeric internal parts, other parts, UV requirements, gasket material requirements, molding methods, metallic material requirements, copper conductors, and sheet steel requirements. Fasteners are focused on as part of the Technology Triangle, and snap fits and bolted joints—related information is provided along with corrosion information.

4.23.1 Material selection

All product sizes should use the same construction, materials, and style of assembly to maintain a common appearance and simplify manufacturing. Reuse of parts and familiarity for the end user is a priority. A rigorous selection process must be followed for the selection of materials to ensure that the product and business needs are met. The selection process should consider the following:

- Technical material requirements and suitability such as strength
- Method of manufacture like forming, machining, injection molding, and others
- Conformance to the applicable standards like UL94 flammability or an index like RTI
- Availability of supply: checklist of approved suppliers and country of origin
- Cost in terms of economies of scale, supplier quality, and competitiveness
- Location; check both country of origin and manufacturing location
- Environmental considerations like REACH and RoHS
- Continuation of supply such as material availability, cost trends, change in legislation, export controls, and others
- Multisourcing issues such as potential interchangeability of different grades and materials

4.23.2 *Polymeric material requirements*

The product casing and internal parts are likely to be entirely or partially formed from polymeric materials. Special grades may be required in places with demanding thermal or physical requirements. A full review of material selections must be made before finalizing the design and committing to any tooling.

- The selection of polymeric materials should consider all available options including amorphous and semicrystalline grades. All choices must be reviewed and the selection process documented.
- The physical properties of the materials like shrinkage, dimensional stability, structural and flexural attributes, and others must be considered in detail for the intended component’s design, use, and manufacturing method.
- Gating points should be located by performing a plastic flow analysis. This is to prevent molecular and associated strength degradation, unsightly witness marks on the parts, particularly on surface components like gate vestige, flow marks, and other imperfections.
- Polymeric materials should be selected in conjunction with purchasing to ensure costing and supply is optimized. However, functional and safety requirements take precedence.

4.23.3 *Polymeric enclosures and external parts*

Enclosures and parts must conform to [Table 4.19](#) and the following:

- UL94-V0 minimum rated material to be used for any parts forming part of the casing of the ZZ product.
- Any flame retardant additives must be halogen free and compounded into the feed stock rather than added at the injection molding machine.

Table 4.19 Design Note 9

Item	Note
Suggested Material for Enclosures, External and Internal Parts, and Ducts	Traditionally polycarbonate (PC) or a mixture of PC/ABS was the choice of most electrical and electronics manufacturer. However, many field failures have shown that these materials cannot sustain current and future thermally induced loadings. Therefore, materials with good flow characteristics, and good electrical and mechanical properties need to be selected, while cost is kept at a reasonable level. It is suggested that material selection is left for the few globally recognized experts. Their fees are miniscule when compared to the true cost of a product recall.

- Wall thicknesses should be kept to the minimum possible while maintaining mechanical robustness, aesthetic qualities, and flammability rating to UL94 V-0, while they need to be balanced against the plastic flow analysis results and available rheological properties.
- Material with suitable thermal, mechanical, and electrical properties for the application must be selected.
- The number of different material grades and colors should be minimized across the product range while still satisfying the industrial design, functional, safety, and aesthetic requirements.

4.23.4 Polymeric internal parts

Internal parts must conform to [Table 4.19](#) and the following:

- UL94 V-0 minimum rated material to be used for internal parts.
- Any flame retardant additives must be halogen free.
- Wall thicknesses should be kept to the minimum possible while maintaining mechanical robustness, aesthetic qualities, and flammability rating to UL94 V-0.
- Internal parts such as ducts, brackets, clamps, and other parts must be formed out of materials with suitable mechanical, electrical and thermal properties; attention must be paid to:
 - Thermal properties (RTI) if contacting thermal elements (e.g., heat sinks).
 - Electrical properties (RTI Elec, CTI, HAI, HWI) if forming an electrical insulation barrier.
 - Materials in contact with and supporting uninsulated live parts must meet the requirements of 4.4.2.1 UL61800-5-1.

4.23.5 Other parts

Where special properties such as sliding elements, sprung members, and other special functions are required, a review of the available materials must be carried out and an appropriate selection made from the approved suppliers and a written approval of the Chief Engineer's Office must be secured prior to any communications across the supply chain.

4.23.6 Ultraviolet requirements of polymers

The ZZ products will not be mounted in locations exposed to ultraviolet (UV) radiation. Therefore, no special UV stability requirements are incorporated. Other products might be exposed to UV radiation and as a result an appropriate material grade must be selected. Additives administered at the injection molding machine hopper are not acceptable.

4.23.7 Gasket material requirements

Any sealing elements should be made from a material complying with BE specification 7022-0019.

Table 4.20 Design Note 10

Item	Note
Management of Tooling	Tooling must be managed in accordance with TS 7022-0098 Tool Life Management. Any exceptions to this must be approved by the Chief Engineer.
Additional Requirements for Thermoplastic Tooling	TS 7022-0103
Additional Requirements for Die Cast Tooling	TS 7022-0104
Transfer of Tooling	All tool movements must be approved in writing by the Office of the Chief Engineer and conform to TS 7022-0126

4.23.8 Molding methods

Due to the estimated production volumes of the ZZ product, an investment in hard tooling has been budgeted for. Selection of tooling and part suppliers must be reviewed by all concerned parties to ensure the business needs are met. The tooling should be designed, sourced, and maintained according to the BE specifications indicated by [Table 4.20](#).

4.23.9 Metallic material requirements

It is likely that part of the product casing, electrical and earth connections, and cable management systems will be formed from metallic materials. Therefore, the terms and conditions referenced in [Table 4.21](#) and the following must be adhered to:

- The selection of materials should consider all available options. All choices must be reviewed and documented.
- Metallic materials should be selected in conjunction with purchasing to ensure costing and supply is optimized. However, functional requirements take precedence.

4.23.10 Copper conductors (bus bar and earth links)

Electrolytic Tough Pitch Copper to the standards listed in [Table 4.22](#) and conforming to the requirements in [Table 4.23](#) is suitable for the earth and bus bar connections.

Table 4.21 Design Note 11

Item	Note
T&Cs for Metal Components	TS 7022-0025 must be applied to all metal components unless authorized by otherwise in writing by the Chief Engineer.

Table 4.22 Bus bar and earth links

Standard	Material
USA	ASTM C11000
Japan	C1100
ISO	Cu-ETP, CW003A
Germany	DIN: E-Cu58
UK	C101
China	GB/T 5231-2001, type T1
India	ETP Copper

Table 4.23 Design Note 12

Item	Note
Plating of Copper Parts	Suitable plating for copper parts exposed to the user and environment must be applied. Suggested plating is Tin Plate 5–15 µm thick.
Finish of Areas Used for Electrical Contact	Drawings for bus bars must specify that areas used for electrical contact must be free from surface blemishes that could have a detrimental effect on electrical performance.

Other materials can be considered if current carrying abilities and other requirements can be met.

4.23.11 Sheet steel requirements

Any sheet steel components should be manufactured using Low Carbon Steel DC01 to BS EN 10130 unless there are special requirements. Plating of steel parts must conform to [Table 4.24](#).

4.23.12 Fasteners

Fasteners have been highlighted as a critical area and were named in the Technology Triangle. Generally, snap fits are preferred to bolted joints. Fastener corrosion is also an important reliability issue.

4.23.12.1 Snap fit fasteners

Snap fit fasteners must conform to the following:

- This method of assembly should be used wherever possible between plastic or plastic and metal parts to keep the number of parts to a minimum and reduce assembly time.

Table 4.24 Design Note 13

Item	Note
Plating of Steel Parts	Plating of sheet steel parts must conform to TS 7022-0044 unless authorized by otherwise in writing by the Chief Engineer.

- For any cover which provides protection of dangerous elements to the user, there must be at least one tool removable fastener or feature to prevent accidental access. However, all mechanical loads must be carried by the snap fit rather than the bolted joint.
- All snap features should be subject to analysis to ensure the material properties are not being exceeded causing permanent deformation.
- Molded in stresses, shrinkage, weld lines, and other features need to be carefully analyzed both in part and tool design, for structural elements of the moldings.

4.23.12.2 *Mechanical fasteners*

Bolted joints must conform to [Table 4.25](#) and the following:

- The number of fasteners used must be kept to a minimum.
- Where fasteners are unavoidable, they should be selected from the BE-approved fastener list.
- Common screw types of generic lengths and diameters should be used where possible to reduce inventory and prevent incorrect fitting.
- The head style used should only have a Torx style drive feature.
- Double SEM Conical or Plain screws must be used in all places except for thread forming screws; clear justification and risk analysis must accompany any exceptions to this and an approval secured from the Chief Engineer.

4.23.12.3 *Resistance to corrosion and degradation of materials*

The selection and combinations of materials and finishes must be suitable for the intended installation environment. A survey of typical installation environments

Table 4.25 Design Note 14

Item	Note
Plating of Fasteners	All fasteners must conform to TS 7022-0140 (Machine Screws) or TS 7022-0141 (Thread Forming Screws).
Machine Screws	TS 7022-0051 Style Conical Plain Double SEM Torx Pan Head screws should be utilized if possible.
Self-Tapping Screws	Taptite or other screws conforming to TS 7022-0004 and TS 7022-0116 must be used.

should be carried out to identify likely contaminants that will be encountered and a strategy to deal with these implemented. Third-party testing may be considered if a competitive advantage can be achieved through certification.

The relevant BE Technical Specifications for the plating of fasteners and sheet metal should be adhered to. These have been developed through testing and field experience to provide suitable protection for the usual environments encountered by ZZ devices.

4.24 Design for maintenance

Design for manufacturing and maintenance issues (Boothroyd, 1994) will be dealt with in the second handbook, but a few highlights are provided here. It is important that users of electrical and electronics equipment ensure that the equipment is properly cared for preferably by trained and competent personnel. This however, cannot always be accomplished. The following information is intended to provide guidance to industrial users. Any regulations or the OEM's instructions concerning installation, safety, or specific hazards area must be complied with.

4.24.1 Installation

Always study the installation instructions supplied by the manufacturer first, prior to starting any installation-related work.

If the equipment is to be lifted, use all the lifting points supplied, ensuring that the securing bolts or eye bolts are of correctly sized. Ensure that the lifting equipment used has adequate capacity to handle the load. Do not lift in any other direction or from any other point than instructed by the manuals. Lift smoothly without rapid acceleration or deceleration. Set the load down gently to avoid mechanical shock.

Heavy equipment must be moved into position with the aid of skates. Weight must be distributed evenly to avoid deformation. The load should not be dragged into position or moved on rollers as such a rough handling will invariably result in substantial damage to the surface finish of the enclosure, the structure, or both.

The following are practical tips, which can ensure a successful installation process:

- Inspect external packaging as soon as the item is delivered as damaged packaging often hides transit-related damage.
- Do not insert a sharp object into the packaging as doing so risks scoring the finish and creates a potential site for corrosion.
- Do not drag enclosures or large housings. Always use approved lifting methods included in the installation manual.
- Clear the installation area. Make sure work surfaces are free from debris before working on housings or enclosures.
- Empty the enclosure of any debris prior to installation. Such a debris may form a focus for condensation and contamination, which may cause corrosion or short circuits.
- Never score painted surfaces outside drilling sites.

- Always use sharp cutting tools. Avoid cracking painted surfaces and immediately repaint bared holes and edges.
- Seek OEMs' advice on seal and paint selection, prior to removing seals or overspraying.
- All work on the housing or enclosure must maintain IP integrity.
- Check the loading of equipment to be fitted. Distortion of mountings or doors will affect the actual sealing and destroy IP integrity.
- Check that mounting brackets are sufficiently robust for the purpose, including withstanding shocks and vibration and if uncertain consult an expert.

4.24.2 Site installation

The following tips can ensure a successful site installation process:

- Ensure adequate site access is secured for the enclosure both in terms of size and weight.
- Ensure walls and floors are vertical, level, and generally in good condition. Site on the lee side of building, that is, out of the wind, where possible on external locations.
- Canopies must be used to deflect direct rainfall. Use pedestals to raise enclosures from wet floors.
- Floor standing enclosures, which are not designed to be free standing, must be bolted to a wall or stanchion to achieve its designed stability.
- Cable entries must be supported externally, so that no stress is applied to the enclosure, as any deformation may inadvertently degrade sealing.
- Earthing continuity and integrity must conform to local standards.
- Make sure maximum design loads on doors and swing frames are not exceeded as this might present a tipping hazard.

4.24.3 Mounting

The following are tips to ensure successful mounting:

- It is essential that the equipment is mounted on a smooth and level surface. Doors or covers may not fit correctly and the overall integrity of the enclosure will be substantially and permanently degraded if the enclosure is bolted to an uneven surface.
- Ensure that the designed fixing method such as internal holes or external fixing brackets is used for wall-mounted enclosures.
- For floor standing enclosures, it is essential that adjacent sections of an assembly are bolted together and aligned prior to final tightening on the floor bolts. Any debris or dust from the enclosure must be removed. Any doors or covers that were taken off during installation must be reassembled.

4.24.4 Cabling

All external cabling associated with the enclosure must be permanently supported so as not to apply stress on either the enclosure bolts or the enclosure itself. Any surface damage caused by the cutting of gland holes must be remedied prior to the fitting of the gland.

4.24.5 Inspection

Ensure that the enclosure has been fully reassembled and all gaskets are in place prior to commissioning the enclosure. All surfaces must be inspected for scratches and other visible damage to facilitate prompt repair of such minor damage. The installation must comply with the relevant local standards. A periodic, planned maintenance program needs to be implemented to check gaskets, paintwork, hinges, locks, and other components for signs of physical damage, tampering, vandalism, and corrosion.

4.25 Design for maintenance example

Any component expected to fail during the normal operational lifetime of the ZZ product must be identified and allocated an operating life expectancy. The serviceability of these components must be considered at the design stage so that their replacement in the field is as practical as possible.

- The fan must be user replaceable, either as a component or as part of an assembly including fan guard and cabling if required.
- The design of the multiaxis system components must consider the ease of servicing for the end user; the replacement of a drive in the center of a multiaxis system should be straightforward.
- Any user configured part of the product like terminals, busbars, and connectors should be able to withstand repeated assembly and disassembly in line with the expected life of the product.

4.25.1 Design for dismantling

Must meet the requirements detailed in the following sections of the Conformance Specification TS 1-000-021-789:

- 21.4 Waste Electrical and Electronic Equipment (WEEE)
- 21.4.1 Design for dismantling

4.26 Harmful substance compliance

Compliance with all applicable environmental and sustainability requirements is a must according to [Ladou and Lovegrove \(2008\)](#). All FRS must highlight this to the NPD team. [Hutter \(1997\)](#) states that ultimately compliance rests with the Chief Engineer of any OEM.

4.27 RoHS and REACH example

The product must meet the requirements detailed in [Table 4.26](#) and the following sections of the Conformance Specification TC 1-000-021-789:

Table 4.26 Design Note 15

Item	Note
Environmental Human Health Requirements	TS 7022-0071 must be noted on all component drawings to outline the supplier Environmental Human Health requirements.

- 21 Materials
- 21.1 RoHS
- 21.2 Reach
- 21.3 Substances to Avoid

4.28 Design compliance

Compliance to this FRS is of paramount importance. [Burgelman et al. \(1996\)](#) emphasize that specific direction must be provided in a real document on handling any change and exceptions.

4.29 Design compliance example

Before P1 prototyping the design must be verified to ensure all requirements of the FRS are met. Design must be completed in full and reviewed in at least one Design Review. Appropriate records must be kept of the design development, demonstrating compliance with the FRS and all relevant standards. Design Data Packs (DDPs) or other test report formats should be used to record such data. Any deviation from the specification must be justified, reviewed, and documented. Changes to this FRS must be agreed and approved by senior product and project management.

4.30 Review

This chapter has reviewed elements of the FRS creation. Practical examples were furnished to supplement core concepts. Based on the work of [Cooper et al. \(2002\)](#) procedural and administrative functions were inserted into the introductory section of the FRS to contribute to a smooth NPD. This topic will be detailed in a subsequent chapter.

A product overview was furnished to supplement understanding and to communicate overall design intent to the NPD team ([Camba et al., 2014](#)). Operating conditions were displayed to orient the design team and to provide the initial seed for the development of valid design concepts in accordance with [Homburg et al. \(2015\)](#).

Modularity instructions were added due to recognition that customization is critical in almost all aspects of housings and enclosure manufacture and even more importantly for achieving sustainable profitability (Wang et al., 2014b).

Aesthetics were addressed and industrial design criteria were added to facilitate positive purchase decisions prior to addressing product safety issues (Tjalve, 2015). Product safety was positioned as a critical aspect of any NPD effort (Stark, 2015). Many important areas were addressed such as conformance to various and relevant standards, desired IP rating, pollution degree requirements, protection from live parts, creepage and clearance calculation guidance, flammability requirements if the enclosure contains polymers, safety labels and markings, and earthing requirements.

Construction-related topics were highlighted including design-related issues, welding, bolted joints, casting, vacuum forming, extruding and molding issues in accordance with Hubka (2015). A finely detailed example was added to anchor understanding of the related material. Many enclosure only topics were discussed in the form of internal fittings, locks and hinges, and lifting arrangements.

It was recognized that thermal management of electronics is of paramount importance (Kordyban, 2005). A practical FRS example displayed information on thermal analysis, system integration, fan requirements, considerations for heat sinks, and PCB cooling.

Structural robustness issues were detailed to avoid duplication of known NPD failures (Dieter and Schmidt, 2013). The importance of appropriate engineering calculations and analysis was emphasized. A structural robustness example was provided to supply vital information about requirements for polymeric enclosures, impact resistance, shock and vibration testing, calculations and analysis, and packaging.

Important aspects of material selection were reviewed based on the work of Ashby and Johnson (2013). A substantial example was provided that contained information on material selection, polymeric material requirements, polymeric enclosures and external parts, polymeric internal parts, other parts, UV requirements, gasket material requirements, molding methods, metallic material requirements, copper conductors, and sheet steel requirements. The criticality of proper fastener selection was also discussed along with corrosion information.

Design for manufacturing and maintenance issues were highlighted in accordance with (Boothroyd, 1994). The importance of compliance with all applicable environmental and sustainability requirements was emphasized. In continuing to develop an in-depth understanding the following chapter will discuss the types of enclosure, housing, and packages that are currently dominating the electronics industry.

4.31 Hot tips

Every chapter contains a few tips and this one is no different. There are many requirements that drive development of any new products. Some are unique, but there are many general criteria that most development projects will encounter. However, the most important three aspects are emphasized here:

- URS to FRS conversion must be done efficiently and in a way as to motivate the NPD team according to [Dick et al. \(2017\)](#).
- Every strategic design criterion must be incorporated into the FRS ([Kiss and Barr, 2017](#)).
- Design compliance must be achieved if the product is to be successful ([Burgelman et al., 1996](#)).

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5.1 Introduction

Description of enclosure types could be made from a variety of perspectives according to [Drury \(2001\)](#). This handbook chooses to focus on standard types in line with [Horowitz and Hill \(1989\)](#). [González et al. \(2001\)](#) point out that this selection needs to be made to facilitate understanding of the novice and to provide a platform from which to grow into the myriad of customized types. Electronics enclosures, housings, and packages were favored as opposed to the purely electrical types in accordance with [Dhar et al. \(2011\)](#). These are also mentioned in their relevant subsections, but no effort for full coverage was extended.

There are three types of enclosures, and they do not accidentally happen to coincide with the title of this handbook series and the definition provided by [Ulrich and Brown \(2006\)](#). They are packages for the miniscule, housings that are roughly human sized, and the large enclosures where transport-related material handling becomes a challenge. However, the word enclosure is still used in its generic sense, as was defined in the first chapter and highlighted by [Pauwels \(2013\)](#). The function of electronic packaging does not considerably change and includes interconnectivity for both signal and power ([Gibbard et al., 2015](#)), the provision of physical support ([Kalbasi and Salimpour, 2015](#)), environmental considerations ([Liu et al., 2014](#)), and very importantly heat dissipation ([Cho and Goodson, 2015](#)). Standardized enclosures much like their customized counterparts function under the constraints of performance, size, mass, testability, reliability, and cost according to [Hughes and Drury \(2013\)](#).

[Sneath and Sokal \(1973\)](#) explicate that the first real issue is to make sense of the classification regime used by both academia and industry. As such levels must be discussed first, state [Ulrich and Brown \(2006\)](#), to create a workable platform for the remainder of this chapter.

5.2 Levels

Currently, enclosures are classified variously by different authors, assert [Newton et al. \(2016\)](#). This handbook utilizes a seven-level classification mentioned by [Moore and Shi \(2014\)](#). Electronics packaging level labels generally start with the number zero and continue until six ([Pecht et al., 1998](#)). [Shaw and Seidler \(2001\)](#) observe that establishment of these levels appears to be arbitrary and diverges depending on the vantage point of the author. However, these levels are critical from the analysis point of view in line with the method established by [Macqueen \(1967\)](#). The control volume concept

defined by [Versteeg and Malalasekera \(2007\)](#) utilized in the thermal management chapter is only understandable by learning these levels.

5.2.1 Level 0 semiconductor

Level 0 refers to an unpackaged semiconductor as per [Piqué et al. \(2007\)](#). The chip-only based device could potentially be functional, but it would be unprotected from its environment ([Mathews et al., 2007](#)). Therefore, while this level is theoretically achievable ([Huttunen et al., 2016](#)), in reality it is seldom used outside of laboratory walls and exists only as a wafer, which utilizes on-chip connections. Hence, the assignment of naught to this level's label is warranted according to [Tatarchuk et al. \(2014\)](#).

5.2.2 Level 1 package

Level 1 refers to a packaged semiconductor or a packaged functional electronic device ([Jon and Welsher, 1994](#); [Feng et al., 2000](#); [Figueiredo et al., 2015](#)). This device can be passive, active, or others such as electromechanical in accordance with [Gad-El-Hak \(2006\)](#). It is often referred to as the die package or chip level as was observed by [Chen et al. \(2017\)](#). This level is usually assigned the numerical value of one, presumably to indicate package engineering activities. The “heart” of this level is a wire-bonded die and described by [Chauhan et al. \(2014\)](#). The packaged article might look like a dual inline package (DIP) according to [Park et al. \(2001\)](#).

5.2.3 Level 2 printed circuit board

[Ball and Magazine \(1988\)](#) advocated a level 2 that referred to a printed circuit board (PCB). This level involves joining already packaged devices to a suitable substrate material. This substrate is most often a laminated fiberglass board such as FR-4, that is, an epoxy and fiberglass board or ceramic based such as alumina ([Hall and Williams, 2007](#)). Level 2 is also known as the circuit card assembly (CCA) or the card assembly level as per [McGinnis et al. \(1992\)](#). This level is also known as the board level. [Fedorov and Viskanta \(2000\)](#) highlight the fact that heat sinks are often placed on top of devices to improve heat dissipation. The type, size, and exact location of both the device and the heat sink needs to be evaluated carefully.

5.2.4 Level 3 subassemblies

[Von Hippel \(1977\)](#) observed a long time ago that level 3 referred to an electronic sub-assembly. This level usually contains several PCBs, normally at least two bonded to a suitable backing ([Tavner et al., 2010](#)). This backing functions both as a mechanical subchassis that is a support frame as well as a heat sink as elucidated by [Smith et al. \(1991\)](#).

5.2.5 Level 4 assembly

Savsar (1997) established level 4 as the electronic assembly. This level consists of many electronic subassemblies mounted in a suitable frame. An electronic assembly, then, is a mechanically and thermally complete system of electronic subassemblies and explicated by Peterson and Ortega (1990). Bar-Cohen (1992) observed that this level is sometimes identified as the rack level. This designator is warranted as this level of packaging is adequate for devices to be inserted into a rack that will provide further protection and heat management interfaces.

5.2.6 Level 5 system

Martin et al. (2010) assert that level 5 is the system. There seems to be no universal agreement on the definition of this level. Like in many engineering problems, this level should be defined to suit solution of the problem at hand (Balarin et al., 2003). This might include several racks inserted into an enclosure (Keutzer et al., 2000; Benini et al., 2000). If the enclosure is the ultimate level of investigation as is often the case with enclosure engineering, then this level should refer to the enclosure in accordance with Rigo et al. (2011). However, if the question is to determine interaction of several devices using the enclosure to be designed, then this level ought to be encompassing the entire studied environment as per Balarin et al. (2003).

5.2.7 Level 6 environment

Level 6 is the environment (Gerstlauer et al., 2009; Sangiovanni-Vincentelli, 2003). Once again there seems to be no universal agreement on the definition of this level. This level should be demarcated to fit a systematic approach solving the actual problem. This might include several systems such as populated racks to be inserted into an enclosure such as a data center. At any case, the simplest definition is for this level to refer to the completed product within its own environment (Balarin et al., 2003).

5.2.8 Simplification

Töpper (2017) observes that while the previous seven levels are instructive in the sense of highlighting important features and differences, it is better to group these levels to arrive at a workable definition. Ward (1963) also established the theoretical framework for this.

Issues of levels 0 and 1 are different from the rest in terms of cleanliness and size, and therefore it is better to create a single relatively homogenous group (Elton and Gruber, 1971). Lu and Wong (2009) state that this group is often referred to as the packaging level. This group currently holds the miniscule components and it is probable that sizes will decrease further into the realm of nanotechnology (Zhang et al., 2014). Therefore, it is highly likely that current nanotechnology efforts will bring beneficial improvements into this area such as described by Pan et al. (2017).

Adams (2002) argues that levels 2 to 4 could also be grouped together. As a rule of thumb, this area is for the human-sized components. In other words, these are the components that one can easily see without the use of magnifying lens or a microscope. Mallik et al. (2011) emphasize that while heat transfer issues, for instance, are similar across all levels, other issues like fastening and connecting are markedly different. Therefore, this level needs its own label according to Sneath and Sokal (1973). A somewhat arbitrary designator of housing was selected to describe this group.

Meller and Deshazo (2001) classify and state that levels 5 and 6 are systems that can become large. Sizes start from the human size to the size of a house and beyond. Ebrahimi et al. (2014) argue that cooling issues are, for instance, much better handled by the HVAC specialist than the average thermal engineer. For this reason, these levels were grouped together and labeled as enclosure.

It is important to keep in mind that these labels are used universally, but their meaning vary on almost every occasion (Macqueen, 1967). Therefore, Sneath and Sokal (1973) explicate that care must be exercised to decipher their intended meanings in every particular context.

5.3 Packages

Integrated circuits (ICs) are placed into protective packages primarily to allow relatively easy handling and fast assembly onto PCBs, according to Pecht (1991). In addition, Blackwell (1999) adds that packages protect the encased chip called dies by the industry from potential damage. An extremely large number of different types of packages do exist (Minges, 1989; Shugg and Mathes, 1995; Tummala et al., 2012). Therefore, it is almost impossible to review all of them here. The focus of this handbook is to provide a reasonable sample to allow emergence of a packaging pattern that is very similar in shape to the innovation waves (Yoon et al., 2015) that were discussed in Chapter 2.

Kheirabadi and Groulx (2016) emphasize that most packages have standardized dimensions, pin or connection spacing, and tolerances. They are registered with one or more of the trade industry associations such as Pro Electron also known as European Electronic Component Manufacturers Association (EECA) or the Joint Electron Device Engineering Council (JEDEC), which later added Solid State Technology Association to its acronym. Other types of packages are proprietary in nature. These are usually made by only one and in rare circumstances by two manufacturers (Prasad, 2013).

IC dies can be arranged to connect directly to a substrate, explains Ghaffarian (2001), that is, without an intermediate header or carrier. In a flip-chip (FC) system, the IC is connected via solder bumps to a substrate according to Pascariu et al. (2003). The metallized pads that would have been utilized for wire bonding connection purposes in a conventional die design are thickened and extended to allow external connections to the circuit to be made in a beam-lead technology, state Chahat et al. (2015). Assemblies using so-called bare chips must have additional packaging to protect the devices from moisture and other environmental penetrants (Lee et al., 2009).

It might be helpful to note that the first IC invented in 1958 had a single transistor on it (Kilby, 2001). On June 8, 1978, the first 8086 microprocessor debuted. According to Morse et al. (1978) it contained 29,000 transistors and had a clock speed of 5 MHz. Hinton et al. (2001) explain that the very first Intel Pentium in 1993 had over 3.1 million transistors. In 2004 the Intel Pentium 4 processor contained 55 million transistors. This processor ran more than 600 times faster than the 8086 processor with a clock speed of 3.06 GHz. Miniaturization, increased speed, and ever-lower cost were the main features of the semiconductor evolution according to Lojek (2007). Chew et al. (2017) argue that as semiconductor devices continued to increase in their complexity, packaging technologies had to evolve as well to provide better ways for the interconnections from the die to the circuit hardware. High clock rates usually are coupled with high-power dissipation presenting the designers with special thermal challenges (Garimella et al., 2008). Garimella et al. (2017) report that current advancements are in the area of multiple die connections to form various new and innovative packages.

5.3.1 Timeline

The earliest ICs were packaged in ceramic envelopes according to Grochowski et al. (1997). Aerospace and defense applications utilized these due to their reliability and relatively small size. Cost, however, was the reason that they could not successfully penetrate consumer markets, state Li et al. (2005). Therefore, a new package needs to be invented for this purpose.

Hashimoto and Stevens (1971) note that the first DIP was designed with a ceramic package but soon was replaced by a much cheaper plastic variety. Low cost meant that this innovation was adopted very quickly across the world.

Very large-scale integration pin counts exceeded the practical limit for DIP packaging in the early 1980s, assert Hsieh and Lin (1992). Lewis (1984) demonstrates that this new need directly leads to development of the pin grid array (PGA) and lead-less chip carrier (LCC) packages. Surface-mount technology (SMT) also appeared in the early 1980s but only was adopted by the general electronics industry in the late 1980s according to Prasad (2013). SMT utilized a finer lead pitch. The leads were formed as either a J-lead or a gull wing. A small-outline IC package was smaller than its equivalent predecessor the DIP, saving about 30%–50% in PCB area. Thickness shrunk even more about 70% less, allowing the creation of much slimmer devices, adds Marcoux (2013).

The next big innovation in packaging was the area array (Liu et al., 2015). This new package placed the interconnection terminals throughout the surface area of the device. This provided an increased number of potential connections, since previous package types only utilized the outer perimeter of the device. Once again, the first area array package utilized a ceramic material, thereby inadvertently identifying the aerospace and defense industries as their innovation patrons. For the same reasons described earlier, plastic ball grid array (BGA) became rapidly one of the most commonly used IC packaging techniques (Nguyen et al., 2017).

The evolutionary plastic quad flat pack (PQFP) and thin small-outline packages (TSOP) replaced PGA packages as the most common high pin count devices in the late 1990s according to [Chauhan et al. \(2014\)](#). PGAs could no longer reign supreme even with their strong hold of the microprocessor markets. Industry leaders Intel and Advanced Micro Devices (AMD) transitioned from PGA packages to land grid array (LGA) in the 2000s further undermining PGA's viability ([Wang et al., 2005](#)).

[Master et al. \(1995\)](#) point out that BGA packages have been patented in the 1970s. These patents expired by the 1990s. [Zhang et al. \(2005b\)](#) observe that new product development created the flip-chip ball grid array (FCBGA) packages inspired by the expired patents of the 1990s. Once again FCBGA packages allowed for a much higher pin count than prior package types ([Wang et al., 2004](#)).

[Lau \(1996\)](#) explicates that the die is mounted upside-down, hence the name flipped in an FCBGA package. Flipping the chip allowed connections to take place through the incorporated package balls via a substrate that is like a PCB rather than by the usual bond wire techniques. Input-output signals, called Area-I/Os, were distributed over the entire die surface rather than being restricted to the border. Thus, FCBGA packages allowed a much greater space utilization ([He et al., 2015](#); [Tsai, 2017](#)).

It is important to note that compared to on-chip signals, traces from the die, through the package, and into the PCB have very different electrical properties. They require different design techniques and require much more power than signals confined to the chip itself ([Pecht, 1991](#); [Ulrich and Brown, 2006](#)). Therefore, recent developments harnessed this phenomenon. Multiple dies stacked in a single package furthered the system-in-package (SiP) in concept and created a three-dimensional IC that lowered power consumption ([Tai, 2000](#); [Miettinen et al., 2004](#)). [Lall et al. \(1995\)](#) assert that combining multiple dies on a small substrate, yet again often on a ceramic one, is called a multichip module (MCM). The boundary between a large MCM and a small PCB is often blurred.

The use of a bare die in a chip-on-board (COB) package and MCM applications is increasing. This is because designers are looking for miniaturization with associated mass reduction state [Garrou and Turlik \(1998\)](#). For instance, in some automotive applications the die's bond wires go straight to the connector ([Fan et al., 2017](#)). [Wang et al. \(2016\)](#) elucidate that the use of a bare die eliminates stray inductance and capacitance associated with the lead frames and the device input/outputs (I/Os), therefore eliminating troublesome timing delays. Bare die devices such as static RAMs offer a 20% improvement in access time ([Ahyi et al., 2015](#)). Portable devices can also utilize FC bonding techniques.

[Pavlidis et al. \(2017\)](#) classify IC packaging into the following categories:

- Through-hole packages
- Surface-mount packages (plastic or ceramic)
- Chip-scale packaging
- Bare die
- Module assemblies

5.3.2 Development drivers

The most visible demand is for consumer electronics and mobile communication devices (Hoene et al., 2014). Castells et al. (2009) argue that these devices keep a globally connected population linked and this trend is the primary driver of innovation and product evolution. Electronics manufacturers need to deliver ever-more compact and portable products faster and at a lower cost to satisfy market demands (Sprecher, 2016). Consumers and industrial users ask for solutions that generally deliver more functionality, increased performance, greater speed, and smaller form factors. Therefore, miniaturization (Bagen et al., 2013) and ever-more complex software systems embedded in billions of networked devices (Wolf, 2014; Zhu and Azar, 2015) are rapidly coalescing into a vast new era: the Internet of Things (IoT).

Development drivers force semiconductor companies to develop new more advanced IC packaging technologies to provide much greater integration and thus creating increasingly miniaturized devices (Tong et al., 2013; Zwenger et al., 2017). Therefore, a new generation of IC packaging now includes fan-out wafer-level packaging (FOWLP), stacked IC packages, and complex SiPs. In addition, advances in substrates, FC interconnection, and through-silicon-vias (TSV) are rapidly taking place. All of these advances improve packaging density and thereby create new market opportunities for well-prepared manufacturers (Na et al., 2014; Liang et al., 2014).

5.3.3 Design considerations

There are three key design considerations. Principal among these is the commercial dimension. Driving cost down rapidly is a supreme and long-term success trend in the industry (Kwon et al., 2014; Lau, 2014; Myles et al., 2015). Electrical functions are also a critical dimension (Na et al., 2014; Landesberger et al., 2016; Lee et al., 2017c). Finally, mechanical and thermal issues form the last hurdle (Jung et al., 2014; Wang et al., 2015).

5.3.3.1 Cost

According to Wang et al. (2013) cost is a significant factor for many designs. Gmelin and Seuring (2014) explicate that lowering costs could improve acceptance of the marketplace along with increased profitability. Economic viability of the end product often depends on appropriate material choices and manufacturing precision, elucidate Ashby and Johnson (2013). Opting for the lowest total cost material systems is often a great solution. Characteristically, an inexpensive plastic package can dissipate heat up to 2 W, adds Lienhard (2013). This is sufficient for many simple applications. Of course, a similar ceramic package can dissipate up to 50 W in the same scenario but a tremendous expense that few outside of aerospace and defense are willing to pay for, asserts Bejan (2013). Therefore, selecting a ceramic package needs to be very carefully evaluated. Importantly, Incropera (1988) points out as chips inside a package get faster and smaller, they also get very much hotter. Consequently, the need for more effective heat dissipation increases. Thus, the cost of packaging rises, observe

Shim et al. (2013). Normally, the smaller and more complex the package needs to be, the more expensive it is to manufacture (Tietze et al., 2015; Garrou et al., 2014).

5.3.3.2 *Electrical functions*

Lee (1998) emphasizes that compared to on-chip signals, electrical properties change as the current-carrying traces exit the die, cross the package, and enter the PCB. This means that they require special design techniques (Sira-Ramírez and Silva-ortigoza, 2006). In addition, Benini et al. (2000) point out that they need much more electric power than signals confined to the chip itself. Therefore, it is important that materials used as electrical contacts exhibit characteristics such as low resistance, capacitance, and inductance (Caponet et al., 2002; Low et al., 2009).

Edwards and Steer (2016) highlight that signal transmission properties must be enhanced both by the selected materials and the structural elements. At the same time, negative signal affects such as parasitic elements must be eliminated or minimized according to Lefranc and Frey (2015). Successfully controlling these affords a platform to create sustainable competitive advantage (Laszlo and Zhexembayeva, 2017), especially since packaging-related delays traditionally make up about half of a high-performance computer's total delay, assert Baby et al. (2015). Pavarelli et al. (2014) and Tobias (2015) expect this bottleneck to increase and point out that harnessing relevant expertise is the only way to move forward.

5.3.3.3 *Mechanical and thermal*

The IC package must keep chips secure and safe from mostly externally induced damages (Anderson and Kuhn, 1996; Zhang et al., 2005a; Kae-Nune and Pessegueir, 2013). Package functionality must include resistance to physical intrusion or breakage (Chong et al., 2006), provision of an effective seal to keep out moisture (Wang et al., 2014b), and most importantly the effective facilitation of heat dissipation (Alexander et al., 2015). In addition, Lin et al. (2016) emphasize that all packages must provide an effective PCB connection. This connection method changes drastically with each new generation of package design (Tietze et al., 2015).

Packaging materials are typically either ceramic or plastic (Ramesham, 2014). Kumar and Vadiraj (2016) highlight that while ceramic packaging generally performs better, it is much more expensive. In fact, in many applications ceramic packaging would be prohibitively expensive (Datta, 2015). Li and Wong (2006) explain that plastic packaging can be made of thermoplastics or thermosets and their properties can vary a great deal as a result. It is possible to make plastics thermally conductive while at the same time electrically insulating (Amarasekera, 2005; Lee et al., 2008). However, Chen et al. (2016b) underline that such efforts add considerable costs. In addition, Zhou et al. (2007) argue that thermally conductive plastics perform best if a brand-new package is designed to take advantage of their properties.

Physics dictate, according to Mazzoco (2001), that an increased package surface area performs better as a convective heat transfer element. Therefore, a few packages utilize extended surfaces such as fins to enhance heat transfer characteristics

(Tsai, 2017). This, however, comes at the cost of space and as such opposes the long-term miniaturization trend, observes Nakayama (2004). Proponents of this method point out that larger sizes also permit easier mechanical connections (Jamnia, 2016; Pecht, 1991). However, technology history underlines the futility of opposing a long-term trend (Munshi, 2017; Kirkpatrick, 2004; Chase-Dunn, 1999). Therefore, Mahalingam (1985) and others argue (Giraud et al., 2016; Kheirabadi and Groulx, 2016) that better heat management is the only answer to these challenges.

Development drivers and design considerations forced the evolution of technology advances in package substrates (Lee et al., 2017b; Shi and Tortorici, 2017; Hoene et al., 2014), FC interconnection (Luo et al., 2017; Tong et al., 2013), as well as stacked IC packages (Chaware et al., 2015; Shi, 2014). New packaging products like FOWLP, complex SiPs, and TSV were developed.

5.3.4 Through-hole packages

Through-hole technology as the name seems to indicate utilizes holes (Tsukada et al., 1992; Datta et al., 2004). These holes are most commonly drilled through the PCB for the purposes of mounting the components. In a through-hole package the device has leads that are soldered to pads on the PCB. Soldering allows electrical connection and mechanical positioning on the PCB.

Therefore, Tummala (2005) explains that these packages mount in holes that are usually plated with metal on the PCB. These device packages include Table 5.1 and the following:

- Batwing, a through-hole package that is sometimes a DIP type, but can also be surface mounted with two side tabs utilized for increasing heat dissipation.
- Ceramic dual inline package (CERDIP). This is a through-hole package that is encased in a ceramic material.

Table 5.1 Frequently used through-hole packages

Acronym	Full name
CDIP	Ceramic DIP
CERDIP	Glass-sealed ceramic DIP
DIP	Dual inline package
MDIP	Molded DIP
PDIP	Plastic DIP
QIP	Quadruple inline package
SDIP	Skinny DIP
SIP	Single inline package
ZIP	Zig-zag inline package

- Dual inline package (DIL), see next item for a more detailed description.
- DIP, a through-hole package with two straight parallel rows of pins or lead wires, hence the dual part in the name. The number of pins might be anywhere from 8 to 68 leads although according to some observers more than 75% of DIP devices have 14–16 pins. The pin spacing generally is 0.100" (2.54 mm). There is also a slightly modified version called the shrink DIP (SDIP).
- Plastic DIP (PDIP), same as a CERDIP or DIP with plastic encasement.
- PGA, a ceramic or plastic encased package. Characteristically, pins cover the entire bottom surface of the square package. Lead pitch is either 0.1" (2.54 mm) or 0.05" (1.27 mm). Devices have various pin counts, usually 68 or even more. The chip is either placed opposite the pins in a cavity up configuration or nested in the grid in a cavity array formation.
- Pinned uncommitted memory array is a PGA package developed for an application-specific integrated circuit (ASIC) memory array.
- Plastic pin grid array (PPGA) is encased in plastic.
- Quad inline package (QIP or QUIL), see next item for a more detailed description.
- Quad inline package (QUIP)—same as a DIP except this package has another dual row of pins along the package edge. Two plus two equals four, hence the word quad in the name. Row to row spacing is again 0.1" (2.54 mm).
- SDIP is a dual inline device with 24–64 pins and 0.07" (1.78 mm) spacing.
- Single inline (SIL) or single inline module (SIM) is a device with electrical connections that are made to a row of conductors along only one side, hence the name single in the label.
- Single inline package (SIP) is a vertically mounted module with one row of pins along the edge for through-hole mounting. The pins are spaced 0.1" (2.54 mm) apart. The benefit of this package is the ease of heat sink inclusion.
- Wafer-on-Wafer (WOW) is a wafer integration process containing a microspring and gold filaments. These are coated with a flexible nickel alloy. The filaments are attached to the bonding pads of each die. This configuration enables efficient high-speed testing and burn-in.
- Zig-zag inline package (ZIP). This device might be either a DIP or a SIP package. Lead spacing is 0.05" (1.27 mm). The leads form a staggered zig-zag pattern.

The benefits of through-hole packages include ease of soldering by hand or most commonly automatically in wave soldering (Beica, 2015; Lee et al., 2016). These devices are relatively easy to desolder and test. The through-hole method implements interconnections between upper and lower layers of the PCB. There are, however, drawbacks, explains Naik (2015), to using the through-hole method. Signals must go through all layers of the PCB. Through-hole packages are considered to be low density due to pin diameter and single-sided mounting. Shi and Tortorici (2017) point out that these drawbacks facilitated developments of denser technologies.

5.3.4.1 Pin grid arrays

PPAs utilize the through-hole method but density is increased from the traditional setup according to Yu and Dai (1995). Ghosal et al. (2001) explicate that the square or rectangular IC package in a PGA incorporates a regular array of pins underneath the package. Hence the name pin grid array or its abbreviated version PGA. A variety of packages evolved from this simple concept and a few of them are listed in Table 5.2. Frequently, these pins are spaced 0.1" (2.54 mm) apart. PGAs are almost always

Table 5.2 Pin grid array acronyms

Acronym	Full name
CPGA	Ceramic pin grid array
FCPGA	Flip-chip pin grid array
OPGA	Organic pin grid array
PAC	Pin array cartridge
PGA	Pin grid array

mounted on PCBs using the through-hole method (Goodman et al., 1995). An alternative method is to insert a PGA into a socket (Field et al., 2014). Jamnia (2016) explains that PGAs allow for more pins per IC than older packages, for instance, a DIP.

5.3.5 Surface mount

Ma et al. (2017) emphasize that plastic surface-mount packages result in a device that is light and small. Thus, SMT can withstand shock and vibration better than previous technologies according to Prasad (2013). Most importantly, Canumalla and Viswanadham (2010) highlight that surface-mount devices (SMDs) are inexpensive due to a single-step manufacturing process. The plastic is simply molded around the lead frame. There are, however, coefficient of thermal expansion (CTE) mismatches between the die and the plastic package in addition to hermeticity issues (Chen et al., 2016a; Liao et al., 2017).

Another issue is that plastic packages are hygroscopic (Wong et al., 2000; Ardebili et al., 2003; Fan and Suhir, 2010). That means that the plastic encasement absorbs moisture from its environment. Yoon et al. (2008) explain that moisture vaporization presents a special challenge during rapid heating. For instance, in a solder reflow process, vaporization creates substantially enough mechanical stresses that can often cause cracking known by the industry as the popcorn effect (Wu et al., 2014; Yi, 2014; Ge et al., 2016). Subsequently, operating the device at a high-temperature and in moist atmospheres allows contaminants to enter the IC and causes failure due to corrosion or shorts (Shirangi and Michel, 2010; Sun et al., 2014; Shrestha et al., 2017).

Importantly, Saponara et al. (2016) elucidate that plastic SMDs shipped in sealed bags preferably with a desiccant charge are designed for a 1-year storage. The bag should only be opened at the time the parts are to be used. Parts stored for longer than a year must be baked to remove moisture according to Pei et al. (2016). Consult an expert on the proper process, advise Conseil et al. (2014).

The above issues have been avoided by hermetic packages according to Schuettler et al. (2012). These are used in harsh applications such as aerospace, defense, and medical where the added cost is balanced by much improved reliability considerations, assert Vanhoestenbergh and Donaldson (2013). Therefore, hermetic SMDs are utilized in avionics, mission-critical communication, navigation systems, and

implantable devices. Reliability of a hermetic package can further be improved by eliminating CTE differences between the device and the PCB material (Ren et al., 2014; Nguyen et al., 2017). This, however, as Gerstlauer et al. (2009) underscore, further increases associated costs.

As a rule of thumb, metal packages incorporating glass seals offer the highest level of hermetic protection, add Torunbalci et al. (2015). Metal encasement is followed by glasses and ceramics, clarify Sharif et al. (2014). Shen (2014) explain that these devices have a higher operating temperature range than devices encased in plastic. Typical operating temperature range is from -55 to $+125^{\circ}\text{C}$. This contrasts with the operational temperature range of plastic-encased devices that generally operate from 0 to 70°C , or in special cases 85°C according to Yang et al. (2014).

Chen et al. (2015a) explain that the most frequently used ceramic material aluminum oxide has a thermal conductivity that is an order of magnitude larger than plastics with small associated CTE variation to the common substrates, resulting in low level of stresses. However, plastic encapsulated devices can often fail after only 250 temperature cycles (Su et al., 2014), which might cause a problem in certain applications. Jurków et al. (2015) state that a more complicated manufacturing process is a disadvantage in specifying ceramic packaged devices (SMDs). These SMDs are made up of three ceramic layers. This accounts for some of the higher costs in the device. Availability is also limited, and lead times are much longer than standard plastic devices. Therefore, ceramic SMDs are avoided unless the customer demands it (Thomas et al., 2014; Doane and Franzon, 2013).

SMT includes many types of packages. Doerr et al. (2017) opine that one of the best known is the ball grid array. Ju et al. (1994) state that this design was developed by International Business Machines (IBM). This package is also known as an overmolded pad-array carrier (OMPAC). Ultimately, a plastic encapsulated version was developed by Motorola according to Jung et al. (1997). Leads and pads were replaced by solder balls in a BGA. BGAs increased connection densities, since several hundred arrayed leads were accommodated in an area that a few hundred peripherally arranged pins or leads would occupy. In addition, a BGA increased heat transfer compared to a QFP. As a consequence, Al-Momani (2016) believes that BGAs replaced high pin count quad flat packs (QFPs) and PGAs.

In summary, the SMT has much higher density because pins can be thinner, devices are often mounted on both sides of the PCB, and components do not block inner layer signals. SMT can be automated to a higher degree than through-hole mounted technology (Marcoux, 2013). McDowell and Hubing (2014) emphasize that SMT also reduces parasitic capacitance and inductance. Most important, however, is that SMT reduced both cost and size of the devices, states Prasad (2013).

A major disadvantage of a BGA device is that solder connections cannot be visually inspected according to Yunus et al. (2003). Also, Yu et al. (2000) warn that removed parts cannot be reused without additional steps. However, failure rates appear to be very low. Teramoto et al. (2007) state that problems generally develop due to defective boards and components. Sometimes setup errors or damaged machines in the assembly line contribute additional source of problems (Mearig and Goers, 1995).

Van Driel et al. (2007) underline that there are many BGA versions. These include the perimeter lead BGA, which does not have any solder balls under the chip and the μ BGA (micro-BGA). The most important SMT acronyms are included in Table 5.3.

Other historically important surface-mount packages in accordance with Jamnia (2016) and their related packaging terminology are as follows:

- Biometric package was developed in 1996. It is a device in which the die is exposed but the interconnections are protected by plastic encapsulation. One application is fingerprint recognition.
- A chip array BGA (caBGA) device is much smaller than a comparable PLCC package.
- Ceramic ball grid array (CBGA) is encased in a ceramic such as aluminum oxide.
- Ceramic column grid array (CCGA) was patented by IBM. Solder columns replaced the solder balls in this design.
- Cerpack is a flat pack device that is structured as a ceramic base and lid. The lead frame is sealed by a frit.
- Cerquad is a ceramic equivalent of a plastic leaded chip carrier consisting of a glass-sealed ceramic package with J leads and an ultraviolet (UV) window.
- Chip carrier (CC) is a square or rectangular device with connections placed on all four sides.
- Ceramic leaded chip carrier (CLDCC) is a chip carrier in a ceramic encasement.
- Ceramic leadless chip carrier (CLCC or CLLCC), see LCCC for a more detailed description.
- Ceramic pin grid array (CPGA) is a PGA enclosed in a ceramic material.
- Ceramic quad flat package incorporating J leads (CQFJ).
- Ceramic quad flat pack (CQFP) is an aluminum oxide encased IC package with four sets of connections, which are extending from the sides and parallel to the bottom surface of the IC.
- Ceramic small outline incorporating J leads (CSOJ).
- Chip-scale grid array (CSGA) is like a BGA, except with a smaller solder ball pitch. A CSGA is utilized with packages incorporating at least 200 leads.
- Dual small outline package (DSOP).
- EDQUAD, is a plastic package that incorporates a heat sink.
- Enhanced plastic BGA (EPBGA) is a package that supports 313 to 750 leads and is primarily designed for high-frequency ASIC applications.
- FCBGA is a design for high-frequency and high I/O devices that is large enough to handle increased thermal requirements.

Table 5.3 Most important surface-mount technology acronyms

Acronym	Full name
CCGA	Ceramic column grid array
CGA	Column grid array
CERPACK	Ceramic package
LLP	Leadless lead-frame package
LGA	Land grid array
LTCC	Low temperature co-fired ceramic
MCM	Multichip module

- Flip-chip on board (FCOB).
- Flat pack or quad flat pack is one of the oldest surface-mount packages utilized mainly on defense applications.
- Flat SIP (FSIP) is a single inline package, but the leads' design incorporates a 90 degrees bend.
- Flat pack (FP).
- Fine-pitch BGA (fpBGA).
- Fine pitch super BGA (fpsBGA).
- Gull-winged leadless chip carrier (GCC). Ease of inspection was its primary design criteria. However, it is structurally weaker than J leads.
- Gull wings. They label leads that exit from the body and curve downward, thereby resembling a seagull in flight, hence its name. Gull wings are typically used on small outline (SO) packages. It must be noted that they are fragile, as they easily bent, and very difficult to socket for testing or burn-in. J leads have solved these problems.
- Hermetic chip carrier (HCC).
- High-density PQFP (HD-PQFP) is a package with more than 196 leads incorporating a 0.4-mm pitch.
- Heat spreader QFP (HQFP) is a package that utilizes a copper heat spreader and sink.
- Hermetic QSOP (HQSOP).
- Hermetic small outline transistor (H-SOT).
- I lead, is IC leads that are formed perpendicular to the PCB and making a butt solder joint.
- J leads are connections that are rolled under the body of the device in the outline of a letter J. Typically, they are utilized on plastic encased chip carrier packages.
- J leaded chip carrier (JCC).
- J leaded ceramic chip carrier (JLCC).
- LCC is a chip package with connections located on the perimeter of the package.
- Leadless ceramic chip carrier (LCCC) also called ceramic leadless chip carrier.
- Leaded ceramic chip carrier (LDCC) packages contain JEDEC types A, B, C, and D.
- LGA this package is like a PGA, but it has gold-plated pads that are called landing pads as opposed to pins.
- Leadless inverted device (LID) is a formed metallized ceramic shape that is used as an intermediate carrier for the die. It is designed for attachment to conductor lands of a film network by reflow soldering.
- Little foot is a small outline integrated circuit (SOIC) package.
- Leadless ceramic chip carrier (LLCC).
- Mini-BGA (mBGA) incorporates combination of layers of polyimide and metal to form a peripheral connection arrangement into an area array configuration.
- Miniflat is a flat package (MFP) that incorporates leads on two sides of the package.
- Multilayer molded (MM) package was designed to improve high-speed operation by separating power and ground planes. Thus, this design reduced device capacitance.
- Multilayer molded PQFP (MM-PQFP).
- Metal quad flat pack (MQFP).
- MQuad is a high thermal dissipation aluminum package existing in plastic leaded chip carrier (PLCC) and QFP packages.
- Miniature SOP (MSOP).
- Pad array carrier (PAD) is a surface-mount equivalent of the PGA package. This package improves surface-mount silicon efficiency from 15% to 40%. However, a disadvantage of

this package is its limited solder joints inspection capacity. Therefore, an X-ray inspection needs to be used for integrity verification. Importantly, another limitation is that individual solder joints cannot be repaired.

- Plastic ball grid array (PBGA).
- Plastic leaded chip carrier (PLCC) a.k.a. quad pack or PLDCC. These devices can be either surface mounted or socketed.
- PQFP. This package incorporates gull-wing leads on all four sides. The body is thicker than the QFP. PQFP packages are vulnerable to moisture-induced cracking if reflow soldered.
- Plastic surface-mount component (PSMC).
- Plastic SOP (PSOP).
- Quad flat J (QFJ) leaded package.
- Quad flat pack no-leads (QFN).
- QFP is a flat pack with leads on all sides.
- Quarter quad flat pack (QQFT).
- Quad surface mount (QSM).
- Quarter-size small outline package (QSOP).
- Quad very small outline package (QVSOP). This package is a half-width 14 pin SOIC.
- Square chip carrier (SCC).
- Small outline (SO) includes versions such as SO narrow, SO wide, and SO large.
- SOIC is a package with 8–28 pin. This package is about half the size of a DIP.
- Small outline package with J leads (SOJ). The leads are curved back around the chip carrier.
- Small outline large (SOL), twice as wide as a standard SO package. It is a bigger version of the shrink small outline package (SSOP).
- Small outline package (SOP), a package with dual rows of gull-wing leads basically the same as SOIC.
- Small outline transistor (SOT). A plastic encased leaded package originally for diodes and transistors.
- Small outline wide (SOW).
- Shrink quad flat pack (SQFP), quarter quad flat pack (QQFT), a.k.a. flat package, which is typically a 64-pin small quad flat package approximately a quarter height of a QFT.
- Square surface mounting (SSM).
- Shrink small outline package (SSOP).
- Shrink small outline integrated circuit (SSOIC) is a plastic package with gull-wing leads on two sides.
- Tape ball grid array (TBGA).
- Thin QFP (TQFP). Representative sizes are 1.0 and 1.4 mm of body thickness and in lengths ranging from 10 mm × 10 mm to 20 mm × 20 mm. This package has 64 to 144 leads.
- TSOP generally used for memory.
- Thin shrink small-outline package (TSSOP) is about half the height of a standard SOIC.
- Thin very-small-outline package (TVSOP), which meets the 1.2 mm height for PCMCIA cards.
- Ultrathin leadless package (UTLP).
- Vertical mount package (VPAK) a package design very similar to a zig-zag package (ZIP), but instead of through-hole leads it has surface-mount L-shaped leads.
- Very small quad flat package (VQFP).
- Very small outline (VSO) usually with gull-wing leads.
- Very small outline package (VSOP).

5.3.5.1 Flat packages

Historically, as [Hu and Liu \(2016\)](#) explain, the QFP packaging method became common in Europe and United States during the early 1990s. [Anjoh et al. \(1998\)](#) elucidate that there was a substantial time-lag as the Japanese used it since the late 1970s. Flat packages are often mixed with hole mounted and socketed components on the same PCB. A QFP is a surface-mount IC device incorporating gull wing—like leads extending from the four sides according to [Bar-Cohen \(1992\)](#). Socketing such packages is seldom done and through-hole mounting is simply not possible ([Mercado and Chavez, 2001](#)).

There are lots of versions and some of the related acronyms are in [Table 5.4](#). These vary from 32 to 304 pins with a pitch ranging from 0.4 to 1.0 mm. Low-profile QFP (LQFP) and thin QFP (TQFP) also exist ([Tummala and Madiseti, 1999](#)). A clear variation is a bumpered QFT with extensions at the four corners to protect the leads from mechanical damage prior to soldering ([Ray, 1991](#); [Hamilton et al., 1989](#); [Seth et al., 1989](#)). Heat sink QFP, Heat sink very-thin quad flat-pack no-leads (HVQFN) is a device with no connections extending from the IC as per [Beijer et al. \(2005\)](#). Pads are located along the sides of the IC. The chip is exposed and can be used as ground ([De Vries et al., 2009](#)).

Table 5.4 Flat packages

Acronym	Full name
BQFP	Bumpered quad flat pack
CFP	Ceramic flat pack
CQFP	Ceramic quad flat-pack, like PQFP
DFN	Dual flat pack
ETQFP	Exposed thin quad flat package
HVQFN	Heat-sink very-thin quad flat-pack no-leads
LQFP	Low-profile quad flat package
MQFP	Metric quad flat pack
ODFN	Optical dual flat no-lead
PQFN	Power quad flat no-lead
PQFP	Plastic quad flat package
QFN	Quad flat no-leads package
QFP	Quad flat package
TQFP	Thin quad flat pack
TQFN	Thin quad flat no-lead
VQFP	Very-thin quad flat pack

The quintessential form is a flat rectangular most often square body with leads on four sides according to [Lu et al. \(2000\)](#). There are numerous variations on this basic design. The variants usually differ only in a particular property such as major dimensions, number of connections, pitch, and materials utilized ([Krishnamoorthi et al., 2003](#)). [Vandeveldt et al. \(2007\)](#) assert that material selection is usually driven by a desire to improve thermal characteristics of the device.

It is important to note that a QFP has leads only around the periphery of the device as explained by [Kariya et al. \(1999\)](#). Therefore, to increase the number of connections, pin spacing was decreased. However, this created a substantial problem. Close lead spacing made the probability of solder bridges greater ([Chong et al., 2006](#)). [Gayle et al. \(2001\)](#) elucidate that this in turn created increased demands on the soldering process. The later developed PGA and BGA packages overcame this difficulty by incorporating connections over the entire underside of the package, observe [Mearig and Goers \(1995\)](#). This simple step created a possibility for larger number of pins while retaining the same package sizes. Close lead spacing—related problems were thus eliminated.

5.3.5.2 Small outline packages

A variety of packages evolved from the small outline concept ([Lau and Harkins, 1988](#)) and a few of the acronyms are listed in [Table 5.5](#).

Table 5.5 Small outline packages

Acronym	Full name
CSOP	Ceramic small outline package
HSOP	Thermally enhanced small-outline package
MSOP	Mini small-outline package
PSOP	Plastic small-outline package
PSON	Plastic small-outline no-lead package
QSOP	Quarter-size small-outline package
SOIC	Small outline integrated circuit
SOP	Small outline package
SSOP	Shrink small-outline package
TSOP	Thin small-outline package
TSSOP	Thin shrink small-outline package
TVSOP	Thin very-small-outline package
WSOP	Very thin small-outline no-lead package

5.3.5.3 Chip Carrier

A chip carrier is a rectangular package incorporating contacts on four edges as explicated by [Knickerbocker et al. \(2005\)](#). Leaded chip carriers have metal J-shaped leads around the edge of the device, while leadless ones have metal pads. Chip carriers use ceramic or plastic as their materials of choice and are secured to a PCB by soldering ([Zweben, 1992](#)). A variety of packages evolved from this concept and a few of the acronyms are listed in [Table 5.6](#).

5.3.5.4 Ball grid array

[Master et al. \(1995\)](#) explain that a BGA is a type of surface-mount packaging that uses the underside of the package to place pads with balls of solder in a grid pattern as connections to the PCB. A BGA provide more interconnections than a dual inline or flat package ([Syed, 1996](#); [Brunnbauer et al., 2008](#)). Conceptually, the whole bottom surface area of the device can be used for connections instead of just the perimeter as was pointed out by [Doerr et al. \(2017\)](#). The leads are also shortened leading to high speed performance increases according to [Yap et al. \(2017\)](#). However, [Bai et al. \(2017\)](#) emphasize that soldering a BGA device requires precise control that can only be achieved by automated processes. In addition, BGA packages cannot be socket mounted, observes [Jamnia \(2016\)](#).

BGAs are improved versions of the PGA. As a quick reminder, a PGA is a type of package with the bottom face covered with pins in a grid pattern, explicate [Ghosal et al. \(2001\)](#). This grid pattern conducts the electrical signals between the IC and the PCB on which it is affixed. The PGA pins are replaced by pads on the bottom in a BGA package. Each pad has a miniature solder ball formed on it. These solder spheres are created by an automated process. The package is located on the PCB with a matching pattern of copper pads. The assembly is then heated to melt the solder balls. The BGA package is aligned with the PCB via the melted solder's surface tension. Permanent connections are formed between the package and the PCB once the solder solidifies.

Table 5.6 Chip carrier acronyms

Acronym	Full name
BCC	Bump chip carrier
CLCC	Ceramic leadless chip carrier
DLCC	Dual lead-less chip carrier (ceramic)
LCC	Leadless chip carrier
LCC	Leaded chip carrier
LCCC	Leaded ceramic chip carrier
PLCC	Plastic leaded chip carrier

Essentially, explain [Mearig and Goers \(1995\)](#), a BGA is a miniature package for an IC that needs hundreds of connections. Historically, predecessors the PGAs and dual-inline surface-mount (SOIC) packages incorporated more and more pins ([Ghaffarian, 2016](#)). This meant that the space between pins drastically decreased. This resulted in major soldering difficulties primarily by accidental bridging of adjacent pins. BGAs do not have this problem as the solder balls are created automatically.

BGA packages have a further advantage compared to packages with discrete leads, that is, packages with legs. This important advantage is the lower thermal resistance between the PCB and the device ([Lee et al., 2017a](#)). Therefore, heat generated by the IC within the device can be transferred to the PCB more readily. [Tsai \(2017\)](#) explicates that better heat management avoids overheating the chip.

Significantly, shortening an electrical conductor lowers its inductance. [Gibbard et al. \(2015\)](#) highlight that this is paramount as inductance distorts signals in high-speed electronic circuit. BGAs substantially shortened the distance between the mounted chip and the PCB. This in turn lead to much lower inductances, thereby increasing performance ([Kamalanathsharma and Rakha, 2016](#)).

According to [Lee et al. \(2017a\)](#), a major disadvantage, however, is that the solder spheres are stiff. Solder balls cannot bend and stretch in the way that legs on pinned connections used to do. The need for movement is a phenomenon due to the difference in CTE between the PCB acting as a substrate and the device ([Suhir and Ghaffarian, 2015](#)). This thermally induced stress can become so large especially if additional forms of stresses are present such as shock and vibration that the solder joints fracture. Once a joint fracture, the device fails. Unfortunately, thermal expansion issues are not easily fixed. [Shekhar et al. \(2016\)](#) warn that matching thermal characteristics of the PCB and the package is easier said than done.

The introduction of lead-free solder alloys created further problems according to [Zhao et al. \(2015\)](#). [Thirugnanasambandam et al. \(2014\)](#) assert that this new solder alloys have lower ductility and thereby increased the probability of joint failures especially in extreme operating conditions such as increased temperature, thermal shock, and extreme gravitational force environments.

Mechanical stress issues can be managed by underfilling, state [Burnette et al. \(2000\)](#). [Wang and Wong \(2000\)](#) explicate that this is a bonding process that injects a suitable mixture between the package and the PCB. In other words, the device is now glued to the PCB. An advantage of this process is that it better controls tin whisker growth ([Qi et al., 2007, 2008](#)). However, [Qi et al. \(2009\)](#) observe that it introduces yet another thermal management problem to an already complex situation. Another solution to the problem of nonflexing connections is to place a compliant layer in the package. This layer allows freedom of movement to the solder spheres. This technique has become standard for certain applications. However, this process did nothing to improve thermal management. There are other techniques for increasing reliability of BGA packages, add [Suhir and Ghaffarian \(2015\)](#). These include the use of low-expansion PCBs, interposers, and if all else fail repackaging a device.

BGAs can also hide problems ([Yu et al., 2000](#)). It is extremely difficult to find soldering faults once a BGA device is soldered into place. [Jin et al. \(2017\)](#) advise that special techniques utilizing X-rays, industrial computed tomography (CT) scanning

machines, microscopes, and even endoscopes are deployed to allow viewing beneath the soldered package. Due to the high cost of such a visual inspection, electrical testing is very often used instead according to [Tietze et al. \(2015\)](#). [Jeong et al. \(2017\)](#) observe that a very common method is to use boundary scan testing.

If a BGA is found to be incorrectly soldered, it can be removed in a specialized rework station according to [Mearig and Goers \(1995\)](#). This is a jig fitted with a controlled heat source and vacuum is provided to lift the loosened BGA package. The device can be replaced with a new one. Alternatively, incorrectly soldered BGAs can be reballed and reinstalled on another circuit board ([Stoyanov et al., 2014](#); [Al-Momani, 2016](#)). Re-balling is only financially feasible if only one or a few spheres need to be reworked ([Heckmann et al., 2016](#)).

A cheaper, easier, albeit totally destructive inspection method is often used simply because it does not require specialized and costly equipment ([Kinyanjui et al., 2008](#)). This method is frequently referred to as dye and pry. The process starts by immersing the entire PCB into a dye. Next step is to dry the PCB. After drying is completed, the device is pried off and the broken joints are visually inspected. The connection was incorrectly made if a solder location contains dye. However, if the connection does not contain the dye, then a functioning PCB was needlessly destroyed ([He et al., 2015](#)).

A great many packages evolved from the fundamental BGA concept according to [Burling et al. \(2015\)](#) and a few of them are listed in [Table 5.7](#).

Table 5.7 BGA acronyms

Acronym	Full name
CBGA	Ceramic ball grid array
FBGA	Fine pitch ball grid array
LBGA	Low-profile ball grid array
LFBGA	Low-profile fine pitch ball grid array
μBGA	Micro-ball grid array
MAP-BGA	Mold array process—ball grid array
OBGA	Organic ball grid array
PBGA	Plastic ball grid array
SBGA	Super ball grid array
TBGA	Thin ball grid array
TEPBGA	Thermally enhanced plastic ball grid array
TFBGA	Thin fine pitch ball grid array
UCSP	Micro- chip-scale package
UFBGA	Ultrafine ball grid array

5.3.6 Bare die

Ho et al. (2014) highlight that an unpackaged or bare chip offers the smallest size. A bare die also has no signal delays associated with the package according to Jamnia (2016). There are, however, issues related to unpackaged chips. The main three issues are packaging, handling, and testing related (Huttunen et al., 2016). Bare dies are usually mounted on a tape for handling purposes. The most common bare chips include the following configurations in accordance with Muniandy et al. (2016):

- C4PBGA is an IC device that attaches the IC chip to a substrate using the C4 process. It uses a multilayer substrate, contrasting with the chip-scale or SLICC package.
- Chip-scale package (CSP) is a device where the IC is surrounded by a protective covering. External electrode bumps on the underside provide electrical contacts. This package is only slightly larger than the die it houses and has a height about 0.4 mm.
- COB is a design in which the chip is mounted directly on the PCB or other suitable substrates such as a tape. Related to this concept are the tape carrier packages (TCB) and tape automated bonding (TAB).
- Chip-on-flex (COF) is a variation of COB. However, instead of bonding the bare chip to a substrate, it is bonded to a polyimide film. This film has a top layer of gold-plated copper. The traces provide bonding areas for wires from the chip and a lead pitch similar to QFP devices. While it has about the same mass and height as COB, failed parts can easily be removed. It uses about the same board area as a QFP package. However, it is more expensive than COB because of the additional polyimide substrate.
- Glob top encapsulation means that a glob of encapsulating material is used in an MCM.
- Sealed chips-on-tape (SCOT) is a process in which dies are mounted on tape-supported leads and sealed most often with a blob of plastic.
- TAB same as TCP.
- TCPs were previously called the TAB process. The die is mounted to a dielectric film. This film has copper foil lead patterns on it. The die itself is sealed with a resin compound. This configuration is mounted directly to a circuit. The plastic or ceramic package is completely absent.
- Tape carrier ring otherwise known as a guard ring package is similar to the TCP package except that it also includes a plastic ring to support the outer rings during the following phases: test, burn-in, and shipment.
- Ultrahigh-volume density (UHVD) is a process to interconnect bare chips on prefabricated and laminated polyimide film.

5.3.7 Chip-scale packages

A CSP is a compromise between the dimensions and performance of a bare chip but with the improved handling and testing characteristics of packaged devices (Ghaffarian, 2001). The package size is no greater than 1.2 times the die itself as per the IPC/JEDEC definition, states Töpfer (2017). Naturally, there are various techniques developed to connect the CSP to the PCB. For instance, FCs have enlarged solder balls, pads, or bumps. FC packages utilize the controlled collapse chip connection commonly referred to as C4 (Howard, 1982), which was originally developed by IBM. An alternative method to use, according to Dehaven and Dietz (1994), is the

Motorola-designed and developed direct chip attachment. Interestingly, add [Brofman et al. \(2001\)](#), FC interconnection technology was developed a long time ago in 1964 to solve joining issues associated with discrete transistors in IBM's production facilities. There are many small packages offered by semiconductor producers according to [Garrou \(2000\)](#) and their most important acronyms are listed in [Table 5.8](#) and general designations are as follows:

- Bottom leaded plastic is a package with die leads molded into the underside of the plastic encapsulation. This CSP is only 0.5 to 0.85 mm thick.
- Bumped chip, see more information under the heading flip chip.
- Flip-chip attach.
- FC package is an IC device in which the input and output connections are formed by bumps on a single side of the package. For this reason, FCs sometimes are referred to as bumped chips. Importantly, the die is flipped over, hence its most commonly used name, and secured to a mating substrate after the die has been passivated. Attachment to a printed circuit carrier substrate is achieved by reflow soldering. Due to thermal CTE mismatch between the die and the PCB substrate, an underfill is applied. The purpose of the underfill is to reduce mechanical stresses developed by the CTE.
- Micro-SMT is a peripheral contact package, which is formed utilizing semiconductor fabrication techniques while the IC is still in its wafer form. A micro-SMT is not much larger than the chip thereby fulfilling the CSP definition criteria.
- Mini-BGA is a grid array and is similar to the FC.
- Repatterned die, see Mini-BGA.
- Slightly larger than IC carrier (SLICC) package.
- Micro-BGA (μ BGA) is otherwise known as chip-scale packaging. It is slightly larger than the IC or an SLICC package. Micro-BGA consists of a flexible circuit incorporating gold traces secured to the die pads. These pads fan into an array of metal bumps utilized at the second-level assembly. Attachment is made by using an elastomeric adhesive between the die and the circuit. This package compensates for the CTE mismatches between the chip and its flexible substrate.

It is important to note that chip-scale is not considered to be a new mounting technology ([Li and Wong, 2006](#)). It is an evolution of the SMT. Passive components must be miniaturized such as resistors, capacitors, and inductors. The benefits of chip-scale

Table 5.8 Chip-scale packages

Acronym	Full name
COB	Chip-on-board
COF	Chip-on-flex
COG	Chip-on-glass
CSP	Chip-scale package
TCSP	True chip-size package
TDSP	True die-size package

packaging are enormous (McCleary et al., 2016). Chip-scale offers a way to achieve pervasive and ubiquitous computing as well as improved high-speed performance. However, there are substantial barriers in terms of PCB fabrication and device mounting. According to Lu and Wong (2009) CSPs are not serviceable and long-term reliability is also suspect.

5.3.8 Module assemblies

Module assemblies is the proper terminology to refer to a packaging scheme that joins either a bare die or packaged parts and creates an assembly according to Ulrich and Brown (2006). This assembly creation might be completed by mounting components to a substrate or PCB. Alternatively, an assembly could be created by stacking dies such as to create dense memory modules (Liu, 2001). This design primarily used as SMT, but on occasion it was converted to be used in a through-hole mounting scenario. On such an occasion, the might have pins or use socket mounting incorporating conductive traces. Some of the best-known variations include the following in accordance with Tummala (2005):

- Dual-inline memory module (DIMM).
- Full stack technology is able to pack anywhere from 20 to 100 dice horizontally, which is commonly referred to as a loaf-of-bread configuration.
- Hermetic DIP (HDIP) module is hermetically sealed. Components are mounted both on top and bottom of a ceramic substrate.
- Hermetic vertical DIP (HVDIP) module is similar to an HDIP but with a vertically mounted ceramic module. Pins are located along the edges for through-hole mounting.
- Leaded multichip module (LMM).
- Multichip module (MCM) is a package that uses SMT for ICs. Bare dies are mounted and connected through a substrate like a multilayer board. MCM-L has a substrate that most often uses polyimide-based laminations. MCM-C uses a ceramic substrate. In this style of packaging the ceramic substrate often incorporates resistors, capacitors, and inductors. MCM-D uses a thin film of a silicon and ceramic sandwich construction, incorporating deposited conductors with capacitors built right into the substrate. MCM-LF is a laminated film made up of several layers of polyimide film. MCM-F is a designator for chips on a flexible circuit. An MCM-V design also exists. The V in this configuration means vertical. An MCM-V is a three-dimensional module.
- Memory cube is a three-dimensional MCM-V module containing of stacked memory devices like DRAMs or SRAMs.
- Modified ring frame (M-RFM) is also 3-D packaging technique. In this method, the IC wafer is separated into strips as opposed to separating all individual dice. This strip is positioned on a polymer adhesive and a ring frame. This frame has a matching CTE. A layer of the polymer adhesive is applied around the top of the strip. Metal traces are then added to route input and output connections to the edge of each die. The dice are separated at this point. They are stacked and solder balls are also added next.
- NexMod is a module designed for RDRAM. NexMod is a complete RAMBUS channel integrated into a single system. NexMod contains a clock generator, memory chips, termination resistors, and a complete voltage regulator module.
- Ribcage is a three-dimensional memory module design.

- Short stack is a method of stacking chips vertically, where memory ICs are assembled into a three-dimensional thin-film monolithic package. The stacking ICs method contains forming connections at the top of the wafer. Short stack adds vias for inner layer interconnections. These are made using IC deposition processes.
- Single inline memory module (SIMM) is an assembly containing memory chips.
- Stackable leadless chip carrier (SLCC) consists of stacked chip carriers. Stacking operation is accomplished by alignment of the devices and tin dipping the four sides. SLCC greatly improves density and can achieve a 40:1 ratio over conventional designs.
- Vertically mounted modules (VDIP).
- Wafer-level chip-scale package (WLCSP).

5.3.9 Advanced package substrates

Advanced packaging is a key technology that offers stability in an uncertain semiconductor industry (Wagner et al., 2017; Bixenman et al., 2016). Liang (2015) elucidates that packaging must offer more functionality, increased performance, tighter system integration, product diversification, and most importantly rapidly lowering manufacturing costs. Hayashi et al. (2017) state that advanced packaging has met the challenge and at the same time also adhered to scaling requirements. Substrates are one of the key interconnect components of forward-thinking architectures and are a critical element in creating innovative products and opening new market segments (De Dobbelaere et al., 2014).

Lu and Wong (2009) explain that advanced substrates in a decreasing order of volume used are FC substrates, 2.5D and 3D TSV assemblies, and thin-film redistribution layers in FOWLP. These substrates are traditionally associated with higher-end logic applications such as central processing units, graphics processing units, digital signal processors, and others according to Klauk (2006). Development of substrates was driven by integrated circuit design progress in the computing, gaming, mobile, networking, smart and high-definition television applications.

Miniaturization and reduction in power consumption mandate wafer-level packaging (WLP) and the use of advanced FC substrates (Bagen et al., 2015). Thus, they are widespread in the majority of smartphone functions like amplifiers, application processors, baseband, codecs, drivers, filters, power management, transceivers, Wi-Fi modules, and others (Kyeremateng et al., 2017).

5.3.10 System-in-Packages

Hu et al. (2014) elucidate that a SiP is a device created with many ICs encased in one package. The SiP performs almost all the associated functions of an electronic system. It is typically used where space is at a premium such as inside a smartphone according to Tummala et al. (2015). Monier-Vinard et al. (2014) explicate that chips containing ICs might be layered vertically on a substrate. Inside they are connected by fine wires (Choi et al., 2015). These are bonded to the package and aptly named bond wires.

Alternatively, solder bumps are used to join stacked dice together, for instance, if an FC is utilized (Tong et al., 2013). SiP chips can be stacked vertically or tiled straight. Das et al. (2013) assert that various 3D packaging techniques have been developed to advance miniaturization.

A SiP can contain several dies like a specialized processor and memory integrated with passive components such as resistors and capacitors (Arakawa et al., 2013). These are all mounted on the same substrate. This means that a complete unit can be built in a single multichip package. Fischer et al. (2016) point out that the obvious advantage is that fewer external components must to be added to finalize its functionality.

SiP technology is developed to miniaturize wearables and mobile devices according to Tian et al. (2017). SiP is also advancing the Internet of Things and microelectromechanical system (MEMS) sensors that can be integrated on a separate die and control connectivity, state Lai et al. (2014). However, Lin et al. (2015) emphasize that SiP solutions require multiple packaging technologies, such as FC, WLP, wire bonding, and potentially many more.

5.3.11 Through-silicon-vias

Motoyoshi (2009) elucidates that a TSV is a vertical electrical connection that passes completely through a silicon wafer. TSVs are currently considered to be high-performance interconnect techniques (Lau, 2011). They are used as an alternative to wire bonds and FCs. Jang et al. (2007) explain that the primary purpose of TSVs is to create 3D ICs. TSVs increase density and importantly the length of the electrical connections becomes shorter, thereby providing a major advantage.

TSVs are used in 3D packages including 3D ICs such as image sensors (Katti et al., 2010). Henry et al. (2008) believe that complementary metal-oxide-semiconductor (CMOS) image sensors (CIS) were the first published application to utilize TSV(s) in mass manufacturing. Initially TSVs were formed on the rear of the image sensor wafer to form connections. This setup eliminated wire bonds and allowed for substantial miniaturization (Gagnard and Mourier, 2010). Chip stacking came later with rear illuminated CIS. Jang et al. (2007) explicate that this new design involved reversing the order of the lens, circuitry, and photodiode.

A 3D package contains at least two ICs layered vertically so that they occupy less space and have better connectivity (Miettinen et al., 2004). The stacked chips are wired together in traditional 3D packages. This wiring is located along the edges and thus increases physical size of the package. In addition, the wiring necessitates an extra layer between the chips labeled the interposer. TSVs replace edge-based wiring by making vertical interconnections through the body of the stacked dies. The advantage is that the resulting device is much smaller (Jiang and Luo, 2008). A TSV 3D package is also flatter than an edge-wired 3D package because the interposer is eliminated. Knickerbocker et al. (2008) explain that this TSV technique is also known as a through-silicon stacking.

5.4 Housings

PCBs or bread-boarding cards must be mounted in some sort of an enclosure or housings according to [Leeb et al. \(2014\)](#). [Akarslan et al. \(2017\)](#) assert that connection to other components, circuitry, inputs, and outputs must be facilitated such as to power supplies, controls, and connectors. The focus of this section is to highlight acceptable methods of situating PCBs together ([Kearney et al., 2016](#)). It is important that circuits are mounted correctly and they remain accessible for testing and repair. This section starts with describing methods for locating circuit boards. Backplanes, cabinets, basic layout, and cooling will also be described.

5.4.1 Circuit board mounting

[Meier et al. \(2015\)](#) elucidate that in the simplest case only a single circuit board must be housed. In this case the simplest solution is to create holes near the corners of the board and mount the card with suitable fasteners ([Roberts-Hoffman and Thompson, 2016](#)). [Nguyen et al. \(2016\)](#) observe that horizontal boards must be oriented component side up to aid heat transfer. [Chen et al. \(2015b\)](#) explicate that boards with plated fingers facilitate connections via a card-edge connector socket. Other possibilities include a flat cable terminated with a connector or with soldered connections to swaged terminals. With edge and ribbon connectors, the board might support the connector sufficiently ([Larmagnac et al., 2014](#)). Therefore, additional connector supports can be eliminated. Independent of the method of connection, observe [Qi and Buechley \(2014\)](#), wiring should be routed in such a manner as to allow the board to be tipped upward, thereby providing access to the bottom portion so that modifications or repairs could be made.

In a slightly more complex system consisting of several circuit boards, the best way to house these boards is to use a card cage. A card cage is a rigid frame with a guiding feature incorporated for sliding individual cards into their mounting position ([Demers et al., 2015](#)). This sliding function can be accommodated with plastic card guides or simply formed dimples in the metal sides to assist in the proper alignment of the cards. Card ejectors attached to the PCBs assist in the removal of the card according to [Klug et al. \(2015\)](#). A card cage also provides aligned holes along the rear surface so as to allow mating edge connectors with the enveloped boards.

Card cages offer flexibility in board width, spacing, and number of cards housed ([Sienski et al., 1996](#)). A common size cage holds cards 4.5 inch wide (114.3 mm) with 44 pin edge connections. There are many other formats often with tight pin spacing (a tenth of an inch is common, which equates to slightly over 2.5 mm). Other designs offer multiple connectors or two-part connectors, which means that one mating portion of the connector is soldered to the board as a component. One of the most popular two-part connector is the Versa Module Europa (VME) connector, which is configured to hold 64 or 96 pins ([Fortner et al., 1991](#)). Cards can be spaced as little as half an inch (13 mm) apart. Usually either a standard 0.6 (15 mm) or 0.75 inch (19 mm) spacing is utilized. This last spacing affords more space for bulky components.

Card cages are offered with flange mounting to a flat surface that is parallel to the cards. [Newberger \(1996\)](#) points out that another popular configuration fits into rack enclosures. Modular enclosures include an integral card cage with room for controls, power supplies, and additional components.

Equipment built with the electronics spread over multiple plug-in circuit boards achieves modularity and quick replacement in case a field repair becomes unavoidable according to [Franklin and Kramer \(1982\)](#). However, this construction method often cause difficulty in circuits with signal levels less than 1 mV or frequency above 10 MHz. The fundamental problem is that a stable and low-inductance grounding system cannot be provided. Mixing analogue signals with digital switching waveforms can lead to increased difficulties ([Li et al., 1984](#)). This predicament, as [Doolittle \(2003\)](#) points out, is very much exacerbated with a hand-wired backplane. There are four possible solutions to this problem: combination of small boards into a larger one, use of wide ground traces, coaxial line, and redundant ground connections.

1. Quality often improves if interconnected small boards are avoided. Building all critical circuitry on an increased board size with an integral ground plane is often a sound decision ([Tsang and Huang, 2015](#)). However, on such a design coaxial lines or twisted-pairs need to be utilized to create connections between displaced parts of the circuit.
2. Achieving a better ground distribution is possible with wide ground traces, rather than a hand-wired backplane in interconnected board designs ([Espalin et al., 2014](#)). A continuous and stable ground connection in a radiofrequency system utilizes flexible metallic fingers incorporated along the card guides.
3. The best way to handle microvolt signals, which are prone to ground-loop noise, is the use of coaxial line combined with differential ground-sensing inputs ([Papistas and Pavlidis, 2017](#)).
4. Redundant ground connections—multiple connections to the chassis also help, state [Becker et al. \(2015\)](#). Doubled connector pins and wires incorporated to reduce the inductance through which ground currents must flow should be designed in.

5.4.2 Backplane connections

Card-edge connectors are available with small pins for insertion into boards, wire-wrap pins, and lugs for solder connections according to [Wong and Salleo \(2009\)](#). Intercard connections should be made with point-to-point wiring linking card-edge connector pins, utilizing edge connectors with solder lugs.

[Kautz \(1974\)](#) explain that efficient assembly requires cabling of wire bundles. It is preferable that wires run in straight lines parallel to the major dimensions of the card cage. Wire-wrap connections on the backplane are often used if there are many connections between the backplane pins without a requirement for connections to other points of the equipment, particularly if there is no necessity for a shielded-cable connection to the backplane.

There is a possibility to use a motherboard backplane, state [Fraeman \(1997\)](#). This is a PCB designed to hold card-edge sockets ([Singh and Viswanadham, 2012](#)). Motherboards are popular in all bussed systems. They are almost universal in computers according to [Xu \(2014\)](#). He also believes that motherboards should be incorporated into the design if the equipment is intended for mass production. Double-sided

motherboards provide the advantage of a ground plane with lower inductance and coupling of signal lines. Both sides could be used for signals if the intercard wiring is complex. Bussed systems utilize a simple backplane matching bus pins on all cards (Kimm and Jarrell, 2014).

A motherboard affords a convenient technique of interboard connection, resulting in reduction in the use of hand wiring and thereby minimizing possibilities for error, while at the same time providing better-quality electrical performance (Krein, 2017). The motherboard and its connectors are mounted firmly at the rear of a card cage in large systems.

5.4.3 Cabinets and racks as enclosures

Applications drive the selection of cabinets or rack systems (Coyne, 1982). An electronic device might be housed in a bench-top cabinet. In a different application a panel for mounting in a standard 19-inch rack might be selected. The panel is either screwed directly to the vertical rack flanges or mounted on rack slides that provide simplified access. Modular equipment is constructed to fit into slots in a larger assembly of rack-mounted bin, cage, or a crate. Crates provide power connections. Standardized connectors located at the rear are used for this purpose.

Haider et al. (2006) elucidate that there are many enclosure configurations available in both rack-mounting and bench-top designs. 17-inch (432 mm) cabinets are popular. These are available in various heights in multiples of one (25.4 mm) and three-quarters of an inch (19 mm). Many cabinets allow the installation of rack-mounting flanges or slides. Note that a 19-inch-wide (483 mm) rack has about 17.5 inches (445 mm) of clearance between the flanges. This means that equipment can be converted from bench-top to rack-mounted format, or vice versa. Convertible cabinets sometimes require removal of the outer casing for rack mounting.

5.4.4 Basic layout

This section offers general comments on construction of equipment. These suggestions allow selection of standard electronics enclosures (Ulrich, 1994). These enclosures in turn can be populated with circuitry in a proper way. Aaron et al. (2000) instruct that the front panel area of the enclosure is reserved for various displays and other human interfaces such as keypads, meters, and various indicators. Controls and frequently used connectors are also located in this area. The rear panel area of the enclosure is reserved for the opposite. Therefore, functions requiring rare access are located there. Large connectors, power cord, fuses, and other rarely accessed features are also located there.

A professional looking front panel is essential according to Wang et al. (2013). Silk-screening legends onto painted, anodized, or brushed metal surfaces have been a frequently used option (Cohen and Maharbiz, 2013). Erosion of the text and graphics is a potential longevity problem. A clear overcoat can protect these features. An alternative is to use an adhesive polycarbonate film. These films are prepared by silk-screening the text and graphics on the back side of a matte-textured 0.25-mm-thick

film to which an adhesive is applied. Lettering, patterns, and graphics can be printed in several colors including colored plastic windows or cutouts. Labeling services provide these custom laminated panel coverings. They need the artwork, which is an actual-size positive or negative of the image.

Bdeir (2009) believes that accessibility to circuit cards and controls is a must. Replacement of any component in the equipment should be possible (Jardine and Tsang, 2013). Professional cabling is needed to enable removal of modules without soldering. Circuit boards also need to be tested in situ, state Wang et al. (2014a). A card cage might be positioned so that the cards are vertical. Bejan (2013) asserts that this is preferred in almost all heat transfer situations. A card can be removed from the enclosure by plugging in an extender card. The front panel needs to be removed, or at least opened, to provide access to horizontally positioned cards. Circuits must not be positioned in layers, where one layer covers another, as heat transfer will be minimized and reliability compromised.

5.4.5 Quick cooling guide

As a quick rule of thumb, state Zhang and Zhang (2015), electronics that consume more than 3 W of electricity will require forced air cooling. A fan will be utilized if a small device turns more than 10 W into heat, or a rack-width apparatus uses more than 25 W (Yeh, 1995). Note that an enclosure packed with electronics may run at a reasonable temperature when it is on the new product development engineer's bench. The test is usually run with the top cover removed, but when the same device is installed in a rack with other heat-producing equipment, it is likely to run at an increased temperature. This is because the outer cover is in place and the ambient temperature increased from a room temperature of 22°C to a temperature often in excess of 50°C, explicates Lienhard (2013). Heat management will be dealt properly in Book 2 Part 1, but for now it is enough to understand that to have heat transfer a temperature difference must exist. This is commonly called delta T (ΔT). Increasing ambient temperature compromises ΔT and minimizes heat transfer leading to early failure of components and general reliability problems (Bergman and Incropera, 2011).

Devices using less than 3 W of power can often be cooled sufficiently with convective cooling (Zhang and Zhang, 2015). These devices do not use a fan thus they are silent. Additionally, reliability is improved by removing a maintenance-prone component.

Convective cooling is aided by placement of perforations. Their locations cannot be optimized by any rule of thumb and must be investigated by scientific methods, states Sultan (2000). Locating an opening above a major heat-producing component like a power resistor, capacitor, or transistor might not afford adequate cooling to the device. Mounting high-power components on the rear panel directly onto heat sinks with their fins aligned vertically might be a good start, but again the situation should be carefully modeled and analyzed by an expert in electronics cooling, elucidate Incropera (1988). Convective cooling is more efficient if PCBs are mounted vertically. If convective cooling is not enough, a fan needs to be installed.

Air should enter the enclosure at one end, flow around all the components, and exit at the far end in an apparatus purposely designed for forced air cooling according to [Mazzoco \(2001\)](#). An apparatus with an internal horizontal partition might benefit from inlet perforations at the bottom rear. Another set of perforation near the front of the device is needed. The exhaust fan needs to be mounted at the top rear, thus forcing the airflow to pass around all critical parts of the device. Note that a PCB will block airflow, and design the air management system accordingly. Significant impedance to the flow of air manifesting itself as high backpressure means that a centrifugal fan is needed. Centrifugal fans have a greater pressure production capability than the axial variety, explicates [Busby \(1914\)](#). In electronics cooling it is important to design conservatively. Note that dust and other particles are seldom considered at the new product development design stages or in early testing according to [Dorman \(2014\)](#). [Ohring and Kasprzak \(2014\)](#) elucidate that associated failure rates rise dramatically when the equipment is operated hot.

5.5 Enclosures

The following enclosure types can be purchased as standards ([Mcclung et al., 2005](#)) and information is displayed in [Table 5.9](#). This section will start with the smallest devices and work toward providing a description of the largest enclosures at the end.

5.5.1 *Small cabinets*

In many ways, most electrical and electronics housings could also be considered as small cabinets ([Rustogi and Gupta, 2004](#)). So, it is reasonable to start with these the smallest type of enclosures after the extended discussion on housings. Small cabinets are utilized to package instrumentation and equipment requiring a maximum volume of approximately 50 L according to [Martin and Strategy \(2016\)](#). Small cabinets include convenience features such as strap handles, tilting bails, latches, sloping fronts, to name a few, state [Avidor et al. \(2003\)](#). They are generally not intended for rack mounting, although mounting hardware may be available for some types. Small cabinets are often made from either polymeric materials or metals ([Chen et al., 2009](#)). Application notes, dimensional and load considerations, and constructional information are shown in [Table 5.10](#).

5.5.2 *Portable cabinets*

Portable cabinets are small cabinet racks used to house a limited amount of 19-inch-wide (483 mm) instrumentation or equipment. Internally, portable cabinets offer limited space for power strips and other accessories according to [Schoofs \(2004\)](#). Generally, no internal framework is present. [Giraud et al. \(2016\)](#) observe that externally, portable cabinets accept rubber feet, but not casters, levelers, or anchor kits.

Table 5.9 Standard enclosures

Enclosure type	Major features	Typical applications
Cabinet racks, including NEMA 12	Fully enclosed floor-standing cabinets. These provide a controllable environment. Front and rear doors are added for additional security. NEMA 12 cabinets have gasketed doors and side panels.	Floor-mounted enclosure for general-purpose instruments and equipment with 19" (483 mm), 23" (584 mm), or 24" (610 mm) wide panel space.
Server racks	Like floor-mount cabinet racks with the difference of heavily perforated side panels and rear door for achieving improved ventilation characteristics.	Used where protection, security, and additional ventilation are needed. Also enables mounting deeper instruments and communication equipment.
Colocation racks	Overall cabinet divided into smaller, individual compartments. Heights from approx. 24" (610 mm) to 39" (991 mm).	Used in applications requiring independent subcabinets.
Seismic racks	Heavy duty shock and vibration resistance. Designed, manufactured, and tested to Bellcore Zone 4 requirements (#GR-63 CORE, Issue 1).	Applications that are subjected to shock and vibration; these include industrial and mobile environments.
Open racks Tabletop racks Swing-frame racks	Open framework designed to mount 19" (483 mm) and 23" (584 mm) panel widths. Includes both swing-frame and wall-mount racks.	Applications include maximum free-air ventilation while offering easy access to equipment sides and rear panels.
Wall-mount cabinets	Small, relatively thin wall-mountable enclosure almost always incorporating a door.	Network hubs, mounting of data and telecommunication, and industrial automation equipment.
Portable cabinets	For assembling desktop 19" (483 mm) systems in heights of approximately 18" (457 mm) to 26" (660 mm).	Small systems where portability is needed.
Card racks	Modular packaging system for mounting circuit boards and custom electronics.	Data acquisition, telecommunications.

Continued

Table 5.9 Continued

Enclosure type	Major features	Typical applications
Small cabinets	Available in a wide range of sizes and styles, including sloping front, cases with handles, tilting feet, and computer-styled enclosures. Typical materials: steel, formed aluminum.	Used for housing of prototype or finished, medium to small electronic products, instruments, telecom devices.
Chassis	Aluminum formed and welded construction, with optional bottom plate.	Construction of products and prototypes. Provides protections and structure.
Accessories	Fans, fan trays, blowers, handles, feet, casters, levelers, slides, panel shelves, power strips, internal cable brackets.	Provide cooling, mobility, slide-out access to instruments, power distribution, etc.
Small metal enclosures Cast metal enclosures	Available in a wide range of sizes and styles. May include covers, gasketing, screws, rubber feet, or other hardware. Typical materials: aluminum.	Used to house and protect small electronic products, components, instruments, telecom devices, etc.
Plastic boxes NEMA, UL, and IEC enclosures	Available in a wide range of sizes and styles. May include plastic or metal covers, gasketing, screws, rubber feet, or other hardware. Typical materials: polycarbonate, polystyrene, ABS plastic.	Used for housing of small or handheld electronic products, component packaging, instruments, telecom devices, etc.

Table 5.10 Small cabinets

Applications	Practically an unlimited range of applications. Used for prototypes or finished, medium to small electronic products, instruments, telecom devices, computer peripherals, control panels, and other applications.
Dimensional considerations	Extremely wide range of dimensions and styles. Typical height and width to 350 × 350 × 400 mm
Load considerations	Often limited not by the box itself but what an operator can carry, given a handle size and position.
Construction	Typical materials: thermoplastics, thermosets, steel, formed aluminum, extruded aluminum and magnesium.

The weight capacity may be up to 500 pounds (227 kg) according to [Huber and Kolar \(2014\)](#), which makes portability somewhat of an issue. Therefore, most portable cabinets are much lighter even when fully loaded. Naturally, heavily loaded cabinets should be supported on well-made surfaces. Application notes, dimensional and load considerations, and constructional information are shown in [Table 5.11](#).

5.5.3 Wall-mount cabinets

Wall-mount cabinet enclosures are a cost-effective alternative where equipment needs are modest and not likely to increase for an application, state [Oates et al. \(2007\)](#). On the other hand, wall-mount cabinets are difficult to relocate and occupy valuable space that users much rather utilize for something else, assert [Hughes and Drury \(2013\)](#). Yet, wall-mount cabinets are truly ubiquitous, observes [Lim \(2016\)](#). As a result, there are myriads of versions of the basic types.

A double-hinged split cabinet is also available, which open like a book to offer access to both rear panels and to provide multiple layers of rack mounting space, while preserving excellent front access. A variety of accessories are available. [Mills and Mcalhaney \(2013\)](#) observe that lockable and transparent doors that are available with some models to provide security or visual access to equipment panels are just some of the features that many vendors offer. Application notes, dimensional and load considerations, and constructional information are shown in [Table 5.12](#) to provide a fundamental understanding about wall-mount cabinets.

Table 5.11 Portable cabinets

Applications	Mounting and enclosing a limited amount of equipment for a desktop, portable, or semiportable application, where enclosed equipment and instruments do not exceed an approximate depth of 500 mm.
Dimensional considerations	19-inch-wide (483 mm) panel opening. External dimensions range from 150 to 800 mm in height and 550 mm in depth approximately.
Load considerations	Typical weight capacity up to 225 kg. Weight limits must be checked when using built-in handles to lift and carry the cabinet.
Construction	Mostly steel or aluminum. Rarely, magnesium or other materials. Usually fully assembled. Front or rear doors and panels, and rear mounting rails might be available depending on vendor-specific designs. Various handles and other accessories may be available to provide portability assistance.

Table 5.12 Wall mount cabinets

Applications	There are almost limitless applications for wall-mount cabinets. Mounting and safely enclosing a predetermined amount of relatively narrow equipment directly to a wall or other vertical surface is the fundamental function.
Dimensional considerations	Generally, 19-inch-wide (483 mm) panel opening External dimensions range from 24" (610 mm) to 48" (1,219 mm) in height, 6" (152 mm) to 22" (559 mm) in depth approximately.
Load considerations	Typical weight capacity ranges from 75 lb. (34 kg) to 400 lb. (181 kg)
Construction	Steel or aluminum. Preassembled to user's specifications.

5.5.4 Chassis

Metal chassis provide support and protection for electronic circuits (Yan et al., 2014). A bottom cover is often available. Polat et al. (2016) note that dimensions and accessories vary greatly for specific models. However, application notes, dimensional and load considerations, and constructional information are shown in Table 5.13.

5.5.5 Card racks

Zuo et al. (2002) believe that a card rack in many respects is similar to a chassis. Card racks are used to assemble circuit boards and various components into modular electronics according to Scherz (2006). The card rack itself is designed to mount in a 19-inch (483 mm) rack. Modules can be changed relatively quickly to provide a convenient way for equipment modifications.

Modular systems can hold a large number of individual submodules (Pfahnl and Liang, 2004), each of which must interface with appropriately sized rails, guides,

Table 5.13 Chassis

Applications	A platform for construction of circuits and subassemblies that generally fit within a larger case, rack, or cabinet. Utilized as a fundamental building block in a very large range of applications.
Dimensional considerations	Extremely wide range of dimensions and styles. Typical height and width from approximately 4" × 4" (101 × 101 mm) to 17" × 17" (432 × 432 mm) and depth from 1" (25.4 mm) up to 6" (152 mm).
Load considerations	Structural issues dictate maximum load conditions.
Construction	Most frequently made from aluminum.

connectors, lock screws, and other hardware within the modular chassis. This demands a greater precision than the other enclosures introduced so far. Therefore, dimensional stability is important, assert [Swanson and Birur \(2003\)](#), to eliminate binding and misalignment possibilities and thus improve reliability. Further information is shared in application notes, dimensional and load considerations, and constructional information in [Table 5.14](#).

5.5.6 Rack-mount chassis

A rack-mount chassis is in many respects similar to an ordinary chassis, observes [Steinberg \(1980\)](#), that provides a range of enclosures for the assembly of specific rack-mountable equipment and instruments. Sometimes, rack mountable equipment is also configured to be used as desktop or other style portable equipment. Therefore, detachable handles, rack mounting brackets, and other hardware might be offered. Perforated ventilation panels must also be included to maintain safe operating temperatures for the enclosed electronics, opine [Pal and Severson \(2017\)](#). Application notes, dimensional and load considerations, and constructional information are shown in [Table 5.15](#).

5.5.7 Open racks

Open frame racks are an excellent choice in maximum cooling applications, state [Zhang et al. \(2016\)](#). Alternatively, free and unhindered access to the front, sides, and rear of the equipment might dictate use of an open rack, as no doors or side covers

Table 5.14 Card racks

Applications	Packaging of electronic circuit cards in modular units that can be installed or removed from a 19-inch (483 mm) subrack. Modular cabinets are often used in mission-critical applications such as in data acquisition, industrial automation, and telecommunications. These applications are governed by standards for construction, fire safety, shocks, and vibrations, among other important factors.
Dimensional considerations	Subrack unit mounts in a 19-inch-wide (483 mm) panel opening. Individual plug-in modules vary in width. Height usually 2U or 3U, that is, 3.5" (89 mm) or 5.25" (133 mm) while depth is 11.5" (292 mm) to 14" (356 mm) approximately. Modules accept cards up to 4.4" × 10.78" (112 mm × 274 mm).
Load considerations	Structural issues dictate maximum load conditions.
Construction	Almost always made from aluminum. Internal card rack construction includes card guides, locks, mounting rails, and other structural members. It is important to note that individual modules utilize small housings with front panels, top, bottom, sides, and back.

Table 5.15 Rack-mount chassis

Applications	Packaging for electronic PCBs, instruments, various other types of circuits, and components that will typically be installed in a 19-inch (483 mm) rack.
Dimensional considerations	Mounts in a 19-inch-wide (483 mm) panel opening. Height is usually 1–8U that is 1.75" (44.5 mm) to 14" (356 mm) while depth is 8.5" (216 mm) to 22" (559 mm) approximately.
Load considerations	This type of chassis can only carry light loads unless supported by external brackets. Structural loadings must always be analyzed prior to implementation to avoid problems.
Construction	Various metals such as steel, aluminum, and magnesium can be used. Handles can be incorporated to provide ease of handling during mounting.

are used. Open frame racks are available to accept 23-inch (584 mm) as well as 19-inch-wide (483 mm) panels. If security is a concern, open frame racks should only be used within lockable enclosures, shelters, or rooms.

Wall-mount and desktop racks are usually a shorter version of the common open rack. They are utilized where floor space is unavailable or at a premium. Wall-mount designs include fixed types, as well as swing-frame constructions. Swing frames open away from the wall to provide rear panel access ([Biran and Collins, 2016](#)).

[Bernuzzi and Maxenti \(2015\)](#) elucidate that it is important to note that loads are supported completely by the rails comprising the rack frame. Specifiers must make sure that load capacity is adequate for the particular application, points out [Den Hartog \(2014\)](#). In addition, the base must be large enough to provide needed stability both when empty and fully loaded. Application notes, dimensional and load considerations, and constructional information are shown in [Table 5.16](#).

5.5.8 Cabinet racks

[Islam \(2016\)](#) opines that floor-mounted enclosed cabinet racks are one of the largest enclosures utilized in electronic applications. They are offered in a variety of styles with an extensive range of accessories. Cabinet racks are available with a 19" (483 mm), 23" (584 mm), or 24" (610 mm) wide panel space.

An enclosed cabinet is often the appropriate choice should rack-mountable equipment required to be housed safely and securely. [Gao et al. \(2015\)](#) point out that an additional advantage is that an enclosed rack offers a controllable environment for equipment cooling. Various types of perforated panels, fan trays, and arrays are available to suitably manage airflow ([Fulpagare and Bhargav, 2015](#)). Thermal management has become increasingly critical as power demands continue to escalate and as a result heat loads are rising, state [Dunlap and Rasmussen \(2014\)](#). Many enclosed cabinet

Table 5.16 Open racks

Applications	Most often used for lightweight, shallow-depth equipment mounting. Applications include data and telecommunications, phone switching systems, and other network-related components.
Dimensional considerations	Accommodate 19" (483 mm) and 23" (584 mm) wide panel openings. External dimensions are 100" (2,540 mm) in height, while 30" (762 mm) in depth approximately. However, various other sizes might be available.
Load considerations	Load capacity ranges from 10 pounds (4.5 kg) for desktop units, to approximately 1000 lbs. (454 kg) for full-size racks. Load capacity must be ascertained by a specialist or the manufacturer.
Construction	Most often made from steel and aluminum. Typically supplied in a knock-down, bolt-together construction, for assembly by the user. Some manufacturers offer availability of kits to permit joining racks, but load considerations must be evaluated very carefully.

designs offer lockable front and rear doors to provide additional equipment security. Transparent doors are also often on offer to permit easy equipment monitoring. Ultimately, the choice of a specific model depends on load, accessibility cosmetic and configuration requirements, and any applicable standards, points out [Islam \(2016\)](#). Application notes, dimensional and load considerations, and constructional information are shown in [Table 5.17](#).

5.5.9 Server racks and colocation racks

Server and colocation racks are ideal for applications requiring maximum ventilation and airflow ([Singla et al., 2014](#); [Chong et al., 2014](#); [Kliazovich et al., 2013](#)). Server racks resemble common cabinet racks. The difference is that server racks utilize side panels and doors that are heavily perforated for ventilation purposes according to [Cho and Goodson \(2015\)](#). A lockable solid metal or transparent front door might be utilized to offer extra protection, security, and monitoring capability. Extra cabinet depth permits mounting of deeper instruments or equipment but should only be utilized in applications with such equipment as it does take up extra floor space that is usually at a premium at most data centers.

[Islam et al. \(2015\)](#) explain that colocation racks look like server racks but have been compartmentalized. Individual sections are manufactured to be fully independent and protected from intrusion. They are available in heights ranging from approximately 24" (610 mm) to 39 inches (991 mm). Characteristically, each section has its very own door. Side panels are often one-piece units that might very well extend the full height of the cabinet rack assembly. Application notes, dimensional and load considerations, and constructional information are shown in [Table 5.18](#).

Table 5.17 Cabinet racks

Applications	General electronic rack mounting applications such as data and telecommunications, industrial automation, test and measurement systems, and various others.
Dimensional considerations	Typical external dimensions to 86" (2,184 mm) in height, while 36" (914 mm) in depth approximately. 19" (483 mm) wide panel space is most common utilized. 23" (584 mm) is used in the data and telecommunication industry. 24" (610 mm) is used for factory automation systems. Adapters are available to convert 19" (483 mm) equipment to mounted with 23" (584 mm) or 24" (610 mm) equipment.
Load considerations	Maximum equipment weight is approximately 1200 pounds (544 kg). Racks utilizing a welded steel internal frame offer one of the highest weight-bearing capacity. Aluminum frames usually provide slightly less capacity.
Construction	Steel and aluminum constructions are common. Fully assembled cabinets can often reduce total product costs by eliminating cabinet assembly time. Flat rack that is user-assembled cabinets on the other hand provide a lower-cost alternative in cases where less weight capacity is acceptable, or where it is inappropriate to transport a preassembled cabinet to the use location. Additional choices and considerations include the width of panel openings either 23" (584 mm) or 24" (610 mm) as well as adequate access holes to simplify cable routing. Removable side panels can deliver additional access to equipment. Adjustable rear mounting rails can be used to support heavy equipment while NEMA 12 cabinets provide gasketed doors and sides.

5.5.10 Seismic racks

Seismic racks offer a high level of protection against shock and vibration. Seismic cabinets are rated according to Telcordia, formerly Bellcore, #63-GR-CORE standards (Berak, 2005). Zone 4 represents the highest requirements according to Bharucha (2016).

Afagh (2010) warns that it is important to note that the rated capacity of a seismic cabinet is based on a uniformly distributed load and not on total load. Seismic cabinets are used in an environment where shock or vibration is given like in any mobile environment such as aboard trucks, ships, railways, and planes or in any industrial plants like forging, ore crushing, and the like. Such an application demands testing under the actual load conditions. Seismic cabinets must be anchored to the floor with a suitable, tested and certified anchor kit (Notohardjono et al., 2012). Application notes, dimensional and load considerations, and constructional information are shown in Table 5.19.

Table 5.18 Server and colocation racks

Applications	Application include data and telecommunication systems, and general electronic rack mounting applications. Server cabinets often provide extra depth. Equipment mounting rails are manufactured to support a variety of commercial servers. Colocation racks are perfect to offer independent, secured subcabinet space.
Dimensional considerations	19" (483 mm) wide panel space. Server racks have a typical external dimension of up to 86" (2,184 mm) in height and up to 42" (1,067 mm) in depth approximately. Colocation racks are similar with a typical external dimension to 86" (2,184 mm) in height and up to 34" (864 mm) in depth approximately.
Load considerations	Typical weight capacity: 1200 lbs. (544 kg) for server racks. Typical weight capacity: 1200 lbs. (544 kg) for colocation racks. Load bearing capacity must be confirmed prior to application.
Construction	Construction is most often steel and aluminum. These racks are available preassembled. They are often offered with optional transparent front doors. Some designs enable server and colocation racks to be utilized together. Kits are offered to improve server rack capacity and stability. Anchoring to the floor or wall is recommended.

Table 5.19 Seismic racks

Applications	General equipment rack mounting in environments that are subjected to shock and vibration.
Dimensional considerations	19" (483 mm) wide panel opening. External dimensions up to 75" (1,905 mm) in height and up to 30" (762 mm) in depth approximately. Other sizes might be offered if requested.
Load considerations	Rated weight capacity is normally based on the uniformly distributed load that the cabinet was tested and rated for. If cabinet will be utilized in a shock and vibration—prone environment, testing under the actual load conditions must be completed.
Construction	Constructions use welded steel or stainless steel. Anchor kits must be used to secure cabinet.

5.6 Review

This chapter introduced standard types of packages, housings, and enclosures. First the seven levels were defined to provide clarity (Newton et al., 2016). Some of these levels were grouped together to form the three final levels providing an easy-to-remember classification exactly coinciding with the title of this handbook series: enclosures, housings, and packages in accordance with Töpper (2017).

This chapter ordered the level classification according to size (Amo et al., 2004) and therefore packages were discussed first. A historical perspective in the form of a timeline was provided as per Hopkins et al. (1998). Development drivers were identified to provide understanding and facilitate new product development planning (Verona, 1999). Design considerations identified by Wallmark (1960) such as cost, electrical functionality, mechanical and thermal characteristics were investigated.

Through-hole (Fillion et al., 1995) and surface-mount technologies (Prasad, 2013) were explicated including PGAs and BGAs. Issues such as packaging, handling, and testing with respect to bare die implementations were discussed. CSPs (Ghaffarian, 2001) and module assemblies (Albrecht et al., 2014) were reviewed to provide a platform for the discussion on advanced package substrates (Bagen et al., 2013). System-in-packages (Nair et al., 2017) and TSV (Marro et al., 2014) were analyzed to further their applications in the field.

The next level: housings were discussed first by focusing on circuit board mounting issues (Andersson et al., 2014) and then by reviewing backplane connections (Gumaste et al., 2016). Selection ideas for the next level: enclosures were also incorporated. Basic layout and a quick cooling guide closed this section of the chapter in accordance with Mallik et al. (2011).

A variety of standard enclosures were reviewed based on Mcclung et al. (2005), such as small, portable, and wall-mount cabinets. Chassis, card racks, rack mount chassis, and open, cabinet, server, colocation and seismic racks were described in detail to assist the professional enclosure engineer as well as academia in accordance with Islam (2016).

5.7 Hot tips

It is important to keep in mind that the most unreliable components in any electronic system utilizing a housing or an enclosure will be the following according to Wang et al. (2014a):

1. Connectors and cables
2. Bolted joints, basically anything that uses screws
3. Cooled components

Always use an electronics cooling specialist when these components are installed (Song and Wang, 2013; Smith, 2017).

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6.1 Introduction

Chapter 2 (Technological innovation) described the interaction, amplification, and reinterpretation of the all-important phenomenon entitled Kondratieff waves (Grinin et al., 2016; Nefiodow and Nefiodow, 2014). This chapter completes the innovation picture. New product development (NPD) is nothing more or nothing less than the application of an innovation strategy according to Chesbrough et al. (2014). Therefore, it must be based on sound understanding of innovation principles (Du et al., 2016; Gmelin and Seuring, 2014b; Burroughs et al., 2013). Many organizations have found themselves in dire straits not because their engineers were incompetent but simply because neither innovation waves nor their strategic application was properly understood by the executives (Camisión and Villar-López, 2014; Christensen, 2013; Tukker and Tischner, 2017; Thomas, 2013).

The following case might illuminate this point. According to Hughes and Drury (2013), drive manufacturer like most in that particular industry has positioned itself as an energy-saving device manufacturer. This appeared to be the right strategy at the time that the organization was growing rapidly based on Cohan (2017). However, when crude oil prices collapsed in 2015 (Baffes et al., 2015; Nazlioglu et al., 2015; Husain et al., 2015), the company found itself struggling. How much? Well, they have lost no less than 50% of their global revenues. Executives were changed quickly by the overseas holding company that owns the organization, but the situation continued unabated. The lean team cut the fat and results were even worse, which is not all that unusual according to Goetsch and Davis (2014). What happened? The most likely cause is pointed out by Netland et al. (2015) that strategy was ill-fitting for the circumstances and none of the executives had a clue as to the real needs of the market. This situation was hinted at in the transition from URS to FRS section 4.2, Creating a functional requirement specification of Chapter 4 (Requirements).

For instance, consider one of the top markets for drives: elevators. Lifts and escalators are an important market in today's world according to Barney and Al-Sharif (2015). Bacci (2017) opines that global populations are skyrocketing as population doubles every 37 years, so vertical transportation is ever more critical. However, in the developed world, populations are ageing, and most are not even at replacement level, point out Bloom et al. (2015). This means that LA, New York, London, or Sydney skylines are not littered with cranes like, for instance, in China according to Kibert (2016). Thus, in the developed world, vertical transport companies rely on refurbishment and maintenance revenues rather than revenues from new installations (Uimonen et al., 2016). Sachs et al. (2015) assert that this point seemed to have been lost on most if not all drives companies. They all go after the Chinese market, a market that more

and more being served by its own manufacturers (Edgett, 2013), instead of trying to satisfy their local needs as highlighted by Mander (2014). There is need for a replacement drive that a maintenance mechanic can install with one hand according to Williams (2018). Why? The answer might dumbfound most in this industry as it is very simple indeed.

Kone has developed the machine room—less lift according to Lee and Lim (2014). Al-Kodmany (2015) underlines that their major competitors: Otis, Schindler, and Thyssen have followed their technological lead. This resulted in a situation where the equipment is in the top of the lift shaft. Have you ever looked down 30-40 stories from a catwalk? That is exactly what a lift maintenance technician is facing in his job. Imagine now dragging a 50 kg or heavier device onto the platform, lifting it up, and fastening it to the supporting wall. Are you Mr. Schwarzenegger? Planning to grow muscles in a jiffy?

The solution is actually very simple. One needs to create a frame that the installer can comfortably lift with one hand. Fastening this frame to the wall is not all that difficult. Once this is done, the heavier drive can be brought onto site and lifted into its cradle without much difficulty. So how many drive companies acted on this simple need of a very large market segment. None.

All of them instead trumpet the energy-saving benefits of drives as per Drury (2001). However, with the price of oil down, their investment proposals that translated to a break-even analysis just simply make no sense (Radomes and Arango, 2015). It is impossible to get a payback period shorter than 2 years, which is exactly what prudent management from the customer's organization is looking for according to Fullerton et al. (2014).

Thus, the point of this story is a simple one. First, innovation waves must be understood, especially their interactions. Then the global drivers must be incorporated into the right innovation strategy. Market needs must be discovered, for instance, if need to be by traveling on top of lifts, perhaps visiting mine sites, ports, and other important potential applications. Only then is the executive management team able to drive NPD to its ultimate success (Leahy, 2013; Troy et al., 2013; Gmelin and Seuring, 2014b). This chapter is about the process on getting there every time.

6.2 What determines success?

In short, success is determined by following the right NPD and new product introduction (NPI) process (Ward and Sobek II, 2014; Cooper, 2013; Cooper, 2014). Success means the process to design a device in conjunction with an enclosure, a housing, or a package that could be manufactured efficiently and ultimately sold profitably, thereby creating a long-term competitive advantage for the host organization and its supply chain (Altshuler, 2014; Ramanathan and Gunasekaran, 2014). Therefore, this chapter first provides an overview of the best current practices and highlights a way to successfully frame enclosures, housings, and packages problems.

6.3 Best current practice

Ahmad et al. (2013) elucidate that rapid and profitable NPD has been identified as a key enabler for the creation of competitive advantage. Tseng and Hu (2014) believe that product life cycles are getting shorter. Global competition is more intense according to Park et al. (2014). Valocchi et al. (2014) explain that customers are ever-more demanding. Companies that fail to develop new customer-driven products fast risk rapid annihilation according to (Cooper, 2013).

Cooper (1994) clarifies that the difficulty is that to create profitable new products is not a simple task. Add a restrictive time to market priority and it seems to become a daunting challenge (Cooper et al., 2006; Porter and Heppelmann, 2015). An estimated 46% of the NPD resources incubate projects that either fail in the marketplace or never even make it to the market according to Solomon (2014).

Ernst et al. (2013) assert that leading original equipment manufacturers (OEMs) and enclosure companies embraced the idea of rapid and profitable NPD like the one displayed in Fig. 6.1. According to research studies (Markham and Lee, 2013; Page and Schirr, 2008; Zirger and Maidique, 1990), between 70% and 85% of leading global companies now use a prescriptive step-by-step NPD approach. Although there are many critics of this approach (McCarthy et al., 2006; Conforto and Amaral, 2016; Ter-vala et al., 2017), it is not so easy to come up with an altogether more promising one (Cooper, 2014). As such this handbook will describe a general NPD process here in accordance with Gmelin and Seuring (2014b) and bolt on design (Pahl and Beitz, 2013) and supply chain elements (Monczka et al., 2015) in Book 2 and 3, respectively.

This process is a conceptual model for creating a viable idea and developing it into a product in the minimum amount of time (Dougherty, 1992). This general mental model subdivides the overall NPD effort into distinct steps (Trott, 2008) and their numbers are displayed in Fig. 6.2. Most processes use management decision gates according to Salomo et al. (2007). This has been found to create extreme difficulties for NPD teams (Kim and Wilemon, 2003; Ajamian and Koen, 2002; Van Oorschot et al., 2017). Chao et al. (2014) state that a better approach is to integrate management functions into the day-to-day operation of the cross-functional NPD team. Berggreen and Kampf (2016) elucidate that preparation for gate reviews is eliminated in this model and senior management is forced to have an in-depth understanding of the important drivers of the process. Jürgens (2013) argues that this abbreviates the model. Therefore, there are only eight steps in the electronic enclosure product development (EPPD) system. Brady et al. (2016) point out that eight steps are not too difficult to memorize. Olive (2004) argues that without memorization, there is no hope of accepting and embedding the whole process. Therefore, this system was designed to be better than all others creating a massive competitive advantage for all enclosure users.



Figure 6.1 A new product development and introduction (NPD/NPI) process map.

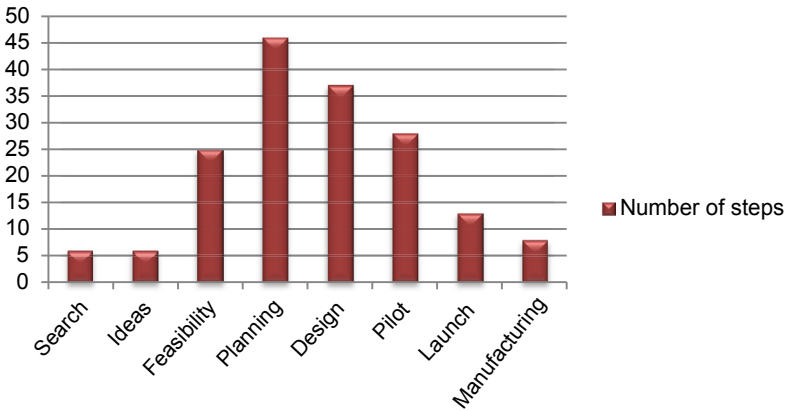


Figure 6.2 Number of steps in the various phases.

6.4 Search for opportunities

Locating opportunities is the very first step in the EEPD process and is demonstrated in Table 6.1. Other processes term this step Market Research (Ernst et al., 2013; Fang, 2013; Hollensen, 2015). Slotegraaf and Atuahene-Gima (2013) argue that labeling this stage in such a way would be slightly misleading as there is no need to have a discrete, impulse-driven research functionality in a well-designed organization. It is instead a continuous search process for new market-driven ideas that are emerging by harnessing enterprise-wide customer relationship and engineering management data (Stark, 2015; Fang, 2013). The secret is in how these two very different worlds are merged into a useful database. Tyagi et al. (2015) demonstrate that it is primarily a qualitative research proposition, and as such quantitative organizations have found the execution of this step nearly incomprehensible but certainly against their “common sense.” However, leading edge methods were developed over a decade ago in Australia (Bazeley, 2003, 2009; Tashakkori and Teddlie, 2010), but a detailed description of those methods is beyond the scope of this handbook.

Table 6.1 The search step: market research

1. Market research phase
End users
Intermediaries
Corporate capabilities
Technology
Intellectual property
Regulatory compliance

The output of this first step is a conceptual “gap” between what is and what could be according to [Kumar and Phrommathed \(2005\)](#). [Marion et al. \(2015\)](#) explicate that this is a synthesis between marketing’s and engineering’s relevant observations. Marketing’s focus is all about determination of unmet needs while engineering’s focus is to determine the societal framework. Ultimately, these two information sources are merged and needs are matched with existing corporate capabilities ([Gmelin and Seuring, 2014a](#)). [Vickery et al. \(2016\)](#) point out that it is important that even in this pre-concept analysis phase opportunities for complexity reduction are considered. Simplification is extremely difficult to consistently achieve but is one of the greatest drivers of corporate profitability according to [Nagle et al. \(2016\)](#). Let us consider marketing’s input first followed by engineering’s function in the search for opportunities stage.

6.4.1 End users

Marketing personnel locates unmet needs primarily by focusing on end users as displayed in [Table 6.2](#). Unmet needs or gaps are the situational motives of users of a product incorporating an electronic enclosure that are currently not being met, explicate [Reid et al. \(2016\)](#). End users are defined as anyone who is involved with the enclosure. These could be users, installers, end users, and maintenance providers. Locating end users is not a simple matter as they often are not involved with specifying and purchasing the product. Therefore, [Khodakarami and Chan \(2014\)](#) point out that they are not usually listed on a company’s sales records.

6.4.2 Intermediaries

The marketing function also analyses intermediaries as per [Table 6.3](#). Once again it is searching for “gaps” or unmet needs according to [Colombo et al. \(2015\)](#). Intermediaries are defined as anyone who is involved with specifying or purchasing the enclosure product, throughout the value chain. However, intermediaries do not actually use the enclosure. These include procurement functions of OEMs, contractors, wholesalers, and retailers.

Table 6.2 End users

1. Market research phase
End users
Intermediaries
Corporate capabilities
Technology
Intellectual property
Regulatory compliance

Table 6.3 Intermediaries

1. Market research phase
End users
Intermediaries
Corporate capabilities
Technology
Intellectual property
Regulatory compliance

6.4.3 Corporate capabilities

Marketing assesses competencies, abilities, and brand equities that are exploitable advantages and matched with unmet needs as displayed in [Table 6.4](#). These insights are used to generate ideas that provide adjacent or totally new market opportunities ([Krasnikov and Jayachandran, 2013](#)). In this respect, capabilities that are unique or superior to the competition are particularly valuable, argue [De Brentani and Kleinschmidt \(2015\)](#). Unique corporate capabilities include engineering, design capabilities, process design, manufacturing know-hows, shorter lead time, superior quality performance, and better customer relationships, list [Cui et al. \(2013\)](#).

6.4.4 Technology

[Melander and Lakemond \(2015\)](#) assert that the engineering team must monitor emerging technologies continuously. The goal is to create actionable technology insights as per [Table 6.5](#). These insights can be gained from transcribing team meetings and collecting this information in a suitable database ([Andriopoulos et al., 2017](#)). [Zikmund et al. \(2013\)](#) explicate that other methods include studying technologies developed by competitors, and any member of the supply chain, including customers.

Table 6.4 Corporate capabilities

1. Market research phase
End users
Intermediaries
Corporate capabilities
Technology
Intellectual property
Regulatory compliance

Table 6.5 Technology

1. Market research phase
End users
Intermediaries
Corporate capabilities
Technology
Intellectual property
Regulatory compliance

The important point is to make these observations available for future studies by properly codifying them (Fan et al., 2015). Laursen and Thorlund (2016) highlight that specialist experts can assist with this step to create better insights.

6.4.5 Intellectual property

Generally, the head of the engineering function in conjunction with legal support performs a periodic state-of-the-art intellectual property analysis as displayed in Table 6.6. Manzini and Lazzarotti (2016) state that the purpose of this analysis is to identify and to understand the nuances of patents that already exist or pending in the enclosure technology area. This process highlights potential barriers while laying the ground work for obtaining patent protection (Sheng et al., 2013; LEE et al., 2017).

6.4.6 Regulatory compliance

Regulatory trends are mapped by senior engineering personnel as per Table 6.7. These include current and already proposed regulations (Blind et al., 2017). Adams et al. (2016) argue that this is one of the many reasons that senior engineering must be aware and preferably should attend standardization activities. The objective is to identify

Table 6.6 Intellectual property

1. Market research phase
End users
Intermediaries
Corporate capabilities
Technology
Intellectual property
Regulatory compliance

Table 6.7 Regulatory compliance

1. Market research phase
End users
Intermediaries
Corporate capabilities
Technology
Intellectual property
Regulatory compliance

insights that, through the next stage, that is, idea generation, may lead to locating significant opportunities for technology leadership, explain [de Medeiros et al. \(2015\)](#). [O'Dwyer and Cormican \(2017\)](#) show that on a practical level, this means participating in consortiums, working directly with governmental groups, and continually monitoring developments. Such regulations include REACH, RoHS, Conflict Minerals, Heavy Metals, and WEEE. Important standardization bodies include ISO, IEC, NEMA, and UL along with national standards institutes.

6.5 Idea generation

Corporate idea generation is a continuous process and its map is displayed in [Table 6.8](#). Potential inventors and innovators need to be motivated and trained, state [Kazmi et al. \(2017\)](#). Ideas need to be continuously collected and sorted so that they could be properly exploited ([Gurtner and Reinhardt, 2016](#)). [Leithold et al. \(2016\)](#) assert that a well-developed plan and organization-wide implementation of idea generation is a pre-requisite for successful innovation in the electronic enclosures field.

[Rajeshwari \(2017a\)](#) argues that it is paramount that all idea initiators receive a prompt feedback, first about the receipt of their ideas, recognition of their contribution,

Table 6.8 The idea generation step

2. Idea generation phase
Idea descriptions
Intellectual property database check
In-house idea screening
Timeline development
Review of the competition
Supply chain improvements

and a feedback on how the idea was dealt with. It is important to provide positive feedback even if the idea is not planned to be used and to provide an honest appraisal of the areas where a match was not perfect. This is a difficult task that requires highly specialized expertise that most organizations especially engineering-driven organizations do not often possess. While it is possible to learn all the skills needed, most organizations are better served to engage an external consultancy to provide such a service.

The overall goal of this stage is to create an innovative environment that foster creation of actionable ideas (Poetz and Schreier, 2012). Ideas need to focus on opportunities that could be feasible within the organizational context. Therefore, ideas must be sorted based on customer and corporate fit (Lilien et al., 2002). It is sensible to establish benchmarks to allow quick assessment of ideas with regard to perceived feasibility.

6.5.1 Idea descriptions

This step is displayed in Table 6.9. Usually, an external consultancy develops idea descriptions. Piller and Walcher (2006) state that ideas that are developed in this step have already passed their first screening. Rochford (1991) explains that idea descriptions capture new enclosure product ideas that are ranging from incremental changes to existing products, to new-to-the-world enclosures. Tzokas et al. (2004) believe that the external consultancy should review these ideas periodically to ascertain their continued feasibility.

6.5.2 Intellectual property database check

The senior engineering executive checks the database created in 6.4.5 for patentability of the idea that was described by the consultants. Roy and Sivakumar (2011) explicate that it is important that a patent budget is developed to protect the idea and to try to eliminate or mitigate competitive pressures that might undercut profitability of the project. Collopy et al. (2014) argue that this step displayed in Table 6.10 cannot be performed by a junior engineering executive without sacrificing potential success of the innovation. While the senior engineering executive checks potential patent protection, he or she becomes familiar with the invention at an intimate level. This allows the

Table 6.9 Idea descriptions

2. Idea generation phase
Idea descriptions
Intellectual property database check
In-house idea screening
Timeline development
Review of the competition
Supply chain improvements

Table 6.10 IP database check

2. Idea generation phase
Idea descriptions
Intellectual property database check
In-house idea screening
Timeline development
Review of the competition
Supply chain improvements

executive to mentor the idea initiator and often to turn this person into a successful idea champion. This step is a departure from other NPD systems. Most NPD processes utilize a gatekeeper whose knowledge is sketchy at best and therefore decisions are made on the appearance of PowerPoint presentations rather than true insights according to O'Connor (1994).

6.5.3 In-house idea screening

A cross-functional team (CFT) consisting of the senior executives of marketing and engineering periodically evaluates all ideas presented by the external consultants. This screening step shown in Table 6.11 is a GO/NO GO decision point according to Stevens and Burley (1997). All submitted ideas must be screened and idea generators need to be notified by the consultants based on the minutes of the screening committee session, advise Kim et al. (2008).

6.5.4 Timeline development

A project timeline is developed as is shown in Table 6.12 by the external consultants or by the idea generation secretariat. This is an estimation of the complete development based on expected deliverables and activities contributed by each functional area,

Table 6.11 Idea screening

2. Idea generation phase
Idea descriptions
Intellectual property database check
In-house idea screening
Timeline development
Review of the competition
Supply chain improvements

Table 6.12 Timeline development

2. Idea generation phase
Idea descriptions
Intellectual property database check
In-house idea screening
Timeline development
Review of the competition
Supply chain improvements

explicate [Harmancioglu et al. \(2007\)](#). [Howe et al. \(2000\)](#) underline that preliminary resource estimates are also developed at this point.

6.5.5 Review of the competition

[Nallusamy et al. \(2015\)](#) suggest that the competition’s relevant product offering is reviewed both by product planning and marketing officials as displayed in [Table 6.13](#). This step involves a review of the NPIs containing electronic enclosures to the market. This team refers to a list of products compiled for the last minimum 3 but preferably 5 years ([Goetsch and Davis, 2014](#)). The team reviews existing products on the market with regard to features, claims, and performance capabilities ([Fleisher and Bensous-san, 2015](#)). Importantly, [Handfield et al. \(1999\)](#) believe that the team must ascertain pricing against perceived quality, reliability, and robustness.

6.5.6 Supply chain improvements

[Petersen et al. \(2005\)](#) highlight that purchasing provides a leadership in the CFT that includes marketing, product planning, and engineering officers. The idea is carefully evaluated in terms of its impact on the supply chain as is displayed in [Table 6.14](#). Unfortunately, this step is usually completely ignored and this creates havoc with the supply chain at a later time according to [Luzzini et al. \(2015\)](#). [Christopher \(2016\)](#) elucidates that project profitability could be negatively affected if this step is eliminated from the overall process.

6.6 Concept feasibility

According to [Hart et al. \(2003\)](#) the concept feasibility phase aims to quickly define the product in sufficient detail to determine its feasibility both from technical and commercial perspectives and it is mapped in [Table 6.15](#). A preliminary business case is developed to justify formation of a permanent CFT, highlights [Cooper \(1996\)](#).

Table 6.13 Review of the competition

2. Idea generation phase
Idea descriptions
Intellectual property database check
In-house idea screening
Timeline development
Review of the competition
Supply chain improvements

Table 6.14 Supply chain improvements

2. Idea generation phase
Idea descriptions
Intellectual property database check
In-house Idea screening
Timeline development
Review of the competition
Supply chain improvements

Table 6.15 The concept feasibility step

3. Concept feasibility phase				
1. Functional requirements	6. Project charter	11. Cost estimation	16. Competitive landscape	21. Copyright protection
2. Estimated budget	7. Technology gap	12. Engineering concept review	17. Value proposition	22. Supply chain feasibility assessment
3. Updated timeline	8. Preliminary design requirements	13. Environmental compliance strategy	18. Initial sales estimate	23. Reverse auction potential
4. Resource plan	9. Patent protection feasibility	14. Manufacturing feasibility assessment	19. Customer partnerships	24. Preferred supplier engagement
5. Business case	10. Alternative technologies	15. Market assessment	20. Phase-out of existing enclosures	25. Financial estimates

The enclosure product concept’s fit with strategic business objectives is assessed in this phase during its 25 steps.

6.6.1 Functional requirements

Jain et al. (2015) elucidate that product planning establishes the functional and other important requirements as per Table 6.16. These provide a high-level description of the product capabilities and characteristics. The following items should be included in the functional and nonfunctional requirements in accordance with Troy et al. (2013):

- A complete description of the product’s function and performance capabilities
- Performance and quality requirements as established by the end users
- Any major innovations that must occur to enable this product to gain long-term competitive advantage for the company
- Consideration of global product needs and local resources

6.6.2 Estimated budget

Page (1993) opines that product planning creates the estimated project budget as the second step in the concept feasibility phase as is displayed in Table 6.17. The estimated project budget provides an estimate of the total costs expected to bring the concept to the global market. DiMasi et al. (2003) argue that it is strongly dependent upon estimated project timeline. Therefore, Moorman and Miner (1998) explain that to minimize associated estimated errors, the budget and the timeline should be estimated simultaneously. Inputs must include resource and budgetary estimates from all

Table 6.16 Functional requirements

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred Supplier Engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial Estimates

Table 6.17 Estimated budget

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

functional areas. A timeline for all tasks in each functional area must also be established in this step. It is paramount that all known assumptions and risks are stated associated with this step are stated in a clear and unambiguous format, adds [Carson \(2007\)](#).

6.6.3 Updated timeline

Product planning updates the estimated project timeline referred to in [Table 6.18](#) that was developed earlier in [6.5.4](#). The estimated project timeline provides an approximation of the total length of each phase of the NPD project ([Tasevska et al., 2014](#)). This evaluation is based on the deliverables and the associated activities in each functional area to successfully complete the project. As stated in the previous section, it is best to complete this task simultaneously with the estimated project budget creation to make decisions on time versus cost trade-offs clearly visible to the decision-makers. Inputs must include resource and budget estimates from all functional areas. A timeline needs to be created for all tasks in the functional areas. [Creemers et al. \(2015\)](#) highlight that all assumptions and risks associated with timing, task dependencies, and critical path activities must be stated.

6.6.4 Resource plan

The estimated resource plan is developed by product planning in accordance with [Table 6.19](#). The estimated resource plan must include both human and equipment-related resources according to [Leonard-Barton \(1992\)](#). The people side includes everyone from all involved functional areas required to complete planned activities

Table 6.18 Updated timeline

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.19 Resource plan

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

and produce their deliverables according to the previously established project timeline. Equipment-related resources include apparatus required for manufacturing and testing. [Arnold et al. \(1998\)](#) state that at this point materials requirements should also be evaluated.

6.6.5 Business case

Product planning also writes the business case as shown in Table 6.20. The business case is a formal method of providing C-level executive management a value proposition (Blank, 2013; Carbonell and Rodriguez Escudero, 2016; Amaral Feris and Zwikael, 2017), basically, the NPD effort versus necessary resources. This must be at least a 5-year analysis to provide appropriate level of supporting documentation for the proposed effort. Shi et al. (2016) argue that financial factors must include net present value (NPV) calculations, required capital expenses, and market sales forecasts. All known assumptions and associated risks must be presented clearly and quantified by using generally accepted accounting principles (Song et al., 2015).

6.6.6 Project charter

Project charter as per Table 6.21 is also developed by product planning officers. Su et al. (2016) explain that the project charter provides the scope of work for the NPD. The scope must be based on satisfaction of the unmet needs and business objectives stated previously. It should include the estimated project budget, estimated timeline, and estimated resource plan (Lo et al., 2016). Deliverables, milestones, key responsibilities, assumptions and constraints, risks, acceptance criteria, and exclusions must also be considered and presented in a straight forward manner.

6.6.7 Technology gap

Engineering creates the feasibility analysis and technology development needs in Table 6.22. The feasibility analysis measures the product requirements definition to

Table 6.20 Business case

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.21 Project charter

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.22 Technology gap

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

determine if the proposed product can in fact be developed by engineering according to Wang and Li-Ying (2014). Most importantly technical risks are identified and classified.

6.6.8 Preliminary design requirements

Engineering also prepares the preliminary design requirements in Table 6.23. Yeh et al. (2017) elucidate that the preliminary design requirements provide a high-level conceptual design of the enclosure. Manufacturing and procurement requirements, serviceability issues, standards like UL, NEMA, ISO, IEC, and prominent local ones are included as well as appropriate quality conditions (Majewicz and Sampson, 2016).

6.6.9 Patent protection feasibility

State-of-the-art intellectual property analysis is completed by engineering in the step depicted in Table 6.24. Soranzo et al. (2017) assert that the purpose of this analysis is to identify and generally understand the scope of patents that may already exist in the technology field of the new enclosure, housing, or packaging improvement. Cooper-Davis (2014) explains that this valuable step assists in understanding potential design barriers and identifying opportunities for obtaining significant IP protection, but it is based on a design concept, so it cannot be considered conclusive. This analysis must be conducted multiple times. However, the first analysis must be done prior to investing significant resources into the enclosure NPD process (Soranzo et al., 2016).

Table 6.23 Preliminary design requirements

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.24 Patent protection feasibility

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial Estimates

6.6.10 Alternative technologies

Engineering performs an alternative technologies assessment in this step, shown in [Table 6.25](#). This assessment provides a mapping of alternative technologies that may be used in lieu of developing a new enclosure product according to [Wang and Li-Ying \(2014\)](#). The following reports are included in the overall technological survey.

Table 6.25 Alternative technologies

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

These include an IP assessment; a formal make or buy assessment; and a procurement assessment for collaboration or partnering or sourcing decision, which includes a matrix of potential suppliers’ design, prototyping, piloting and manufacturing capabilities.

6.6.11 Cost estimation

Product BOM (bill of material) cost estimate is created by engineering leveraging information gained from the current and potentially extended supply chain (Altavilla et al., 2017). This step is depicted in Table 6.26. Flanagan (2013) opines that a cost estimate of the product should be created from the preliminary design requirements and pertinent historical records. Larson and Gray (2013) highlight that variances between targets and estimates must be evaluated. Inputs include functional requirements, preliminary design requirements, and the downstream value proposition, which incorporates target costs according to Anderson (2014).

6.6.12 Engineering concept review

Concept design review is performed by engineering and this step is displayed in Table 6.27. This allows the NPD team to independently assess technical risk at the concept feasibility or concept development and project planning phases (Toh et al., 2015). Schramm et al. (2014) advise that often this process results in a clear new product concept design path with mitigated technical risk. West and Bogers (2014) argue that outside consultants must be considered for new-to-the-world and new-to-the-company enclosure products. In addition, new technologies and new product platforms also need an independent validation by an appropriately qualified consultant team.

Table 6.26 Cost estimation

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.27 Engineering concept review

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

6.6.13 Environmental compliance strategy

Environmental compliance strategy needs to be developed in this step displayed in [Table 6.28](#). by the Engineering function explain [Mombeshora et al. \(2014\)](#).

Table 6.28 Environmental compliance strategy

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

This step provides an essential roadmap for the design team to follow through the NPD process to ensure product compliance. Key elements include the following:

- Identification of the geographic regions in which the product is intended to be sold. This area of the strategy document will define the list of countries whose legislation must be understood.
- Identification of the geographic regions in which the product is intended to be manufactured to understand legislation affecting the production facilities.
- Identification of key pieces of legislation that impose constraints on design, material, water, emissions, energy, restricted or banned substances, recycling requirements that will need easy to disassemble construction, and others.
- Identification of corporate environmental compliance documents affecting the product design.
- Definition of the process for collecting compliance information from suppliers as product is developed like collecting material declarations as new parts are defined and ultimately designed.

6.6.14 Manufacturing feasibility assessment

In this step displayed in [Table 6.29](#), operations conduct a manufacturing feasibility assessment. [Tuli and Shankar \(2015\)](#) state that the manufacturing feasibility assessment reviews preliminary design requirements for the purposes of making a new product manufacturability determination. The sales forecast estimate should also be reviewed to assess feasibility of mass manufacturing. Major innovations and new processes needing development or implementation assistance must also be identified at this step ([Haghighi and Pons, 2014](#)).

Table 6.29 Manufacturing feasibility assessment

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.30 Market assessment

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

6.6.15 Market assessment

Market assessment is performed by the marketing department in this step shown in [Table 6.30](#). The market assessment provides a high-level analysis of the target market and provides insights on the target customers' needs and enclosure gaps according to [Durmuşoğlu et al. \(2015\)](#). Therefore, this assessment needs to examine and prioritize customers' needs, and provide an estimated market price potential customers will pay for the enclosure, housing, or package. [Jakobs et al. \(2015\)](#) explain that this report must provide an estimated market size and growth potential and specify preliminary market-driven performance expectations.

6.6.16 Competitive landscape

Marketing performs a competitive assessment in this step mapped in [Table 6.31](#). [Hollensen \(2015\)](#) elucidates that this is an assessment that provides an analysis of key competitors' market positions, competitors' product strategies, and high-level strengths, weaknesses, opportunities, and threats also known by its acronym as SWOT analysis. Additional detail will be added to the assessment later, during the project planning phase ([Grant, 2016](#); [Claudy et al., 2016](#)).

6.6.17 Value proposition

Downstream value proposition is established by marketing according to [Bocken et al. \(2014\)](#). This step portrayed in [Table 6.32](#) identifies the value proposition of the new enclosure product to a direct customer and the end customer. A price range is

Table 6.31 Competitive landscape

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.32 Value proposition

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

developed based on the value delivered and not by the cost plus methodology (Clarysse et al., 2014). Foerstl et al. (2015) state that an overall target product cost is derived from this price range for use by engineering as the upper bounds for designing the new enclosure, housing, or package. Zeschky et al. (2014) explain

that the target cost is based on the market price that customers will likely accept and the margin that the company's shareholders anticipate. Several key questions and their perceived answers are helpful in understanding downstream values in accordance with [Tyagi et al. \(2015\)](#):

- Performance—Will it work the way the customer expects?
- Affordability—Will it be within cost goals of the customer?
- Maintainability—Easy to keep in service?
- Durability—Robust enough to withstand abuse?
- Delivery—Ready for the customer when wanted?
- Integration—Easy to install, learn, and use?

6.6.18 Initial sales estimate

Initial sales forecast estimate is prepared by marketing in this step displayed in [Table 6.33](#). A common mistake is to allocate this step to the sales force. However, [Mahajan et al. \(1991\)](#) emphasize that they must be consulted in the preparation of this important document primarily to secure their buy-in and to solicit real-world feedback for the NPD process. An initial sales forecast should be developed before committing resources to further concept and product development. The estimated units and revenue of the new product should at this point be determined ([Nagle et al., 2016](#); [Ghose and Han, 2014](#)). Assumptions must be carefully documented since at this initial stage associated forecasting error is usually relatively high ([Fleischmann et al., 2015](#); [Bodie, 2013](#); [Hyndman and Athanasopoulos, 2014](#)).

Table 6.33 Initial sales estimate

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.34 Customer partnerships

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

6.6.19 Customer partnerships

At this step [Table 6.34](#) a customer agreement is prepared by marketing. [He et al. \(2014\)](#) explain that identification of key customers who will cooperate in the development of the new product is performed. This step solicits opinions from direct customers, intermediaries, and end users ([Yli-Renko and Janakiraman, 2013](#)). [Song et al. \(2013\)](#) suggest that they may be invited for focus groups, interviews, surveys, and other NPD events.

6.6.20 Phase-out of existing enclosures

Estimated product lifecycle and phase-out plan is developed by marketing in this step [Table 6.35](#). [Biemans and Hillebrand \(2015\)](#) advise that an estimated duration of the product lifecycle and the linkage to existing products is established. The phase-out plan includes the existing product sales and production forecast, inventory positions with suppliers, ramp-down plan of shipments and inventory levels of existing product, and the ramp-up transition to the new product according to [Mylan \(2015\)](#). [DiMasi et al. \(2016\)](#) emphasize that inputs must include sales forecast estimate, estimated project schedule, current inventory levels of existing products, and existing product sales and production forecasts.

6.6.21 Copyright protection

Marketing in this step shown in [Table 6.36](#) assesses the potential for copyright protection. [Cho \(2015\)](#) explains that the purpose of this analysis is to determine whether a

Table 6.35 Phase-out of existing enclosures

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.36 Copyright protection

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

copyright registration could be obtained for any of the documentation, manuals, inserts, point-of-sale displays, and other written materials that will accompany and support the sale of the new enclosure product or housing and package improvement. The likelihood of a competitor or counterfeiter copying sales information must be considered at this point (Cohen et al., 2015).

Table 6.37 Supply chain feasibility assessment

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply Chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

6.6.22 Supply chain feasibility assessment

In this step portrayed in [Table 6.37](#), supply chain feasibility assessment is performed by procurement. The preliminary design requirements should be assessed to determine if the materials for the defined product can be sourced according to [Bowersox et al. \(2002\)](#). The feasibility of volume sourcing should be assessed by reviewing the sales forecast estimate. Potential sourcing risks must also be identified. Inputs to the feasibility assessment must include preliminary design requirements, projected BOMs, and sales forecast estimates ([Petersen et al., 2005](#); [Srivastava, 2007](#)).

6.6.23 Reverse auction potential

In this step shown in [Table 6.38](#) e-sourcing opportunity assessment is completed by procurement ([Jap, 2007](#)). According to [Chen-Ritzo et al. \(2005\)](#), reverse auctions enable the best available market purchase price via an automated, online, real-time bidding process on components used in the new design. For efficient implementation, a focus on high-spend parts must be facilitated. An identification of parts by commodity classifications that are best suited for the e-Sourcing process must be made at this point ([Emiliani and Stec, 2001](#); [Cintuglu et al., 2015](#)). [Standaert et al. \(2015\)](#) warn that supplier capabilities must be evaluated by engineering to assure the supplier can meet the company needs.

6.6.24 Preferred supplier engagement

Preferred supplier identification and engagement is completed by procurement in this step shown in [Table 6.39](#). [Chiang and Wu \(2016\)](#) explain that this step includes

Table 6.38 Reverse auction potential

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.39 Preferred supplier engagement

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	financial estimates

selecting preferred suppliers for quoting of components, communicating project-specific quality requirements, and evaluating new suppliers per the relevant department procedures in areas of cost, quality, performance, processes and capacity. Lynch et al. (2014) emphasize that it is always advantageous to solicit feedback on

manufacturability of the proposed design including other potential areas of expertise of the preferred supplier.

6.6.25 Financial estimates

Assessment of financial project estimates is conducted by finance in this last step shown in Table 6.40 of the concept feasibility phase. Finance must analyze and evaluate the estimated resource plan, the estimated project budget, target costs, and the business case according to Bajaj et al. (2004). They must highlight any issue or valid financial concern. These issues or concerns must be addressed prior to moving onto the project planning phase.

6.7 Project planning

In the project planning phase shown in Table 6.41, the CFT collaborates to substantiate discovered market needs and product value drivers based on the proposed functional requirements according to Salomo et al. (2007). Chen et al. (2003) assert that the primary goal of the NPD CFT is to complete the conceptual design and thus demonstrate a proof-of-concept. Jeffrey Thieme et al. (2003) argue that several product alternatives must be developed incorporating various features and combination of features that deliver the proposed benefit to the customer. The CFT is responsible during the project planning phase to assess and justify required resources and capital investment (Swink et al., 2006). Stockstrom and Herstatt (2008) explain that the CFT is also responsible to develop an actionable project plan that meets stated project objectives with reasonable

Table 6.40 Financial estimates

3. Concept feasibility phase				
Functional requirements	Project charter	Cost estimation	Competitive landscape	Copyright protection
Estimated budget	Technology gap	Engineering concept review	Value proposition	Supply chain feasibility assessment
Updated timeline	Preliminary design requirements	Environmental compliance strategy	Initial sales estimate	Reverse auction potential
Resource plan	Patent protection feasibility	Manufacturing feasibility assessment	Customer partnerships	Preferred supplier engagement
Business case	Alternative technologies	Market assessment	Phase-out of existing enclosures	Financial estimates

Table 6.41 Project planning

4. Project planning phase				
1. Refined product specification	11. Product requirements verification	21. Advanced engineering requests	31. updated sales estimate	41. Review of serviceability
2. Refined project timeline	12. Detailed design specification	22. Updated patent protection feasibility	32. updated phase-out	42. Service plan
3. Updated project budget	13. Prototype design	23. Intellectual property acquisition requests	33. Product alternatives development	43. Product quality specifications
4. Updated resource plan	14. Development schedule	24. Updated environmental compliance	34. Preliminary sourcing plan	44. Quality verification plan
5. Risk analysis	15. Enclosure schematics	25. Manufacturing strategy development	35. Supply chain development effort	45. Design for quality review
6. Appropriation request	16. Enclosure electronics interface	26. Review of enclosure concept for manufacturability	36. Updated preferred supplier engagement	46. Updated financial analysis
7. Team infrastructure	17. Direct competitors	27. Updated market analysis	37. Updated product cost model	
8. Project management plan	18. Product cost model	28. Pricing based on value proposition	38. Strategic sourcing review	
9. Trade compliance assistance requirements	19. Preliminary validation test plans	29. Aftermarket strategy	39. Reverse auction potential updated	
10. Trade compliance analysis	20. Concept design review	30. Research with customers	40. Updated enclosure electronics interface	

certainty and within established time lines. [Kim and Wilemon \(2003\)](#) emphasize that opportunities for complexity reduction must be considered as well as global product needs.

6.7.1 Refined product specification

Detailed product specification is developed by product planning ([Xue and Huang, 2015](#)). This is fundamentally a description of the end product in accordance with [Galli \(2017\)](#):

- Any major innovations that must occur to enable this product
- Manufacturing and operations requirements
- Supply chain requirements
- Performance and quality requirements
- Standards
- Aftermarket strategy

6.7.2 Refined project timeline

Product planning also develops a detailed project timeline. [Abrantes and Figueiredo \(2015\)](#) explain that this timeline provides a detailed list of activities and associated durations for each phase of the NPD process. [Marmier et al. \(2014\)](#) elucidate that functional areas responsible for the activities are documented in the CFT's constitution document and its information is utilized to establish proper reporting and NPD responsibilities. This timeline is a function of the projected budget. Therefore, both should be completed simultaneously in order to understand and facilitate decision-making with respect to time versus cost trade-offs ([Taheri et al., 2017](#)). A product introduction date is utilized as a baseline. Inputs must at the minimum include an updated resource plan, detailed project costs, risk analysis, and task dependencies ([Richtnér et al., 2014](#)).

6.7.3 Updated project budget

Updated project budget developed by product planning. The budget provides a detailed explanation of the total costs to bring the concept to market and is dependent upon the detailed project timeline. As stated previously, it is best to complete this simultaneously with the detailed project timeline to facilitate executive decision-making. Inputs must include detailed project timeline, updated resource plan, risk analysis and mitigation plan, manufacturing strategy and volume ramp-up plan, a procurement plan, and a service plan ([Cui, 2016](#)).

6.7.4 Updated resource plan

Product planning must update the resource plan. [Rijsdijk et al. \(2014\)](#) explain that the resource plan created in the concept feasibility phase must be updated at this point. Justification needs to be provided based on subsequent development activities. Human

resources must be determined including the functional areas and skills required. Equipment needs for manufacturing, testing, prototyping must also be determined in this step.

6.7.5 Risk analysis

Product planning develops a risk analysis and mitigation plan. This plan provides a point of focus on circumstances that may compromise project success (Yan-Ling et al., 2017). Product planning needs to ask the question: what can go wrong? The answers to this simple question provide a real-world mechanism for contingency planning and a means for leveraging lessons learned from past projects. Risk factors are collected from each functional area. Once this task is completed, an impact analysis must be performed. The next task is to categorize factors and group them into defined risk categories before prioritizing these for proposed mitigation.

6.7.6 Draft appropriation request

Pemartín and Rodríguez-Escudero (2017) elucidate that product planning updates the business case and creates an appropriation request (AR). The business case prepared during the concept feasibility phase is updated now. The underlying intent is to provide C-level executive management with a justified value proposition for the NPD effort. A 5-year analysis must be included to justify the proposed NPD effort. The project NPV need to be utilized to justify required capital expenses, engineering tax deductions, market sales forecasts, and additional external funding according to Egbide et al. (2013). Assumptions and risks must be clearly identified and quantified.

6.7.7 Team infrastructure

Team infrastructure is established by product planning (Reid et al., 2016). Collaboration mechanisms and workflow processes should be established and must at the minimum include the following in accordance with Frank et al. (2015):

- Schedule for equipment ordering and lead times.
- Schedule for quality investments, like supplier qualification, quality testing facilities, and other potential areas.
- Design the NPD environment such as virtual meeting facilities, laboratory and office space for hot desking while the design team is on site, production team and environment, tools for development prototyping and virtual and real-world testing capabilities, and lines of reporting.
- External consultants for design and engineering assistance.

6.7.8 Project management plan

Product planning is also responsible for the project management plan. A project management plan is established and maintained as the basis for managing the NPD project.

Papke-Shields and Boyer-Wright (2017) argue that the plan must always present the effort and schedule agreed upon for completing all work required to produce deliverables. A work breakdown structure (WBS) is mandatory because it organizes and defines the scope of the project (Fleming and Poole, 2016). Work to be done by the project team is decomposed into deliverable-oriented pieces of work in the WBS.

6.7.9 Trade compliance assistance requirements

Trade compliance assistance analysis is created by product planning. This is a process whereby the trade compliance and the engineering team evaluate the new products' and supporting materials' value. This is a continual process as the product progresses through the NPD process to ensure compliance upon release to market. A key activity is to evaluate the value of the potential assistance requirements such as engineering work, dies, molds, tooling, and others provided free or at a reduced cost to an overseas supplier for items being developed or manufactured. This is especially important for enclosure products that are developed in the United States, manufactured elsewhere, and then transported into the United States.

6.7.10 Trade compliance analysis

Trade compliance analysis is performed by the product planning team. This is a process whereby the trade compliance team evaluates the new products' features and technology and applies the applicable legislation to obtain the proper classification and associated approvals for the product. This is also a continual process as the product progresses through the NPD process to ensure compliance upon release to market. A key activity in the United States is to evaluate the engineering BOMs and component functionality against the Commerce Control List. Similar activities must also be performed in the European Union and elsewhere.

6.7.11 Product requirements verification

The engineering team performs the product requirements verification step according to Goffin and New (2001). Design attributes must be validated against justified marketing requirements. The engineering team checks to ensure that any deviation from the initial product requirements is clearly documented, communicated broadly, and well-founded based on direct customer feedback, competitive intelligence, or technology hurdle (Dooley et al., 2002). It is paramount to verify and validate that features match customer requirements.

6.7.12 Detailed design specification

Osteras et al. (2006) explain that the engineering team develops a detailed design specification at this point. A design specification is created from the product requirements

and will include items such as reliability requirements and system performance and capacity specifications (Mikkola, 2003), in other words, all the detail that is necessary to produce a product design.

6.7.13 Prototype design

Prototype design is completed by the engineering department. Simulations and prototype builds to design specifications are utilized in this task according to Campbell et al. (2007). These aid to showcase viable concepts and to generate confidence in the proof-of-concept. Finite element analysis and computational fluid dynamics tools as well as computer aided design (CAD) tools must be utilized for both electrical and mechanical work during this step (Riek, 2001).

6.7.14 Development schedule

Tao et al. (2017) assert that the development plan and level of effort are created by engineering. The team establishes a development schedule and resource load for engineering through production. Mohammadi et al. (2014) explain that they identify technology gaps and develop a resolution plan for outsourcing, recruiting, subcontracting, and others to bridge the existing or potential gaps in the desired schedule.

6.7.15 Enclosure schematics

Product schematics is developed by the engineering team. The engineering team creates basic schematics and mechanical layouts of components, subassemblies, and assemblies, explicate Macdonald et al. (2014). This task produces drawings, preliminary BOMs, initial mock-ups, and initial simulation runs.

6.7.16 Enclosure electronics interface

Embedded Software and Firmware Design Specification and Level of Effort is created by engineering. The team generates software architecture and high-level design from the functional requirements. Level of effort required should be included for communication requirements, compatibility requirements, configurability requirements, and controllability requirements.

6.7.17 Direct competitors

Engineering performs a direct competitor technology assessment. The team assesses direct competitors' technological capabilities and provides an overview of the design, specifications, and performance capabilities of the proposed new product versus that of direct competitors. Atuahene-Gima (2013) explains that the team generally looks for any noteworthy advances that competitors have made and any technology innovations to which the company must respond.

6.7.18 Product cost model

Engineering produces a Product Cost model. [Altavilla et al. \(2017\)](#) assert that members of the team create a cost model for the product using detailed design specifications. Finance must provide standard labor and overhead rates so that product and development costs can be captured properly. Variances between targets and estimates should be reviewed and evaluated in the context of the overall product cost target to identify opportunities for sourcing.

6.7.19 Preliminary validation test plans

Preliminary Validation Test Plans step is completed by the engineering team. Test requirements and acceptance criteria are identified based on evaluation of design attributes against customer requirements and established competitor and industry benchmarks to validate the product requirements ([Buede and Miller, 2016](#)). Types of approval such as UL, NEMA, and others, regulatory and standards compliance, and quality, reliability and robustness testing must be determined here.

6.7.20 Concept design review

Concept design reviews are performed by engineering. The concept design review is a business tool that enables the CFT to independently assess technical risk at the concept feasibility or project planning phase ([Dick et al., 2017](#)). Often this process results in a clean new product concept design path with mitigated technical risk. [Cooper \(2013\)](#) emphasizes that external consultants must be utilized for new-to-the-world and new-to-the-company. New products as well as new technologies and new product platforms should also utilize external review assistance as these also benefit from accumulated global expertise.

6.7.21 Advanced engineering requests

Advanced engineering request and notification is completed by engineering. This process is used to capture and prioritize changes in design and specifications according to [Becerril et al. \(2016\)](#). Each request is assessed by function to determine the cost impact, savings, and investment required. Once approved, the change is communicated to all functions. This NPD process methodology recommends a change request template that facilitates assessing the impact to cost, scope, and schedule for any requested change. Once the impact is determined, the change is presented to the original project plan approvers for a decision to either approve, reject, or hold until adequate information is provided ([Adler et al., 2016](#)).

6.7.22 Updated patent protection feasibility

A state-of-the-art intellectual property analysis is performed by engineering. According to [Manzini and Lazzarotti \(2016\)](#) the purpose of this analysis is to identify and

generally understand the scope of patents that may already exist in the technology domain or market segment of the new product or product improvement. It assists in understanding potential design barriers and identifying opportunities for obtaining significant IP protection, but it is not conclusive at this phase. This analysis can be conducted during any of the NPD phases and must be conducted multiple times, but it is usually completed before significant time and expenditures are invested.

6.7.23 Intellectual property acquisition request

Engineering develops an intellectual property clearance analysis. The purpose of this analysis is to identify and analyze patents, if any, that may arguably block the manufacture, use, and sale of the new product or product improvement (Zirger and Maidique, 1990). To initiate the analysis, the team identifies key elements of the new product design and conduct a clearance search for relevant patents.

6.7.24 Updated environmental compliance

Environmental compliance analysis is updated by the engineering department. Environmental compliance analysis is a process whereby the design team evaluates the new product's compliance to all applicable legislations (Mombeshora et al., 2014). This is a continual process as the product progresses through the NPD process to ensure compliance upon release to market. A key activity is to evaluate the engineering BOMs against restricted and banned substance lists.

6.7.25 Manufacturing strategy development

Operations creates a manufacturing strategy and volume ramp-up plan. An analysis of the requirements and impacts of the product and its associated quality, reliability, and robustness requirements on facilities, personnel, and equipment is evaluated (Swamidass et al., 2001). Operations must perform at least the following tasks in accordance with Jia and Bai (2011):

- Develop a high-level value stream map to identify business processes and manufacturing process flows.
- Initiate development of any new processes and identify any special skills required.
- Define the general facility requirements for manufacturing the new enclosure product.
- Define the necessary processes and the necessary skills for personnel to fabricate, tool, assemble, test, and support the product.
- Identify any specific tools or equipment necessary to build and test the product.
- Compile capital requirements for manufacturing and testing product based upon the sales forecast.
- Establish target fabrication, assembly, and test times.

6.7.26 Review of enclosure concept for manufacturability

Review of design for manufacturability is completed by the operations team. Boothroyd (1994) explains that this process provides an assessment of the product specifications

from a manufacturing and assembly perspective. The primary intent is to provide early and ongoing feedback to the engineering team where design improvements could be made, to decrease manufacturing and assembly costs while improving capability and overall production quality. Additionally, the design review should evaluate prototype design and process alternatives versus established program goals.

6.7.27 Updated market analysis

Marketing updates the market and competitor analysis. The marketing team evaluates the competitive assessment conducted in the concept feasibility phase (West et al., 2015). Team members provide updates where necessary. Additionally, more detail is added to this analysis including the following items as a minimum:

- Examine and prioritize customers' needs.
- Estimated the market price and specific customers will pay for the end product.
- Estimated market size and each market segment's growth potential.
- Provide proof of quality, reliability and overall robustness requirements from the customer's perspective.

6.7.28 Pricing based on value proposition

Value-based pricing strategy and plan is completed by the marketing department. Members of the marketing team update and validate the downstream value proposition deliverables initiated in the concept feasibility phase. They check against the product BOM and service cost model. Using the output from applicable market research, they generate appropriate value-based pricing strategy by considering product positioning over the life of the product, bundling, and product and customer segmentation (Nagle et al., 2016). Finally, and importantly, the team translates these strategies back into the product design requirements.

6.7.29 Aftermarket strategy

Marketing also establishes the aftermarket strategy. The aftermarket strategy defines the catalog of approved aftermarket products stock keeping units (SKUs). These requirements are fed back into the Detailed Product Specification. Supply chain processes to support these additional SKUs are developed with a focus on customer value, reverse logistics, inventory management, order management, distribution operations, transportation, and service (Cohen et al., 2006).

6.7.30 Research with customers

Marketing performs a product-specific market research with customers in the form of a conjoint analysis according to Simonson (2005). Marketing validates customer requirements and their perceived value of the strongest product alternatives identified by the product alternative iteration interviews, using a focused market research

analysis. The team use appropriate methods such as questionnaires, focus groups, and surveys. This analysis helps to establish price expectations with customers as well as determine price elasticity. It is important not to communicate any price information to customers until the final value-based product pricing has been completed in the design and development phase.

6.7.31 Updated sales estimate

Marketing updates the sales forecast estimate. An updated sales forecast must be developed before committing further resources to concept development and product development (Ernst et al., 2013). An updated forecast is necessary if, since the initial forecast, any of the following have changed significantly: features of the product or service, forecast inputs, such as distribution and price, and competitive marketplace or market segment conditions. Marketing determines the estimated units and revenue of the new product that can be sold and documents all relevant assumptions. At this interim stage, usually only a concept of the product or service exists, along with a good understanding of forecast inputs. Therefore, forecast error range is medium to high.

6.7.32 Updated phase-out

Updated product lifecycle and phase-out plan is completed by marketing. Fichman et al. (2014) explain that the team updates the estimated duration of the product lifecycle and the linkage to other existing products. Additionally, the phase-out plan includes market price actions, inventory positions with current suppliers, ramp-down plan of shipments, and inventory levels of existing product and the ramp-up transition to the new product.

6.7.33 Product alternatives development

Product alternative iteration is performed by the marketing department. The marketing team members develop several product alternatives with various feature set combinations that each, in their own right, meet an unmet need or several needs identified in the market research and deliver savings to the supply chain (Colombo et al., 2015). The goal of this step is to optimize the innovation platforms simultaneously with the target end-customer and the CFT to maximize the value to the customer and maximize price realization for the company. Interviews are completed with direct customers to expose them to the prepared end-customer innovation concepts as well as concepts for supply chain enhancement.

6.7.34 Preliminary sourcing plan

Procurement develops a preliminary sourcing plan. Pedraza-Acosta et al. (2016) elucidate that the preliminary sourcing plan provides a time-phased forecast of sourcing requirements for the purposes of procuring direct materials at an optimal total cost for use in production.

6.7.35 Supply chain development effort

Supply chain plan and level of effort is developed by procurement. The procurement team develops a plan, which identifies the procedure and specific requirements for buying materials for the new product, as well as resources required to support development (Rajeshwari, 2017b).

6.7.36 Updated preferred supplier engagement

Preferred supplier identification and engagement is updated by the procurement team. The team selects preferred suppliers for quoting components. It is important to communicate project-specific quality requirements. If appropriate, solicit input on manufacturability of design or other area of preferred suppliers' expertise. The team evaluates new suppliers as per applicable department procedures in terms of cost, quality, performance, processes, and capacity (Jia et al., 2017). This step was initially taken during the concept feasibility phase. Therefore, the procurement team updates the information as needed.

6.7.37 Updated product cost model

Procurement updates the product BOM cost model. At each development stage, a working cost model is required to evaluate material costs and assess cost targets, evaluate the iterations of the product design, and develop appropriate sourcing plans according to Bajaj et al. (2004). To accomplish this task, the team members analyze design and manufacturing plans in reference to cost, choose best cost alternatives, and consider the cost of quality.

6.7.38 Strategic sourcing review

Procurement conducts a strategic sourcing review. This review is recommended for all development programs to ensure the components in the design are in line with the company strategic sourcing initiatives (Siddhartha and Sachan, 2016). The intent is to provide early and ongoing feedback to engineering where design improvements could be made to decrease sourcing and component costs while improving capability and overall production quality. Team members manage and validate target costs and identify current and future cost reduction opportunities. Also, the team reviews design specifications to identify critical to quality (CTQ) tolerances and processes.

6.7.39 Reverse auction potential updated

Procurement updates the e-sourcing opportunity assessment. Reverse auction via e-sourcing enables to secure the best available market purchase price via an automated, online, real-time bidding process for components used in the new product's design

(Standaert et al., 2015). Several items are key to success. These include the following in accordance with Chen-Ritzo et al. (2005):

- A focus on high-spend parts for efficient implementation.
- Identification of parts by commodity type that are best suited for the e-sourcing process. Commodity parts include machined parts, stampings, fasteners, connectors, and others.
- Identification of parts that can be manufactured by more than one supplier. A determination if a catalog part is readily available in the marketplace and can be used in lieu of a custom designed part.

6.7.40 Updated enclosure electronics interface

Procurement conducts an external software sourcing review. This step is recommended for development programs that include a significant investment in third-party software packages for use as part of a BOM or an internal design effort (Cintuglu et al., 2015). The review is designed to ensure that the vendor selection, price, and contract terms are in keeping with the company's software procurement strategies and industry best practices.

6.7.41 Review of serviceability

Service reviews the design for serviceability. The service team members assess the design from a service and maintenance perspective according to Von Hippel (1986). The intent is to provide early and ongoing feedback to engineering where design improvements could be made to provide for better service and maintenance over the long term. Aspects such as mean time to repair, repair cycle time, modularity, reliability, diagnostics, and quality should be included in the design for serviceability review. External consultants might also be needed to efficiently perform this task (Bhamra et al., 2017).

6.7.42 Service plan

Service plan and level of effort are developed by the service department. The team members develop a plan for the services department identifying the procedure and specific requirements for servicing the new product, as well as resources required to support development. The plan must include the following elements according to Yang et al. (2016):

- Product technical review for performing installations, and with respect of serviceability.
- Establish warranty programs such as standard coverage, optional extended coverage, reserve rates, and overall warranty costs.
- Identify service training program including product familiarization.
- Identify postsale literature requirements.
- Recommend specific parts standardization.
- Reverse logistics for returns and serviceability.

6.7.43 Product quality specifications

Product quality specifications developed by the quality team. A detailed definition of the metrics by which product quality will be measured should exist must be developed in this step. [Economou \(2004\)](#) elucidates that the metrics to consider must include the following: design life, component reliability targets such as failure-in-time, mean time between failures, and annualized failure rate. Product manufacturing quality specifications include scrap, downtime, rework, warranty, field failures, customer complaint rates, and are also inserted into the specifications.

6.7.44 Quality verification plan

Quality verification plan is performed by the quality team. The team members establish a performance tracking plan based on quality metrics such as considering the viability of a statistical process control (SPC) or an alternative tracking system according to [Amaral Feris and Zwikael \(2017\)](#). Team members also establish functional responsibilities for metrics tracking and consider a tracking mechanism for warranty costs and component reliability.

6.7.45 Design for quality review

Quality performs a review of design for quality. Team members assess the designed product from a quality perspective ([Chan and Wu, 2002](#)). The intent is to provide early and on-going feedback to engineering where design improvements could be made to decrease field failures and increase overall product quality based on historical root cause analysis.

6.7.46 Updated financial analysis

Finance updates the financial analysis. This step is an update of the financial analysis completed during the concept feasibility phase owing to more detailed knowledge of design and effort requirements being available. Team members estimate the projects ROI based on analysis of the following updated items in accordance with [Wu et al. \(2015\)](#):

- Project budget
- Business case
- Product BOM cost model
- Manufacturing costs
- Capital expenses
- Sales forecast
- Cost of quality
- Service cost model

6.8 Design development

In the design development phase shown in [Table 6.42](#), detailed design, development, and system integration are completed using best cost components and processes ([Ernst et al., 2013](#); [Frost, 2016](#); [Moretti and Braghini Junior, 2017](#)). Additionally, [Surbier et al. \(2014\)](#) advise that a preproduction run is completed that proves manufacturing and the supply chain are ready to execute and provides testing with a small number of prototypes to ensure product requirements and specifications have been met. In parallel, sales and marketing finalize pricing, complete product literature, and develop field sales and service training programs according to [Marion et al. \(2015\)](#). [Kim and Wilemon \(2003\)](#) emphasize that opportunities for complexity reduction should be considered as well as global product needs.

6.8.1 Final product and project cost analysis

Product planning executes a final product and project cost analysis ([Gmelin and Seuring, 2014b](#)). This analysis provides a final explanation of the total costs to bring the product to market. It is also used to update the final project budget. The project time versus cost trade-offs for the remainder of the NPD project are completed at this phase to account for new market developments, design issues, and strategic considerations ([Fang, 2013](#)).

6.8.2 Appropriation request

Product planning updates the business case and final AR as advised by [Hamilton \(1981\)](#). An updated business case confirms the value proposition demonstrating compelling reasons why mass production should be undertaken. [Mukherjee \(1988\)](#) advises that the 5-year analysis supporting the business case must also be updated. NPV must be recalculated to provide financial justification for the required capital expenses, engineering tax deductions, market sales forecasts, and additional external funding requirements. Risks and assumptions must be stated and once again reassessed.

6.8.3 Product documentation

Product documentation is provided by product planning. [Rocha et al. \(2013\)](#) explain that this documentation will provide all functional groups with the necessary level of information. Key contents include the following in accordance with [Dubinsky \(2015\)](#):

- Product specifications
- Component part drawings
- Key product characteristics
- Product performance information
- Test data
- Parts list and BOM
- Operating instructions

Table 6.42 Design development

5. Design development phase				
1. Final product and project cost analysis	9. Fabricated and tested prototype enclosure	17. Finalized value-based enclosure pricing	25. Approval of components	33. Alpha and beta version prerelease
2. Appropriation request	10. Finalization of bill of materials	18. Sales forecast	26. Reverse auction	34. Sales order process development
3. Product documentation	11. Patent acquisition analysis	19. Updated market analysis	27. Finalized supplier selection	35. Field sales training plan
4. Updated risk analysis	12. Safety review	20. Communications strategy	28. Finalization of specific quality requirements	36. Updated financials
5. Approved technical specifications	13. Environmental compliance control plan	21. Updated enclosure phase-out plan	29. Serviceability and maintainability assessment	37. Product Cost evaluation audit
6. Engineering change requests	14. Patent applications	22. Trademark acquisition and protection	30. Training needs analysis	
7. External design review	15. Manufacturing process requirements	23. Finalized copyright protection	31. Confirmation of product quality specification	
8. Updated verification test plans	16. Process quality control tables	24. Component suppliers	32. Process quality control plan	

- Service plan and manual
- Troubleshooting guide
- Benefits versus competitive and legacy products in terms of compatibility issues.
- Orderable items

6.8.4 Updated risk analysis

Product planning team updates the risk analysis and mitigation plan. [Ayyub \(2014\)](#) emphasizes that the risk profile should be updated based on activities completed in the design development phase. Team members reassess risk parameters for unresolved issues and analyze emerging risks. They also determine whether the risk management actions have been carried out as planned and if these actions were in fact effective according to [Aven \(2015\)](#). Product planning team updates the risk profile based on completed activities in the appropriate phases ([Haimes, 2015](#)).

6.8.5 Approved technical specifications

Approved technical specifications and detailed designs are developed by engineering. Final designs should be approved and signed off by all functional areas, thereby securing their buy-in, state [Samanta et al. \(1994\)](#). [Penzel et al. \(2007\)](#) assert that product specifications must be tested and verified for functional, cost, environmental, reliability, quality, and specific customer requirements. Any potential or actual deviation from requirements specifications must be flagged with an engineering change request (ECR) and addressed according to [Nadia et al. \(2006\)](#).

6.8.6 Engineering change requests

ECRs are completed by engineering. Changes in design and specifications must be documented and prioritized ([Syed-Mohamad et al., 2014](#)). [Eckert et al. \(2004\)](#) argue that each change request should be assessed by each functional area to determine cost impact, potential savings, and additional investment required. Once approved, the change should be immediately communicated to all functional groups according to [Knisely and Knisely \(2014\)](#).

6.8.7 External design review

External design reviews are organized by engineering. [West and Bogers \(2014\)](#) advocate that external design reviews are a tool to manage technical risks in the NPD process. External consultants must be engaged for this process. Technical focus of these reviews, at a minimum, must include design for functional performance, reliability, manufacture, and sourcing instruct [Lande and Oplinger \(2014\)](#).

6.8.8 Updated verification test plans

Verification test plans are completed by engineering. [Rubin and Chisnell \(2008\)](#) explain that team members complete design verification testing according to the test plan and

requirements. Typical test plans will include the type of test to be completed, the acceptance criteria, and the number of units to be tested along with approval agency and applicable standards information (Chen et al., 2017; Hartley III, 2017; Wu et al., 2016).

6.8.9 Fabricated and tested prototype enclosure

Fabricated and tested prototypes are completed by engineering. Blanchard et al. (1990) explain that designated team members manufacture and assemble the required number of design prototypes per the product verification test plan. After the required units are assembled, team members test performance and reliability of the units in accordance with the verification test plan according to Cross and Roy (1989). Pahl and Beitz (2013) advise that they also evaluate these prototypes against the acceptance criteria documented in the test plans and implement adjustments or changes as required.

6.8.10 Finalization of bill of material

Final BOM is created by engineering and released to manufacturing (Hastings and Yeh, 1992). Hegge and Wortmann (1991) emphasize that once satisfactory results are obtained from the design verification tests, the design is frozen and the BOM at this point is finalized. All product costs must be loaded and available in the corporate enterprise resource planning (ERP) system (Sustainment, 2014; Shaul and Tauber, 2013; Tarhini et al., 2015). Tian and Xu (2015) explain that the ERP system is the division of the corporate information technology (IT) system that supports the planning, execution, analysis of manufacturing, supply chain, and product lifecycle functions.

6.8.11 Patent acquisition analysis

Abbas et al. (2014) advise that an intellectual property clearance analysis is performed by engineering. Sandal et al. (2017) state that the purpose of this analysis step is to identify and analyze patents, if any, that may arguably block the manufacture, use, and sale of the new product or product improvement into any markets. To initiate the analysis, engineering personnel identify the key elements of the new product design and conduct a clearance search for relevant patents, add Lee et al. (2016).

6.8.12 Safety review

Safety review is organized by engineering. Zhu et al. (2016) expound that designs and prototypes are evaluated against global safety standards to ensure all safety-related risks are retired. All product manuals and related literature must include the required safety information, warnings, and cautions per the requirements of ANSI Z535.6 or equivalent local standards.

6.8.13 Environmental compliance control plan

Environmental compliance control plan is completed by engineering. Crane and Matten (2016) assert that this is a mechanism to ensure that the enclosure product's

compliance is maintained during both the NPD process and all subsequent production. As changes are made to the product like component selection, suppliers, production process, and others, or to global environmental legislation, the control plan ensures that the compliance status is maintained. Therefore, the control plan must define procedures for changes so that the final product is compliant.

6.8.14 Patent applications

Intellectual property protection analysis is performed by engineering. Team members identify and protect the design elements, features, and other aspects or factors that will make the new product or product improvement successful and provide it with a competitive advantage (Wang and Li-Ying, 2014). Zhou et al. (2016) highlight that the first task is to identify factors that make the product unique. Once this task is complete, the engineering team member must determine what IP protection will best protect those factors and take action to secure that protection, like file for patent protection, keep as a trade secret, or register a copyright (Zhou et al., 2016).

6.8.15 Manufacturing process requirements

Manufacturing process requirements are completed by operations personnel. Requirements of the facilities and processes and associated costs are identified to enable building production units according to the requirements of volume, time, and safety. Product or process modifications are identified as necessary. These include the following in accordance with Hoefer et al. (2017):

- Identify additional manpower requirements for production and testing.
- Create and update training plan.
- Conduct and update process failure modes and effects analysis (PFMEA).
- Establish process capability requirements.
- Create and update control plans and work instructions.
- Identify assembly processes.

6.8.16 Process quality control tables

Pyzdek and Keller (2014) explain that operations completes the process quality control tables. Mitra (2016) explains that manufacturing quality control plans are completed to enable the shop floor to track the manufacturing process control against critical product specifications. Goetsch and Davis (2014) instruct that inputs include product quality specifications, product specifications, and quality control criteria such as process capability, scrap, rework, and others for the completion of this task.

6.8.17 Finalized value-based enclosure pricing

Nagle et al. (2016) instruct that marketing issues the final value-based product pricing. This provides a final value-based pricing model that leverages innovation to maximize

profitability of the enclosure (Töytäri et al., 2015). This is the maximum price that the customer is willing to pay for. Customer-originated inputs must be validated through marketing and sales qualifications.

6.8.18 Sales forecast

Marketing issues the detailed sales forecast. Shi et al. (2016) highlight that a detailed sales forecast must be developed before committing resources to production and launch. An updated sales forecast is necessary if, since the initial forecast, any of the following have changed in accordance with Fan et al. (2017):

- Features of the product or service
- Forecast inputs, such as distribution and price
- Competitive marketplace conditions

6.8.19 Updated market analysis

Marketing updates the market and competitor analysis. Market and competitive assessments are conducted to identify more detailed information from what was completed in the project planning phase according to Hollensen (2015). Gamble and Thompson (2014) elucidate that inputs for this task must include at least the following: key competitors, competitive products, competitive pricing, competitors' product strategies, and a high-level SWOT analysis.

6.8.20 Communications strategy

Communications strategy is developed by marketing. Marketing, with input from product planning and sales, must outline a plan for the announcement of the new enclosure product to internal sales channels, various media channels, and key customers according to Andersen and Andersson (2017). Key messages and timing are defined for each event. Development of customer product literature begins at this step. Typically, the product literature includes instruction and operation manuals, product data or specification sheets, and outline drawings (Tang et al., 2015). All product manuals and related literature must include the required safety information, warnings, and cautions per the requirements of ANSI Z535.6 or equivalent.

6.8.21 Updated enclosure phase-out plan

Marketing updates the product lifecycle and phase-out plan. Marketing team members update the estimated duration of the product lifecycle and the linkage to other existing products. Additionally, Biemans and Hillebrand (2015) point out that the phase-out plan includes market price actions, inventory positions with current suppliers, ramp-down plan of shipments and inventory levels of existing product, and the ramp-up

transition to the new enclosure product. The inputs must include the following in accordance with [Riel and Flatscher \(2017\)](#):

- Detailed sales forecast
- Detailed project timeline
- Existing product planning forecast
- Current inventory levels of existing products

6.8.22 Trademark acquisition and protection

Trademark clearance and protection actions are completed by marketing. [Burmam et al. \(2017\)](#) explain that the purpose of this analysis is to clear candidate trademarks and service marks for possible use with the new enclosure product or product improvement considering the trademark rights of other parties and, once a mark has been selected, to determine where and to what extent the selected mark should be registered. To initiate the analysis, the marketing team generates a prioritized list of possible marks that are being considered for use on the product, on its packaging, or on any documentation or other materials delivered with the product, and develops a written description of the products and services which will use the mark ([Alexander, 2016](#)).

6.8.23 Finalized copyright protection

Marketing is to complete copyright protection actions. The purpose of this analysis is to determine whether a copyright registration should be obtained for any of the documentation, manuals, inserts, point-of-sale displays, and other written materials that will accompany and support the sale of the new enclosure product or product improvement ([Joyce et al., 2016](#)). Marketing team members take into consideration the likelihood of a competitor or counterfeiter copying any written information and the potential impact of such copying on sales of the new product.

6.8.24 Component suppliers

Suppliers for component parts is listed by procurement. Using the preferred supplier list, a supplier supply chain risk analysis is completed on the availability, cost, performance, and quality criteria to segment suppliers and identify risk mitigation strategies ([Brewer and Arnette, 2017](#)). Negotiations with suppliers are initiated. [Adler et al. \(2016\)](#) elucidate that team members identify multiple approved sources to prevent sole-sourcing situations and provide approved suppliers with production ramp-up and long-range sales forecasts.

6.8.25 Approval of components

Qualification and first-part approval on all components is performed by procurement. Strategic sourcing officers check that all supplier tooling is complete and conduct first-part approval on all components and complete process capability studies on critical

components and processes (Verrollot et al., 2017). They use first-part approved components in pilot and preproduction runs. They also evaluate supplier's capabilities and processes.

6.8.26 Reverse auction

Procurement e-sourcing opportunity assessment is completed. Procurement driven e-sourcing secures the best available market purchase price via an automated, online, real-time bidding process for components used in the new enclosure (Standaert et al., 2015). There are several items that assure success in this step. These include the following in accordance with Setia and Speier-Pero (2015):

- A focus on high-spend parts for efficient implementation.
- Identification of parts by commodity type that are best suited for the e-sourcing process. Commodity parts include machined parts, stampings, fasteners, connectors, and others.
- Identification of parts that can be manufactured by more than one supplier including a determination if a catalog part is readily available in the marketplace that can be used in lieu of a custom designed part.

6.8.27 Finalized supplier selection

Preferred supplier identification and engagement is completed by procurement. Team members select preferred suppliers for quoting components. It is important to communicate project specific quality requirements according to Brindley (2017). If appropriate, team members solicit input on manufacturability of design or other area of preferred suppliers' expertise. They also evaluate new suppliers per procurement department procedures in terms of cost, quality, performance, processes, and capacity. This step was initially taken during the concept feasibility phase and repeated during the project planning phase.

6.8.28 Finalization of specific quality requirements

Procurement communicates project-specific quality requirements. Technical quality requirements must be communicated to the production suppliers and manufacturing. Generally, these can be communicated through a division supplier quality manual or general instructions and procedures. Project-specific quality requirements may be communicated via a technical review meeting or by other means. Communication topics must at least include the following in accordance with Schilling and Neubauer (2017):

- CTQ and key product characteristics
- Expected quality levels like maximum parts per million, yield, and others
- Product and process qualification methods to be used for each part or product
- First article samples

6.8.29 Serviceability and maintainability assessment

Serviceability and maintainability assessment is performed by service. This is an assessment of the designed product from the perspective of service and maintenance to estimate service and warranty costs. Items to consider include the following in accordance with [Chauhan et al. \(2017\)](#):

- Service duration
- Service call interval
- Ease of maintenance for customer
- Impact on warranty costs
- Special maintenance and repair procedures
- Warranty process and procedures
- List of approved diagnostic tools

6.8.30 Training needs analysis

Service and application engineering (AE) training plan is completed by service. Service team members develop a service training plan. It should include the following in accordance with [Covin et al. \(2016\)](#):

- Training schedule for service and application engineers, service contractor, and customers
- Documentation regarding the nuances of the new product, operation, maintenance, and troubleshooting
- Ordering processes via coordinators, regional managers, and application engineers to support product sales
- Certification process

6.8.31 Confirmation of product quality specifications

The quality department confirms product quality specifications. This step provides detailed definition and confirmation of the metrics by which product quality will be measured ([Wetherill, 2013](#)). Measurements should include scrap, downtime, rework, supplier lot pass-rate, warranty, returns, and field failures.

6.8.32 Process quality control plan

Process quality control plan for manufacturing is issued by the quality department. The process quality control plan provides the guidelines for conducting and controlling all quality control activities, identifies the measures to be performed during volume production, and clearly defines how the analysis will occur ([Dale, 2015](#); [Paolucci and Sacile, 2016](#)).

6.8.33 Alpha and beta version prerelease

Customers for alpha and beta version prerelease are selected by sales. [Xue and Huang \(2017\)](#) explicate that sales professionals determine the customer base to utilize for

alpha and beta version prerelease unit testing of new products or enhancements to existing products. This includes making customer contacts and setting up customer meetings to qualify the site. This step includes the following tasks in accordance with (Abrahamsson et al., 2017):

- Review customer base and select key customers who have a need for new product or enhancements.
- Contact selected customers through proper channels to qualify them.
- Review customer agreements as appropriate.

6.8.34 Sales order process development

Sales order process for configurable and orderable items is developed by sales. Viio and Grönroos (2014) explain that assigned members of the sales team prepare a preliminary product configuration plan, identifying components and materials that contribute to product attribute variance. A key activity is to provide a high-level plan for creating sales channel documentation that will discuss how to promote and sell the product (Rodriguez et al., 2015).

6.8.35 Field sales training plan

Sales develops the field sales training plan. The sales team creates a sales force training plan for all field sales staff in relevant regions. They identify training times and training schedules including various mechanisms such as large-scale presentations, small hands-on interactive sessions, and small sales scenario sessions (Phillips and Phillips, 2016).

6.8.36 Updated financials

Updated financials are created by finance. The finance team updates the assessment of financial project estimates based on more detailed knowledge of design and effort requirements. They estimate the project's return on investment (ROI) based on analysis of the updated business case and AR, manufacturing requirements, capital expenses, and sales forecasts (Babafemi, 2015).

6.8.37 Product cost evaluation audit

Hartley (2017) advises that product cost evaluation and auditing of project costs is completed by finance. The assigned member of the finance team conducts a preliminary evaluation of product cost factoring in updated development and manufacturing costs, including the cost of quality (Khodakarami and Abdi, 2014; Scholes, 2015).

Table 6.43 Pilot

6. Pilot phase				
1. Updated product documentation	7. Final external design review	13. Manufacturing review and release	19. Service manuals	25. Special offers
2. Product launch matrix	8. Finalized environmental compliance control plan	14. Finalized pricing discount authority	20. Training delivery	26. Finalized sales automation tools
3. Validation tests on preproduction units	9. Manufacturing fixtures	15. Sales and marketing documentation	21. Service strategy	27. Sales force training
4. Completed agency approvals	10. Manufacturing work instructions	16. Finalized phase-out plan	22. Finalized quality assessment	28. Updated financials
5. Pilot studies with customers	11. Preproduction prototype building and verification	17. Cost containment assessment	23. Updated sales plans	
6. Finalized engineering change requests	12. Mass production preparation	18. Reverse auction for commodity parts	24. Existing contract analysis	

6.9 Pilot

In the ramp up otherwise known as pilot phase (the steps are shown in [Table 6.43](#)), the product design is validated, customer beta testing is completed, and manufacturing processes are verified to assure operational readiness ([Surbier et al., 2014](#)). In parallel, sales and marketing set up order entry systems, and announce the product to the field according to [Armstrong et al. \(2015\)](#). Manufacturing, field sales, and service training programs are implemented ([Phillips and Phillips, 2016](#)). [Loch and Kavadias \(2008\)](#) highlight that the product is maintained throughout this phase under change control.

6.9.1 Updated product documentation

Updated Product Documentation is provided by product planning. Documents and electronic files that provide all functions with the necessary level of product

information must be updated. Key contents include the following in accordance with [Dubinsky \(2015\)](#):

- Product specifications
- Product design drawings/CAD files
- Product attributes and configurations
- Product performance information
- Support materials for initial anticipated customer questions
- Verification test data
- Parts list and BOM
- Operating instructions
- Service plan and manual
- Troubleshooting guide
- Benefits versus competitive and legacy products compatibility
- Orderable items
- Agency approvals
- Customer pilot beta test results
- Validation test data
- ECR log
- Manufacturing processes
- Manufacturing work instructions
- Manufacturing release reports

6.9.2 Product launch matrix

Product Planning creates the product launch matrix. This is a report where product launch activity status is communicated to all relevant functional areas. Status and documentation from all functional areas should include the following in accordance with [Ward and Sobek II \(2014\)](#):

- Engineering verification test
- Validation test
- Beta testing and feedback
- Agency approval
- Preproduction pilot runs
- Plant readiness
- Sales and services training
- Supplier readiness

6.9.3 Validation tests on preproduction units

Validation tests on preproduction units are completed by engineering. Assigned team members update verification test plans, if required, and conduct validation testing and design and reliability testing on preproduction units ([Rubin and Chisnell, 2008](#)). Testing may be conducted within a company-owned facility or at a contracted facility.

6.9.4 Completed agency approvals

Engineering coordinates completion of agency approvals. A member of the engineering team finalizes and communicates completed agency approval tests and documentation. The associated tasks include the following in accordance with [Millson et al. \(1992\)](#):

- Confirm required agency approvals and schedule tests
- Complete specified agency tests
- Submit required documentation to obtain agency approval
- Submit preproduction units to agency for testing

An expert consultant can usually expedite agency approvals such as UL certification.

6.9.5 Pilot studies with customers

[Piller and Walcher \(2006\)](#) state that customer pilots are completed by engineering. Pre-release units are provided to preidentified customers, assembled, and set up per product specifications and customer requirements. The purpose of customer beta test is to identify potential issues with the sustained use of the product. Beta testing is initiated as soon as feasible, depending on the status of validation testing and manufacturing readiness according to [Fuchs and Schreier \(2011\)](#).

Product test protocol and operating procedures are developed and customer signoff is required before testing can commence. Product testing parameters are monitored on a regular schedule as specified in the test plan. Specifically, performance data and reliability data such as failures and failure modes are monitored as per [Ogawa and Piller \(2006\)](#). In addition, customer comments, processes, and practices are captured by field visits and periodic meetings.

Results from customer pilots, that is, from beta tests are communicated with engineering and operations, along with other relevant functions ([Knisely and Knisely, 2014](#)). Any issues identified in the pilot are immediately flagged as an ECR and addressed based on priority and severity. Close coordination with suppliers, service, and engineering or manufacturing activities is essential for rapid recovery from any new issues identified ([Witell et al., 2014](#)).

6.9.6 Finalized engineering change requests

ECRs are completed by the engineering department. [Knisely and Knisely \(2014\)](#) elucidate that ECRs are captured and assessed to determine if any can be combined into a product release. ECRs are captured from sales, services, engineering, operations, and product planning. Engineering is responsible for maintaining the product under change control and communicating changes to all relevant functions.

6.9.7 Final external design review

External design review is organized by engineering. External design reviews are a tool to manage technical risks in any NPD process. According to [Mital et al. \(2014\)](#)

external consultants must be considered for this process. [Gmelin and Seuring \(2014b\)](#) add that technical focus, at a minimum, must include design for functional performance, reliability, manufacture, and sourcing and should occur as early as the design and development phase. Inputs from the company must include a clear technical scope statement and comprehensive data-based briefing materials.

6.9.8 Finalized environmental compliance control plan

Environmental compliance control plan is compiled by engineering. This is a mechanism to ensure that the product's compliance is maintained during both the NPD process and all subsequent production. As changes are made to the product like component selection, suppliers, production process, and others or to global environmental legislation, the control plan ensures that the compliance status is maintained according to [Mombeshora et al. \(2014\)](#). The control plan must define the procedures for changes so that the final product is compliant.

6.9.9 Manufacturing fixtures

Test fixtures and equipment are completed by operations. All required manufacturing fixtures and equipment are tested and validated prior to the start of production ([Black and Kohser, 2017](#)). The tests must be per specifications agreed upon by quality, engineering, and manufacturing.

6.9.10 Manufacturing work instructions

Manufacturing work instructions are issued by operations. Create manufacturing work instructions based on the following inputs. These inputs should be reviewed by quality, engineering, and operations prior to their use in preproduction runs. These inputs are in accordance with [Hoefer et al. \(2017\)](#):

- Manufacturing BOM
- Detailed designs
- Manufacturing quality control plan
- Routings or operation sequence charts
- Manufacturing process requirements
- Inspection criteria for CTQ characteristics

6.9.11 Preproduction prototype building and verification

Preproduction prototype building and verification completed by operations. Units should be assembled using structures, routings, stock locations, work instructions, and drawings in the scheduled production environment. According to [Kahn \(2012\)](#) the intent is to:

- Fabricate and assemble preproduction units
- Validate inventory control systems
- Validate actual manufacturing processes to requirements

- Validate and establish production documentation
- Validate BOM and standards for accuracy
- Validate and establish inspection processes
- Validate manufacturing test processes to test plan requirements

6.9.12 Mass production preparation

Operations prepares for mass production. [Glock and Grosse \(2015\)](#) highlight that to prepare for mass production, several tasks should be accomplished including:

- Review volume and timing changes from the most recent sales and operating plan
- Execution of procurement plan to fill production lines
- Workflow documentation
- Worker training
- Material routing
- Quality assurance and SPC processes
- Plant tooling and qualification
- Establish target fabrication, assembly, and test times.

Inputs to the start of mass production include final in accordance with [Li et al. \(2014\)](#):

- Engineering signoff on product design and specifications
- Manufacturing signoff on production process, tooling, equipment and quality assurance
- Procurement approval on supplier contracts and logistics
- Manufacturing BOM

6.9.13 Manufacturing review and release

Manufacturing review and release is completed by operations. Members of the operations team formally review plant capability and readiness onsite with the plant manager and document all necessary product changes, facility changes, and process changes to enable mass production. These include modification reports on facility and equipment, manufacturing processes, product and process documentation, BOMs, product designs, and inventory controls ([Atuahene-Gima, 2013](#)).

6.9.14 Finalized pricing discount authority

Finalized pricing discount authority is issued by marketing. The team members establish the finalized pricing discount authority structure for local, regional, national, and international leadership according to [Nagle et al. \(2016\)](#). Discount percentage levels are established based on product-specific market research.

6.9.15 Sales and marketing documentation

Sales and marketing documentation and collateral are completed by marketing. Marketing members prepare sales documentation to provide all necessary literature and

collateral to train and support sales associates (Chang and Taylor, 2016). Key activities include the following in accordance with Babin and Zikmund (2015):

- Training modules and outline
- Support materials for initial anticipated customer questions
- Sales forecasting
- Sales literature, product information brochures
- Service plan
- Pricing and parts list
- Develop problem reporting and resolution mechanism
- Communicate warranty period to sales

6.9.16 Finalized phase-out plan

Marketing updates the product lifecycle and phase-out plan. Team members update the estimated duration of the product lifecycle and the linkage to other existing products (Saaksvuori and Immonen, 2008). Additionally, according to Stark (2015) the phase-out plan includes market price actions, inventory positions with suppliers, ramp-down plan of shipments, and inventory levels of existing product and the ramp-up transition to the new product.

6.9.17 Cost containment assessment

Procurement completes a cost containment assessment. This assessment provides a review of the actual sourcing costs in comparison to planned sourcing costs (Durmuşoğlu et al., 2013). Any variations from the sourcing plan should be closely evaluated. Additionally, state Di Benedetto et al. (2003), the cost containment assessment should identify any additional cost reductions that may further reduce component sourcing costs.

6.9.18 Reverse auction for commodity parts

Procurement completes e-sourcing opportunity assessment. Performing an e-sourcing secures the best available market purchase price via an automated, online, real-time bidding process for components used in design (Bartezzaghi and Ronchi, 2004; Schoenherr and Mabert, 2011; Yu et al., 2015). Several items key to success include in accordance with Bartezzaghi and Ronchi (2003):

- A focus on high-spend parts for efficient implementation
- Identification of parts by commodity type that are best suited for the e-sourcing process. Commodity parts include machined parts, stampings, fasteners, connectors, and others.
- Identification of parts that can be manufactured by more than one supplier. Determination if a catalog part is readily available in the marketplace and can be used in lieu of a custom designed part.

6.9.19 Service manuals

Service completes application and service manuals. All product manuals and related literature must include the required safety information, warnings, and cautions per the requirements of ANSI Z535.6 or equivalent according to (Bhamra et al., 2017).

6.9.20 Training delivery

Delivery of service and AE training by service. Training should be provided to the following people according to Phillips and Phillips (2016):

- Service and AE on product features and functionality
- Customer engineers, service contractor, and owner on operation, maintenance, and troubleshooting of the new product
- Order coordinators and regional managers to support product sales
- Service technicians for certification

6.9.21 Service strategy

Product support strategy is developed by service. Bhamra et al. (2017) assert that service team members define all activities required to properly support the product in the field such as customer service, installation, maintenance, repair, and ongoing training.

6.9.22 Finalized quality assessments

Quality assessments are done by quality. Quality team members ensure the quality measurement systems are in place to collect and report data during production. It is also important to do the following in accordance with Schilling and Neubauer (2017):

- Confirm production and supplier inspection accuracy through measurement system analysis and correlation study.
- Measure process capability and reconcile conflicts as needed by making final design and process adjustments.
- Eliminate special cause process variation to meet preestablished minimum capability requirements.
- Finalize work instructions.

6.9.23 Updated sales plans

The sales team updates the sales plan created during the design development phase. They include according to Calantone et al. (2003) more detailed information that may have been received from each region. Sales teams should execute against the guidelines as defined by the department procedure for the new product, states Pelham (2015).

6.9.24 Existing contract analysis

Analysis of existing contracts is completed by sales. This analysis will provide sales with insight into the trends of what sales techniques are working better than others. Additionally, it provides sales with a better understanding of key customers and their

procurement habits (Posner, 2014). Based on the knowledge gained from this analysis, sales plans, special offers, and selling techniques may need to be modified (Sekaran and Bougie, 2016; Jeston and Nelis, 2014).

6.9.25 Special offers

Special offers are developed by sales. Based on market and competitive assessments, sales may define special offers in order to achieve the following in accordance with Johnston and Marshall (2016):

- Gain access to new market segments.
- Provide similar solutions to rival competitors.
- Increase penetration in the market.
- Deplete existing inventory.

6.9.26 Finalized sales automation tools

Sales automation tools are finalized by sales. At this point according to Mariadoss et al. (2014), sales automation tools are loaded with all relevant product and marketing information to assist sales in quotation, order entry, and presentations. Product documentation is made available via Web-based tools to house customer-focused marketing materials.

6.9.27 Sales force training

Delivery of sales force training is by the sales department. Sales force training should be provided to all field sales in all regions with specific information to assist sales in better understanding the product, features, product warranty, benefits, market strategy, sales techniques, and all supporting product and customer-focused marketing materials, explain Albers et al. (2015). Avlonitis (2011) adds that they should also be trained on diagnostic and troubleshooting procedures as well as escalation processes.

6.9.28 Updated financials

Finance updated the financials. Members of the finance team update the assessment of financial project estimates based on more detailed knowledge of design and effort requirements. Estimate the project's ROI based on analysis of updated business case and AR, manufacturing requirements, especially capital expenses and sales forecasts (Phillips and Phillips, 2006; Ledwith and O'Dwyer, 2009; Hertenstein et al., 2005; Bhuiyan, 2011; Maltz et al., 2003).

6.10 Launch—new product introduction

In the NPI phase, which is mapped in Table 6.44, the enclosure encapsulated product is available to customers within the prime target markets according to Trott (2008). This

Table 6.44 Launch

7. New product introduction phase				
1. Business plan to actual results comparison	4. Engineering development review	7. Price management	10. Service feedback	14. Cost accounting
2. Project evaluation	5. Environmental compliance	8. Enclosure lifecycle	11. Quality assessments	
3. Engineering change requests	6. Mass production start-up	9. Cost containment	12. Sales forecast	

means that the product might not be available universally. There are reasons for this, add [Johnston and Marshall \(2016\)](#); for instance, a product launch might be planned to coincide with a particular industry show. At this point, production is increased to fulfill forecasted sales volumes ([Linares-Mustarós et al., 2015](#)). [Dale \(2015\)](#) highlights that enclosures must meet target quality, yield, and cost objectives. A project audit of the development effort is completed in this final development step, advise [Hempelmann and Engelen \(2015\)](#).

6.10.1 Business plan to actual results comparison

Comparison of business case to actual results done by product planning. This comparison provides an assessment of the business case against actual results ([Kerzner, 2013](#); [Vanek et al., 2017](#)). The comparison must include at least the following in accordance with [Tuli and Shankar \(2015\)](#):

- Validating sales forecasts and pricing plans
- Adjusting forecasts and pricing models as required by market conditions
- Validating the BOM cost model
- Identifying, documenting, and analyzing any variances for future business cases

6.10.2 Project evaluation

Project evaluation is completed by product planning. The project evaluation will provide an overall assessment of the cross-functional performance from concept through launch. This evaluation should consider actual versus planned costs, budget, and schedules according to [Jandaghi and Hosseini \(2015\)](#). Also, augment [Adler et al. \(2016\)](#), resource capabilities, lessons learned, and risk identification and mitigation should be evaluated.

6.10.3 Engineering change requests

ECRs for future releases are done by engineering. [Anderson \(2014\)](#) emphasizes that ECRs from sales, services, engineering, and product planning should be captured so

that feature gaps and product strengths or weaknesses can be addressed for future releases.

6.10.4 Engineering development review

External design review is organized by engineering. External design reviews are a tool to manage technical risks in NPD processes, assert [Doultsinou et al. \(2009\)](#). [West and Bogers \(2014\)](#) advocate the use of external consultants for this process. Technical focus, at a minimum, must include design for functional performance, reliability, manufacture, and sourcing and must occur as early as the design development phase according to [Lande and Oplinger \(2014\)](#). [Benassi et al. \(2011\)](#) emphasize that inputs from the company must include a clear technical scope statement and comprehensive and data-based briefing materials.

6.10.5 Environmental compliance

Engineering completes the environmental compliance control plan. [Pujari et al. \(2003\)](#) assert that this is a mechanism to ensure that the product's compliance is maintained during both the NPD process and all subsequent production. As changes are made to the product, for instance, component selection, suppliers, production process, and others or to global environmental legislation, the control plan ensures that the compliance status is maintained ([Mombeshora et al., 2014](#)). [Handfield et al. \(2001\)](#) explain that the control plan must define the procedures for changes so that the final product is compliant.

6.10.6 Mass production start-up

Mass production start-up is done by operations. The outcome is a fully operating supply chain that can accept, assemble, and ship to meet customer demand ([Inaba et al., 2008](#)). Manufacturing processes are stabilized with respect to quality specifications and yield. Team members continuously adapt and maintain assembly lines to within defined manufacturing specifications. [Meller and Deshazo \(2001\)](#) highlight that members of the operations team continually update the value stream map, balance operations, and implement key enclosure improvement projects. The operations team reviews volume and timing changes from the most recent sales and operations plan.

6.10.7 Price management

Price management is done by marketing. Marketing continues to monitor sales and compare with forecasts ([Stevenson and Hojati, 2007](#)). In addition, [Burkert et al. \(2017\)](#) add that marketing also adjusts forecasts based on actual results and leverage information to motivate the sales force.

6.10.8 Enclosure lifecycle

Product lifecycle plan is completed by marketing. [Stark \(2015\)](#) highlights that the product lifecycle plan provides the estimated date for product retirement and the activities required to periodically assess the feasibility of keeping the product in production. Additionally, [Wiesner et al. \(2015\)](#) assert that it includes the list of activities required to retire the product.

6.10.9 Cost containment

Procurement provides a cost containment assessment. This assessment provides a review of the actual sourcing costs in comparison to planned sourcing costs according to [Shellenbarger \(2016\)](#). Any negative variations from the sourcing plan should be closely evaluated to determine if alternative methods could reduce sourcing costs back to within plan ([Arnette et al., 2017](#)). Additionally, point out [Brewer and Arnette \(2017\)](#), the cost containment assessment should identify any additional cost reductions that may further reduce component sourcing costs.

6.10.10 Service feedback

Field feedback assessments are completed by service. These assessments should provide a summary analysis of positive and negative feedback captured during installation and customer operation ([Bhamra et al., 2017](#)). The analysis should focus on field failures, customer comments, experience of application engineers, and installation issues and feedback ([Doultsinou et al., 2009](#)). [Anderson \(2014\)](#) state that ECRs should be initiated for root cause analysis as appropriate.

6.10.11 Quality assessments

Quality updates quality assessments. [Schilling and Neubauer \(2017\)](#) explain that updated quality assessments are a summary report of selected field unit results versus designed quality specifications. A root cause analysis is completed and ECRs are submitted to engineering as appropriate ([Anderson, 2014](#)). [Hartley \(2017\)](#) elucidates that actual cost of quality results are compared to the forecasted cost of quality. Product and service quality results should be compared to the metrics established in the concept feasibility phase according to [Mitra \(2016\)](#).

6.10.12 Sales forecast

[Trapero et al. \(2015\)](#) advise that sales forecasts are updated with refined information based on actual sales performance. These include regional, country-specific, and global results.

6.10.13 Cost accounting

Finance performs an audit of the full project costs in accordance with [Hempelmann and Engelen \(2015\)](#).

6.11 Manufacture

This is the final step in the new enclosure development process (Black and Kohser, 2017). Once the manufacturing phase is reached, the enclosure encapsulated product is universally available to customers. In this phase production rates have been increased to coincide with previously forecasted sales volumes.

6.12 Feedback loop

The importance of the feedback loop in the NPD and NPI process is paramount according to Garcia et al. (2003). Armstrong et al. (2015) explicate that this process needs to be customized to the needs of a particular market and of course, to the needs of the company desiring to be a successful enclosure product developer. Yeh et al. (2017) elucidate that no two companies are completely alike, so no two product development processes should exactly be the same.

Importantly, Saaksvuori and Immonen (2008) add that information on the product must be collected not only while it is in development but throughout its entire lifecycle. Stone and Woodcock (2014) emphasize that this information must also be qualified, checked, and classified to be useful for the next NPD initiatives. Quagini and Tonchia (2010) highlight that this task is neither simple nor cheap. However, if it is not done correctly, many of the NPD and NPI activities will be based on erroneous assumptions according to Goffin and New (2001).

Most companies that successfully develop products found that another critical element originating from the above business intelligence gathering methodology is the proper compilation of the user requirements specification (URS) and subsequent translation into a workable functional requirement specification (FRS) document (Yeh et al., 2017; Galli, 2017; La Rocca et al., 2016; Chang and Taylor, 2016; Berggreen and Kampf, 2016).

6.13 Abbreviated NPD/NPI

A new enclosure, housing, or package development process generally takes about 3 years. The actual length of time might be arguable, but most executives and especially customers agree that this is too long (Fuchs and Schreier, 2011).

Experienced product development experts point out that time has already been shortened as not too long ago such a development process lasted as long as 8 years according to Franklin and Kramer (1982). Advancements were accomplished primarily with the introduction of computerization (Chang et al., 2013). Software technology, however, cannot cut much more time off from the process. It has reached the diminishing return stage points out Cennamo (2016).

Goffin and Pfeiffer (2002) emphasize that abbreviated NPD/NPI programs can be developed. Adding concurrency to the serialized EEPD process fundamentally and

irreversibly transforms the traditional, highly specialized, serial engineering model into a massively parallelized and highly successful EEPD model.

In the “old school” sequential product development model, tasks such as electrical design or mechanical feature development occur in a serial manner according to Cooper (2014). Lockwood et al. (2013) state that the traditional process design limits team members’ ability to contribute fast and meaningfully to each task. Thus, time to market is merely the summation of the tasks completion time (Kahn, 2012). In the EEPD product development model, tasks occur in parallel. The innate ability to perform tasks within the eight phases in parallel and additional techniques provided later in Book 2 and 3 to shorten the duration of each task significantly reduces total project length. This in turn critically shortens time to market.

Admittedly, the idea of concurrent engineering is not a new one according to Pennell and Winner (1989). It was developed in the 1980s and it was largely forgotten by the time the new millennium rolled around. However, concurrent engineering methods, combined with the NPD/NPI program described in detail before, can create a massive parallelism. A brief practical example can illustrate some of the advantages of such a hybrid system.

Many product development efforts suffer from the creation of injection molding tooling according to Rosato and Rosato (2012). 3D printing technologies have not been able to eliminate this process despite substantial technological advances (Campbell et al., 2011; Bak, 2003). Madan et al. (2015) underline that injection molding is still the most frequently utilized process if the enclosure is produced in large quantities.

However, in a linear process shown in Fig. 6.3 injection molding tooling is not even discussed until the planning phase. Tooling is not ordered until the design is frozen. Another problem Gopalakrishnan et al. (2015) state is that most programs experience changes despite that the design was frozen. Costly tool changes will result according to Dang (2014).

This situation can easily be changed. Once the intention of a NPD program is known, new tooling can be ordered. Let us rephrase this. Parts of the tool can be ordered. Ferreira et al. (2014) argue that all the NPD programs need to create rapid modular tooling in lieu of the previously favored hard tooling. The base of the tooling can be ordered as early as the initiation of the NPD process takes place. King and Tansey (2003) state that the tool inserts can be made overnight. Of course, there is still the assembly time. Adding a few hours, this could also be done. The injection mold trial could be cut to a few hours and good parts will be produced if the process has been developed properly (Yao and Kim, 2002). Book 3 will provide the necessary details. The important point to remember is that the result of such a massive parallelism is that development time shrinks from 3 years to 6 months. Concurrent engineering coupled with best practice NPD/NPI can work fantastically and successfully. The



Figure 6.3 A new product development and introduction (NPD/NPI) process map.

difficulty [Dorn and Dustdar \(2010\)](#) highlight is that such abbreviated activity needs a well-motivated expert team. Creating such a team is neither fast nor comes cheap.

Despite of the greatest possibilities, many new enclosure product developments fail. Consider the potential consequences of such failures. Tuninter Flight 1153, which crashed into the Mediterranean Sea 29 km from Palermo, is one such an example according to [Carella and De Donno \(2017\)](#).

Seveteen people died because of this one crash. This accident could have been avoided if a critical enclosure was designed properly. The accident was the result of unnoticed fuel depletion due to the installation of the wrong fuel quantity indicator. The installed indicator was designed for the smaller ATR 42. The wrong fuel quantity indicator was not only fitted the larger ATR 72 but also appeared to have worked as it indicated an amount of fuel. Unfortunately, its indicated values were false. This mistake resulted in an indicated fuel quantity of 1800 kg when in fact the tanks were completely empty. Without fuel the flight had no chance.

The important point of this example is to avoid similar mistakes in an enclosure, housing, or package design. Therefore, the right framing of an enclosure problem is paramount.

6.14 Framing an enclosure problem

In any text book, example problems are worked out and students are left with the comfortable feeling of accomplishment ([Heller and Hollabaugh, 1992](#)). However, the first challenge of a real-life engineer is to understand how complex problems could be subdivided to create a solvable problem. The solution to any enclosure engineering problem should conform to a simple tiered priority. In order to assess a new enclosure development problem, one needs to follow the Regulatory-Function-Cost-Schedule-Budget system. Let us look at each in turn.

6.14.1 Regulatory

This is the legal framework created by the government. It could be trading block driven (e.g., European Union), country driven (United States), or state driven (like California). This heading encompasses rules, regulations, guidelines, and generally accepted practices. [Sutinen and Kuperan \(1999\)](#) highlight that violating any item in the list and the project will become either unfeasible or liable to prosecution at any time (usually at the worst possible time).

6.14.2 Function

Like all engineering handbook this one is no exception in that it aims at providing a state-of-the-art description of the functional makeup of its subject ([Dick et al., 2017](#)). Function in this context is synonymous with technology, although not interchangeable. For instance, heat management would be an extremely important function of an electronics enclosure.

6.14.3 Cost

It is important to understand that cost is only third priority. Both complying with all relevant regulations and to deliver a well-functioning device supersedes the importance of cost according to [Bajaj et al. \(2004\)](#). This is logical. Any company might be sued and be closed because of ignoring the relevant laws. Consider that if a device is nonfunctional, then its value rapidly approaches zero.

6.14.4 Schedule

This is the time it takes to complete the NPD cycle. Project management officers often believe that this time is the most important aspect. Yet, in practice it only enjoys fourth priority ([Swink et al., 2006](#)). Sales and marketing professionals need to collate the necessary and accurate business intelligence to enable the product development team to perform fulfilling its top priorities; that is, to follow all applicable regulations, make sure that the device functions as it was intended and that its cost is acceptable to the market and provide the profitability demanded by the shareholders of the enterprise. This handbook series will show shortcuts that will allow the development team to catch up to preagreed time lines.

6.14.5 Budget

Budget refers to development costs, NPD costs. It is a worthy effort to try to minimize these expenditures as long as they are not getting in the way of meeting the previous four criteria according to [Neale \(1994\)](#). This handbook series will demonstrate the way to substantially reduce electronics enclosure NPD budgets.

6.15 Electronic enclosure product development—new product development process review

Following a well-described NPD and NPI process is a critical factor to create a long-term competitive advantage for the host organization. This process is a conceptual model for creating a viable idea and developing it into an enclosure, housing, or packaging product in the minimum amount of time. This general mental model subdivides the overall NPD effort into eight distinct phases.

Each phase is subdivided into manageable steps that are assigned to a function within the NPD CFT. All 161 steps displayed in [Fig. 6.4](#) are described to present a complete map of the EEPD process.

Most NPD processes use management decision gates. This has been found to create extreme difficulties for NPD teams. A better approach is to integrate management functions into the day-to-day operation of the cross-functional NPD team. Preparation time and effort for gate reviews is eliminated in this model. In addition, senior executives are persuaded to have an in-depth understanding of the most important process drivers.

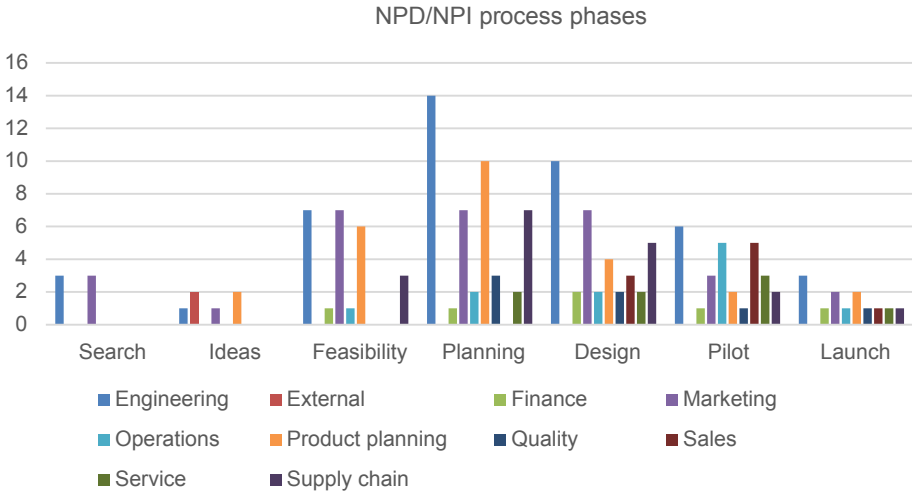


Figure 6.4 Functional involvement in the electronic enclosure product development process.

Locating opportunities is the very first phase in the EEPD process. Other processes name this step Market Research. It is instead a continuous search process for new market-driven ideas that are emerging by harnessing enterprise-wide customer relationship and engineering management data. A secret ingredient of the NPD success formula is in the way these very different two worlds are merged into a useful database.

A well-developed plan and organization-wide implementation of idea generation is a prerequisite for successful innovation in the electronic enclosures field. The overall goal of this phase is to create an innovative environment that fosters creation of actionable ideas. Concepts need to focus on opportunities that could be feasible within the organizational context. Therefore, ideas must be sorted based on customer and corporate fit.

The concept feasibility phase aims to quickly define the product in sufficient detail to determine its feasibility both from technical and commercial perspectives. Another secret ingredient of the NPD success formula is that the concept feasibility phase development is quick but very thorough at the same time. Up front engineering investment within a framework of a well-functioning CFT pays huge dividends downstream in the EEPD process.

The CFT collaborates to substantiate discovered market needs and product value drivers based on the proposed functional requirements in the project planning phase. The primary goal of the NPD CFT is to complete the conceptual design and thus demonstrate a proof-of-concept early in the EEPD process.

Detailed design, development, and system integration are completed using best cost components and processes in the design development phase. A preproduction run is completed that proves manufacturing and the supply chain are ready to execute and provides testing with a small number of prototypes to ensure product requirements and specifications have been met.

In the ramp up otherwise known as pilot phase the product design is validated, customer beta testing is completed, and manufacturing processes are verified to assure operational readiness. While in the NPI phase, the enclosure encapsulated product is available to customers within the prime target markets. Once the manufacturing phase is reached, the enclosure, housing, or package is universally available to customers.

The solution to any enclosure engineering problem should conform to a simple tiered priority. Assessment of a new enclosure development problem is most efficiently performed by following the Regulatory-Function-Cost-Schedule-Budget system. This is the last secret ingredient of the EEPD success formula.

6.16 Hot tips

First, innovation waves must be understood, especially their interactions. Then the global drivers must be incorporated into the right innovation strategy. Market needs must be discovered, for instance, by travelling on top of lifts, visiting mine sites, ports, and other important applications. The right process must be followed and parallelism opportunities must be harnessed. Only then is the executive management team being able to drive NPD and NPI to its ultimate success.

6.17 Part 1: ubiquitous products summary

Enclosures, housings, and packages are truly ubiquitous. There is probably no part of human life that these products have not touched. Even a cursory look at Chapter 3 (Market segments) supports this view. It is therefore more curious that there has not been a concerted effort to establish a unified engineering practice in this area. Many aspects of enclosure engineering are currently under investigation such as thermal management, but the material contained in *Contextual Drivers* have been left out of the reach of both academia and industry. Yet this material is the very foundation for developing a unified and generally accepted enclosure engineering practice around the globe.

6.17.1 Chapter 1 Introduction

Chapter 1 opens this first part by asserting that some enclosures are designed and made very well, while others could be improved. This improvement potential is the very topic of this handbook series. Enclosure-related labels are discussed to clarify and unify the language of the enclosure engineer and the supply chain. A definition of enclosure is provided to offer a fundamental building block of understanding. It is proposed that a new discipline enclosure engineering be instituted. Fastener and connector-based issues have been identified as significant improvement possibilities, as well as heat management. These three areas form the technology triangle, which in turn forms the fundamental purpose for creating this Handbook series.

6.17.2 Chapter 2 Technological innovation

Miniaturization is the most important current driver of advancements in the enclosure engineering field. This means that the global trend is to get ever more power into an ever-smaller space in electronics. There is a remarkable long-term trend to integrate. In this context, it meant along electrical elements, but now it also means to integrate between the active circuitry and its substrates. This is the driving factor behind micro-electromechanical systems (MEMS).

Electronics innovation waves were investigated and their effect on the electronic enclosure industry was explicated. Six emerging technologies and their potential disruptive influences were analyzed in addition to MEMS. It was found that nonlinear optics, splintronic, and memristors while interesting concepts present no short- to medium-term disruptive power in electronic enclosures. However, 2-D, organic and molecular electronics present exciting current potentials.

6.17.3 Chapter 3 Market segments

This chapter has reviewed the various market segments for electronic enclosures. Segments such as the chemicals, explosive environments, energy and offshore, food, beverage, tobacco, material handling, off-road, and pharmaceuticals require very specialized expertise. These segments can of course learn from this handbook series but they will need supplementary materials to successfully address their industry-specific challenges.

Other industries such as aerospace and defense, automotive, built environment, consumer electronics, electrical, instruments, medical device, and robotics will find this handbook series almost completely satisfying their demands. It was found that automotive, the built environment, consumer electronics, electrical, instruments, medical device, and robotics offer the highest growth market segments at present.

6.17.4 Chapter 4 Enclosure requirements

This chapter has reviewed elements of the FRS creation. Practical examples were furnished to supplement core concepts. Procedural and administrative functions were inserted into the introductory section of the FRS to contribute to a smooth NPD. A product overview was furnished to supplement understanding and to communicate overall design intent to the NPD team. Operating conditions were displayed to orient the design team and to provide the initial seed for the development of valid design concepts. Modularity instructions were added due to recognition that customization is critical in almost all aspects of housings and enclosure manufacture and even more importantly for achieving sustainable profitability.

Aesthetics were addressed and industrial design criteria were added to facilitate positive purchase decisions prior to addressing product safety issues. Product safety was positioned as a critical aspect of any NPD effort. Many important areas were addressed such as: conformance to various and relevant standards, desired ingress protection rating, pollution degree requirements, protection from live parts, creepage and

clearance calculation guidance, flammability requirements if the enclosure contains polymers, safety labels and markings, and earthing requirements.

Construction-related topics were highlighted including design related issues, welding, bolted joints, casting, vacuum forming, extruding and molding issues. A finely detailed example was added to anchor understanding of the related material. Many enclosure-related topics were discussed in the form of internal fittings, locks and hinges, and lifting arrangements.

It was recognized that thermal management of electronics is of paramount importance. A practical example displayed information on thermal analysis, system integration, fan requirements, considerations for heat sinks, and PCB cooling. Structural robustness issues were detailed to avoid duplication of known NPD failures. Importance of appropriate engineering calculations and analysis was emphasized. A structural robustness example was provided to supply vital information about requirements for polymeric enclosures, impact resistance, shock and vibration testing, calculations and analysis, and packaging.

Important aspects of material selection were reviewed. A substantial example was provided that contained information on material selection, polymeric material requirements, polymeric enclosures and external parts, polymeric internal parts, other parts, UV requirements, gasket material requirements, molding methods, metallic material requirements, copper conductors, and sheet steel requirements. The criticality of proper fastener selection was also discussed along with corrosion information. Design for manufacturing and maintenance issues were highlighted. The importance of compliance with all applicable environmental and sustainability requirements was emphasized.

6.17.5 Chapter 5 Types

This chapter focused on types and introduced standard types of packages, housings, and enclosures. First the seven levels were defined to provide clarity. Some of these levels were grouped together to form the three final levels providing an easy-to-remember classification exactly coinciding with the title of this handbook series: enclosures, housings, and packages.

This chapter ordered the level classification according to size and therefore packages were discussed first. A historical perspective in the form of a timeline was provided. Development drivers were identified to provide understanding and facilitate NPD planning. Design considerations such as cost, electrical functionality, mechanical and thermal characteristics were investigated.

Through-hole and surface mount technologies were explicated including pin grid arrays (PGAs) and ball grid arrays (BGAs). Issues such as packaging, handling, testing with respect to bare die implementations were discussed. Chip-scale packages and module assemblies were reviewed to provide a platform for the discussion on advanced package substrates. System-in-packages and through-silicon-vias were analyzed to further their applications in the field.

The next level: housings were discussed first by focusing on circuit board mounting issues then by reviewing backplane connections. Selection ideas for the

next level: enclosures were also incorporated. Basic layout and a quick cooling guide closed this section of the chapter.

A variety of standard enclosures were reviewed, such as small, portable, and wall-mount cabinets. Chassis, card racks, rack mount chassis, and open, cabinet, server, colocation, and seismic racks were described in detail to assist the professional enclosure engineer as well as academia.

6.17.6 Chapter 6 New product development

This final chapter of the first part in the handbook series has mapped a successful new product development (NPD) and introduction (NPI) process. Implementing this process is a critical factor in creating a long-term competitive advantage for the host organization. This process is a conceptual model for creating a viable idea and developing it into an enclosure, housing, or packaging product in the minimum time with the minimum amount of resources. This general mental model subdivides the overall NPD effort into eight distinct phases.

Locating opportunities is a continuous search process for new market-driven ideas that are emerging by harnessing enterprise-wide customer relationship and engineering management data. A secret ingredient of the EEPD success formula is in the way these very different two worlds are merged into a useful database.

The concept feasibility phase aims to quickly define the product in sufficient detail to determine its feasibility both from technical and commercial perspectives. Another secret ingredient of the EEPD success formula is that the concept feasibility phase development is quick but very thorough at the same time. Up front engineering investment within a framework of a well-functioning CFT pays huge dividends downstream in the EEPD process.

The solution to any enclosure engineering problem should conform to a simple tiered priority. Assessment of a new enclosure development problem is most efficiently performed by following the Regulatory-Function-Cost-Schedule-Budget system. This is the last secret ingredient of the EEPD success formula.

6.17.7 Summarizing part 1: ubiquitous products

Fastener and connector-based issues as well as heat management were identified as an applied problem facing the enclosure industry. In addition, five important aspects were reviewed.

Technology waves are important as they represent the fundamental understanding on which to build a robust and long-term enclosure strategy. Review of the relevant market segments justified the use of the word ubiquitous as enclosures, housings, and packages are truly everywhere.

Enclosure types and requirements were reviewed in Chapters 5 and 4, respectively. They serve as an orientation for the novice and review for those with substantial experience in the industry. This last chapter offers an insight in to the secretive world of new product development and introductions by providing a map of the process and a few additional helpful hints for the practitioner.

Therefore, this first part provides a strong foundation on which to build an understanding of the Social and Environmental Framework to complete a review of the Contextual Drivers affecting successful enclosure development.

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7.1 Introduction

This chapter and the next one are correlated, in that standards establish the prerequisites to enter a globally competitive market segment, while intellectual property protections establish a temporary monopoly according to [Telser \(2017\)](#) and [Rich \(1993\)](#). All competitors must meet various standards, including enclosure, housing, and package developers and producers ([Hui et al., 2013](#)). [Mair \(2006\)](#) asserts that meeting relevant standards allows entry of the field but no more. A successful product must offer points of differentiation ([Dickson and Ginter, 1987](#); [Sun et al., 2017](#); [Davoudi Nasr and Cheraghi, 2017](#)). This ability to differentiate in the marketplace is directly related to innovation according to [Walter and Peterson \(2017\)](#). Therefore, without innovation, there is no differentiation. However, [Zeschky et al. \(2014\)](#) state that innovation requires substantial resource commitment and thus it is expensive. An imitator could reap the benefits without expending the same level of resources, add [Casadesus-Masanell and Zhu \(2013\)](#). Therefore, [Camagni \(2017\)](#) asserts that market forces do not provide the necessary impetus for innovation. Hence, intellectual property protection is critical to foster innovative practices ([Lin and Wong, 2017](#); [Bently and Sherman, 2014](#); [Cimoli et al., 2014](#)).

[Pelkmans \(1987\)](#) observes that standardization establishes the rules of the game. Participation in standardization is therefore critical for the success of the participant, explain [Gandal et al. \(2007\)](#). Immediate benefits are emanating from the restrictive potentials. This means that certain products and activities including innovative ones can be excluded from the marketplace by the inclusion of subtle requirements, add [Gandal and Shy \(2001\)](#). Therefore, standardization can be quite restrictive from the point of view of new entrants to the field according to [Gaul \(2016\)](#). [Gu \(2017\)](#) believes that incumbents benefit from such regimes. These are the very organizations that can afford the luxury of attending committee meetings and the like. [Kang and Motohashi \(2015\)](#) highlight that standardization, much like innovation, is an expensive proposition.

An additional benefit of standardization is the temporary knowledge gap between the standards committee and the rest of the industry. This temporal benefit could, however, be long enough to pay massive dividends on the standardization investment, elucidate [Fomin et al. \(2003\)](#).

7.2 History of standardization

The earliest recorded history of standardization originates from the advanced stages of the agricultural revolution from around the 4th millennium BC. The first effort was

focused on the standardization of weights and measures (Fischer, 1925; Hoppit, 1993; Judson, 1976). Hart (1978) explains that hunting and gathering does not produce massive surplus to be traded with the community or externally. Therefore, an impetus for such activities was missing. However, Lee (2017) argues that more complex civilizations developed primarily around the capacity of being able to produce surplus food and beverages. Thus, civilizations needed to insure uniformity of measurement for the purposes of trade primarily for financial instruments but also for extensive barter according to Barzel (1982).

Early standard units only applied to a single jurisdiction, explain Ritchie-Calder (1970). This meant that every similarly advanced civilization and many areas within one such system developed their own standards, for instance, for weight, that is, for mass, lengths, areas, and volumes, adds Klein (2012). In addition, systems were often related to one field of use, creating a further complexity. For instance, volumetric measures utilized for grains were not compatible with liquid measurements (Webster and Eren, 2014).

Werle and Iversen (2006) elucidate that, first, the growing importance of trade between communities provided a renewed interest in standardization. However, the Industrial Revolution provided a renewed need for regional and later globally harmonized standardization according to Musson and Robinson (1969). The first innovation wave introduced mechanized production (Hudson, 2014). This meant that the guild-based manual workshop was superseded by factories. Foster (2003) observes that mass production created a need for cheap labor without the skill sets of the former guild-certified masters. Thus, there was a need for process standardization in addition to weights and measures. This need introduced the in-company standardization process according to Koebner (1959).

Knoedler and Mayhew (1994) point out that wars provided yet another important factor. Particularly, ammunition sizes needed to be standardized so that fighting could continue with generic ammunition products, asserts Arvidsson (2008). Additionally, Wills et al. (1996) emphasize that a less frequent but even more severe need was discovered in the form of fasteners, thus heralding the age of parts interchangeability (Womack et al., 1990).

The 19th century introduced such complex products that it was no longer always feasible to produce them in a single enterprise (Alm, 2003). Buying in parts for a more complex product produced the first supply chains with its associated interfaces. These interfaces much like the trading activities that started standardization of weights and measures provided the impetus for further standardization that was not even recognized by the public. As such, association- and country-based private standardization was born according to De Vries (2013).

Today, most standards organizations are a variation of this private model, despite the erroneous view of the public that they are part of the governmental organization, emphasize Mattli and Büthe (2005). For instance, Underwriters Laboratories commonly known as UL has no governmental vested authority. ASTM, SAE, and others would be association-based standardization communities. Continental European Standardization organization often was supported by the respective governments. However, this is no longer the case. De Vries (2013) explains that there are many layers of standardization in effect today as is demonstrated in Fig. 7.1



Figure 7.1 Standardization levels.

and so it is extremely important to understand not just standards but also their development process.

7.3 Definition of a standard

[Thompson \(1954\)](#) states that standards are documents primarily setting out technical specifications. Many procedures are also standardized. Additionally, guidelines are often developed to interpret the intention of a particular standard and therefore, to aid in its wide implementation. [Vandenberghe \(2016\)](#) argues that the strongest justification for creating these instruments is to ensure product safety. There are additional benefits in the forms of reliability and consistency according to [Levitt \(1993\)](#).

Essentially, standards are accepted rules for measurement, defines [De Vries \(2013\)](#). They are derived from an economic or social activity. Standardization is an activity to develop such measurement. The primary goal of the measurement is to establish harmonization across a particular domain, which could be international, national, an industry association, or enterprise level ([Pelkmans, 1987](#)).

Standards are anchored in industrial experience, grounded in science and technology. [Bozeman \(2000\)](#) opines that standards need to be regularly reviewed to ensure their relevance. [De Vries \(2013\)](#) argues that given the huge number of various standards, regular review of a national or international standard is more of a wish than a reality.

Standards cover all aspects, consumer products, various services, construction methods, most fields of engineering, information and computer technology, business aspects, human services, energy and other utilities, the environment, and even more, asserts [Koch \(2017\)](#). However, there are only six kinds of standards: international, regional, national, association based, industrial, and company based according

to [De Vries \(2013\)](#). Regional and national standards work similarly so they could be grouped together. Association and industrial standards are often grouped together as well.

International standards are developed by global organizations such as ISO, IEC, and a few others ([Buck, 2009](#)). Entire regions like the European Union, North America, and others can adopt these standards directly as do national standardization bodies ([Abbott and Snidal, 2001](#)). [Nadvi \(2008\)](#) informs that wherever possible, the responsible national standardization bodies embrace adoption of international standards as it is a relatively simple process and thereby saves resources. However, development of these standards is often very difficult and very few countries' stakeholders are completely satisfied with the end result, argue [Mattli and Bütthe \(2003\)](#).

[Baller \(2007\)](#) points out that for this reason, regional standards are often prepared, which later can be adopted by the international equivalent bodies, thereby offering an avenue for national adoption. An example would be the European Union, which develops EN standards. These are often adopted not only by EU member states but also around the world. Another example of regional standardization effort is the joint Australian/New Zealand standards.

[De Vries \(2013\)](#) explains that it is worth noting that there are other technical documents that provide guidance on standards implementations. These include various handbooks and technical reports issued by the standardization bodies or by independent authors. These authors often have experience with standardization either by chairing a committee or by other participation in the standardization process. Standards are so complex these days that very few people other than the originating committee are in the position to effectively interpret their technical requirements, argue [Rosenkopf et al. \(2001\)](#). Therefore, participation in these committees presents a significant advantage to the stakeholder ([Mattli and Bütthe, 2003](#)).

7.4 The concept of net benefit

Net benefit is an important standardization principle and it means that a standard must have an overall positive impact on relevant stakeholders ([Hoekman, 2005](#)). [Palmer et al. \(1995\)](#) argue that every standard must demonstrate positive net benefit. A little understood and seldom practiced fact is that lack of a demonstrable net benefit along with a statement as such from an affected stakeholder starts the withdrawal process in any jurisdiction according to [De Vries \(2013\)](#). This means that all standards must provide a value that exceeds its total costs including implementation costs to society, define [Keohane and Olmstead \(2016\)](#). The following is important in assessing potential and accrued net benefit to society: public health and safety; social, environmental, and economic impact; and the effect on competition. [Kang et al. \(2007\)](#) emphasize that standardization experts can assist in starting a standardization process or redrafting existing standards to create net benefit or to reduce the harm of previous standardization efforts.

7.5 Benefits of standards

Standards fundamentally ensure that goods and services consistently perform in a predictable, desired, and intended way. As such standards support the relevant part of the economy. Standards often are created to improve safety and health. [Jones and Hudson \(1996\)](#) underline that standards provide businesses and consumers with a level of confidence that the goods and services that businesses are developing or using are fit for purpose. Standards also provide a platform on which to build new inventions. As the global world changes, new standards are created to embrace the latest technologies, innovations, and communal needs ([Tassey, 2000](#)). Redundant standards that have little or no net benefit are discarded. How fast, that depends on the stakeholders according to [De Vries \(2013\)](#).

[Acemoglu et al. \(2012\)](#) argue that products that comply with a standard or set of standards have a competitive advantage. Exporters using the relevant international standards have met the first hurdle when they penetrate new foreign market segments. Essentially, standards ensure that products manufactured in one country can be sold and used in another, state [Jho \(2007\)](#). Therefore, well-developed standards reduce technical barriers to international trade. Standards also increase the size of potential markets and allow companies to compete in a global economy.

International standards aid to make laws and regulations consistent across the world according to [Büthe and Mattli \(2011\)](#). In effect, standards offer an alternative to regulation. Standards are part of the global technical infrastructure that allows trade to be efficient and thereby businesses to function. Everyday commercial transactions need accurate units of measurement and therefore demand a robust conformance system ([Klein, 2012](#)).

7.6 Developing standards

The standardization process is often ill-understood even by committee members, explain [Matutes and Regibeau \(1996\)](#). Importantly, anyone can propose the development or revision of a standard or technical document. The first step in this process is to create a proposal that meets the accredited standards body's development criteria. [Khajeh-Hosseini et al. \(2012\)](#) emphasize that there are only two main criteria to be concerned with. These are net benefit and stakeholder support.

[Cowan \(1992\)](#) explains that net benefit means that the proposal must demonstrate value to the community. Stakeholder support means that the same proposal must be supported by a wide and diverse group of relevant organizations according to [Werle and Iversen \(2006\)](#). Once a proposal is received, it is reviewed along with all other proposals in a project prioritization process according to [De Vries \(2013\)](#). However, if the proposal is for an international adoption, it can be submitted at any time, highlights [Hallstrom \(2004\)](#). Each proposal is supposed to be considered on the strength of its statement of net benefits, the evidence presented of the stakeholder support, and total required resources. However, a successful submission needs a standardization

champion, argues [Gordon \(1992\)](#). The champion will make sure that the proposal is converted into a project.

7.7 Standards and the law

Most accredited standardization bodies are not part of any government these days, explain [Gow et al. \(2000\)](#). Therefore, standards institutes do not directly make laws or regulations, assert [De Vries \(2013\)](#). Importantly, [Timmermans and Epstein \(2010\)](#) emphasize that standards are not legal documents. However, when a government references a standard in legislation, it becomes mandatory according to [Burk \(2005\)](#). This fact escapes the attention of many stakeholders often to their substantial cost, state [Jones and Hudson \(1996\)](#). In addition, standards or a specific clause of a standard is also often incorporated into legal contracts ([Burk, 2005](#)). The way a standard is referenced in a private contract is critical. For instance, what happens if a newer version of the referenced standard is developed? What happens if the specific clause is removed from the new standard? Will the contract become void? How much notice will be given if the specific clause is removed? Most engineers or even the standard committee members never think about the inadvertent outcomes, but they should, highlight [Knoedler and Mayhew \(1994\)](#).

7.8 Development pathways

[Swann \(2015\)](#) explains that it is paramount to understand the main options available to develop standards. According to [Weiss and Cargill \(1992\)](#) there are four generic pathways for any standards development process as displayed in [Fig. 7.2](#).

7.8.1 National standards resourced

This pathway uses national resources, project management expertise, and infrastructure. This often means that any approved project requires substantial commitment and vigorous contribution from stakeholders over a relatively long but well-defined period of time. Proposals for nationally developed and resourced projects are to be submitted through the local equivalent of the prioritization process.



Figure 7.2 Standards development pathways.

7.8.2 Externally funded

Externally funded pathway offers stakeholders customized solutions to their needs. This pathway offers greater choice in resourcing levels, and project timeframes are often accelerated as a result. Most national accredited standards bodies (NASBs) highlight that externally funded project proposals must meet the same net benefit and stakeholder support requirements. However, proposals for externally funded projects are not part of the general prioritization process. This means that they may be submitted to the NASB at any time. Of course, provision of external funding is not supposed to give the funding entity any preferential consideration, but it can set the tone of the activity and can shape the technical agenda, content, and output, and in effect shape the standard.

7.8.3 Association managed

The opportunity exists for individual organizations, such as trade associations to be formally accredited as standards developers. The obvious benefit is that ownership of the standards development process enables the organization to determine its program, level of resources, and associated timeframes. Therefore, the association can better meet its stakeholders' needs. Accreditation is usually carried out by the NASB.

7.8.4 International standards development

The NASB also manages national involvement in international projects and development programs. Proposals to participate in international technical committees (ITCs) should be submitted as part of the prioritization process. This is to ensure that national and NASB resources are allocated effectively to represent and protect national interests. Supporters submitting ITC proposals may choose any of the previously described development pathways. However, the NASB will usually determine the level of support. This is usually based on the strength and scope of the submitted proposal.

International text adoption is a proposal for the adoption of an international standard. A proposal must be submitted because this process relies on Standards Australia's resources. These proposals can be submitted at any time.

7.8.5 Prioritizing and selecting projects

Selection is usually based on the merit of the net benefit case; well-defined scope statement; stakeholder support; and above all the availability of national resources. There are four main types of proposals according to [Gill \(2016\)](#):

- Revision of an existing standard
- Development of a new standard
- Proposal of national participation in an international standards committee
- Adopting an international standard (either an identical text adoption or with modifications for the national context as a modified text adoption)

The prioritization and selection process takes place only a few times each year (De Vries, 2013). This means that there are only a few periods per year in which a NASB accepts proposals from the public domain. These are called project prioritization rounds.

7.9 Standards development

Any NASB brings together many academic, business, community, government, and of course technical experts to constitute appropriate technical committees (TCs). Committee members are representatives of their nominating organizations. These could be from academia, consumer or industrial associations, government, or scientific institutions. Aspinwall and Greenwood (2013) emphasize that they are nominated by their organizations to represent solely their interests and not their employer's interests. Many NASB enlists the assistance of over 1000 nominating organizations according to De Vries (2013). Their large number is sufficient to fulfill one of the most important principles, that is, to develop standards based on consensus (Susskind et al., 1999). Committee members' contribution to standards development is paramount.

A TC will work on a limited number of projects annually according to Rosenkopf et al. (2001). These projects might include revising existing standards and technical documents. The TC might assess international standards for adoption by their NASB, or drafting a brand-new standard for an emerging industry or technology.

Ito (2016) elucidates that being a part of a TC has its rewards such as increased knowledge and cultivation of stronger business networks. Competitive advantages are often secured although these are not advertised openly. Of course, a TC member can always claim the lofty aim of making the world simply a better place.

7.10 Project development stages

The NASB standards development process is based on three internationally recognized principles (De Vries et al., 2003; Wang, 2011; Hale and Held, 2011; Murphy and Yates, 2009; Spivak and Brenner, 2001) shown in Fig. 7.3.

There are eight stages in the development of a NASB standard, explicates De Vries (2013): proposal, approval, TC formation, drafting, public comment, comment consideration, committee ballot, and publication. This is a sequential process as is displayed in Fig. 7.4.

7.10.1 *Proposal for a new or revised standard*

A formal proposal must come from the national community. The proposal is often from an industry association or from an interested government department. This latter proposal regularly produces more indirect regulation in the form of a referenced standard. NASBs do not initiate new standard projects; they merely respond to requests

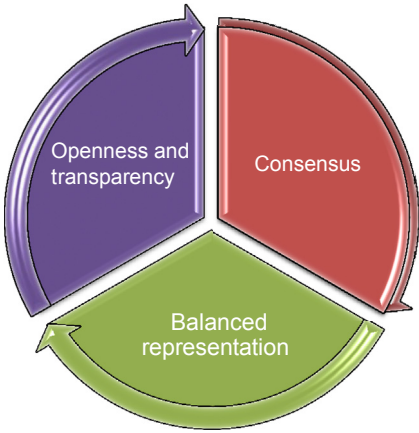


Figure 7.3 Fundamental standardization principles.

that are initiated by external stakeholders. These proposals must demonstrate net benefit and stakeholder support prior to any resource allocation.

7.10.2 Project approval

Projects are selected based on the merit of the proposal, which includes a well-defined scope statement, stakeholder support; and available resources. The NASB Accreditation Committee (NASB-AC) approves and manages a portfolio of projects that match available resources and expected timeframes.

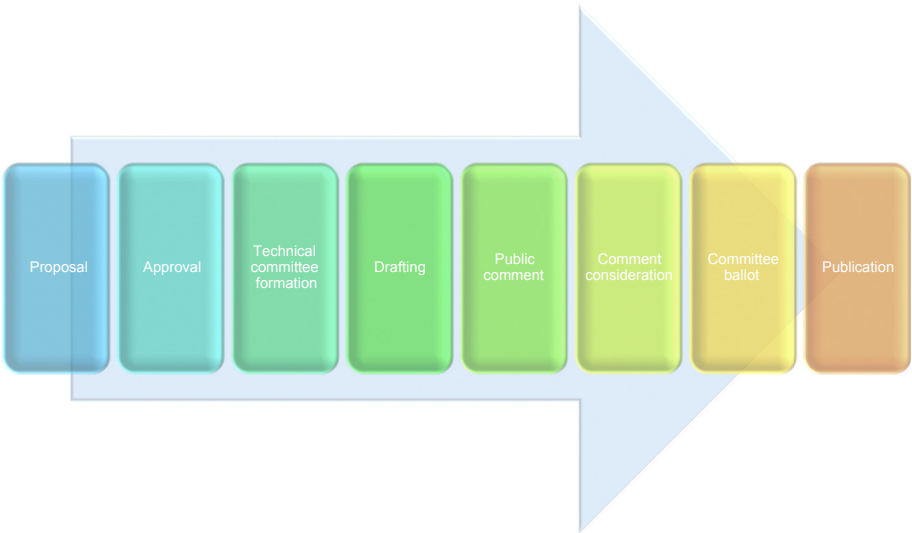


Figure 7.4 Stages of standards development.

7.10.3 Formation of a technical committee

Once a proposal has been approved, it becomes a project that is assigned to a relevant TC. Each TC is led by an appointed chairperson. The chairperson is supported by a project manager (PM), responsible for coordinating the allocated work. The PM also ensures that the draft standard follows the fundamental principles of standardization. Importantly, if no suitable TC exists, the project initiator needs to suggest constitution of new committee and must also demonstrate that the proposal has the support of stakeholders.

7.10.4 Drafting of the standard

Drafting of a new standard could take many months, even years. However, a lot depends on the interplay of the PM and the chairperson. The TC meets to agree to a proposed drafting schedule, to coordinate activities, and most importantly to establish a consensus on the technical content of the draft. A new national standard must only be developed if there is no appropriate international version available. All national standards must not act as a barrier to trade, competition, or innovation. Committees must verify these conditions prior to developing a new national standard.

7.10.5 Public comment

The public comment stage ensures that the broader community has an opportunity to review and comment on the content of a proposed new standard. All draft standards are made available to the public for comment for unusually no less than 9 weeks. For simple adoptions of international standards this period is shortened somewhat to 6 weeks and is also conducted in parallel with the committee ballot process.

7.10.6 Consideration of comment

All comments received from the public are considered usually in detail by the TC. Further drafting is then undertaken to accommodate public comments.

7.10.7 Committee ballot process

The entire TC then votes on the final draft. Importantly, for a standard to reach the publishing stage, the TC must reach consensus on the entire content of the document.

7.10.8 Publication of standard

Final approval of a standard is given by the NASB and the standard is ready for publication. Normal publishing steps are then incorporated and hard copy and electronic versions are produced and made available through the ordinary standards distribution networks.

7.11 Corporate standardization

Jakobs (2017) asserts that corporate standardization occurs for a variety of reasons. Many standards are utilized for human resources and general management purposes (Robbins and Meyer, 2016). The scope of this section is focused to deal with technical standards only. General standardization rules apply in this area. This means that all stakeholders should have an input into the creation of the document. This rule is seldom followed and the consequences are severe, such as lack of buy-in and complete ignorance of the document according to Swann (2000). Stadtler (2015) explains that such a situation often results in serious disagreements, disrupting the supply chain and sometimes even an expensive litigation follows. As a result, it is recommended that internal standardization activities are carried out with the same diligence that national or international standards creation would demand (De Vries, 2013). Four examples are provided to illustrate the variety of perspectives that could be encompassed by corporate technical standardization activities.

7.12 Material example

This example is shown as it is a brief document and the topic is especially relevant for the enclosure and housing segments of the industry. Polycarbonate has been preferred by companies for a long time either as a neat (pure without fillers or additives) material or in some mixture such as PC/ABS.

7.12.1 Scope

This specification covers the requirements for a flame-retardant thermoplastic material based on PC polycarbonate. Injection-molded parts are intended to be general purpose and nonsignificant in appearance. Filled or unfilled grades are permissible, provided the minimum UL requirements under the Section 7.12.2 are complied with.

7.12.2 Specific requirements

7.12.2.1 Color

7T6D027 as per Sabic Lexan 915R. Any alternative color or other materials used must be approved by the company's engineering department.

7.12.2.2 UL minimum requirements

Material must be UL-recognized in the specified color and minimum thickness as listed below. Relative temperature index (RTI): 125 °C.

7.12.2.3 Regrind

In general, 15% max is permissible, but nothing which would affect the UL Listing or the original physical properties as listed in the OEM's supplier data sheets.

7.12.2.4 *Restriction on hazardous substances*

Company specification 7022-0071 applies to these materials.

7.12.2.5 *Qualified materials*

Options are numerous. Supplier must keep the company informed of the initial choice and any subsequent changes during the life of the product. Typical qualified grades that meet this specification are: Lexan 915R as per SABIC Innovative Plastics or company-approved equivalent.

7.12.3 *Potential improvements*

This standard was clearly created internally, with input from one specific supplier. Such a specification is not a standardization and can easily upset the supply chain. First, there is no statement as to the reason for selecting these and only these criteria. Such a reasoning should be shared with potential suppliers, engineering, procurement, and senior management staff.

The specification starts with stating color requirements. There should be a logical priority list in a standard; this follows neither an alphabetical nor a logical order. Not a format that should be copied. It is all right to have a specific agency approval in mind, but it is highly unlikely that there are no other equivalent standards around the globe. This instrument is silent about those. Not very helpful from a global supply chain perspective.

Plastics engineers love to discuss regrind levels. However, this is not very helpful and it is nearly impossible to enforce such a statement. Regrind levels tell the reader that the creator of this standard has not invited injection molders to participate in the development of this instrument.

Sustainability issues also get a very cursory treatment. Furthermore, the reader is asked to secure another document, which is a typical way for standardization bodies to get more revenues. In a short standard like this there is ample room to recite the important clauses of the other document. However, it is a good practice to refer to other standard so that in case the underlying principles are updated, there is no cascading effect to many other documents. So, from this point of view this short standard is well written.

Under qualified material everything is in plural, which betrays its good intent of citing at least two or more materials. Yet, there is only a single grade offered. This practice is completely unacceptable. Overall, standards like this must be rewritten with qualified input from all stakeholders. Writing standards is time-consuming, and if it is done incorrectly, it costs much more than corporate resources. It will tarnish the reputation of the initiating organization. Therefore, it is recommended that good standardization practices are followed.

7.13 Mechanical example

7.13.1 Scope

This specification describes the procedure and rationale for the creation of mechanical engineering drawings and 3D CAD (computer aided design) files that define and specify components or assemblies that are purchased by the company (Co).

The document is applicable to permanent staff and mechanical design engineers of the company. External engineers or companies contracted to design parts for Co. Any other division within the Corporation delegated or commissioned by the “design-control” function of Co to design parts or assemblies for use in company’s products.

7.13.2 Significance statement

The written specification, the drawing or the 3D CAD file which defines what Co purchases is our *legal* contract with the supplier. It is the *most* important form of communication. Errors within these documents, later discovered when the product is in production, can sometimes *never* be rectified without great cost and schedule implications to Co. In more extreme cases, unreliable products, shipped to the marketplace, caused by poor design or poor specification cause a loss of customer base.

Before engineering release, only a qualified mechanical engineer, who has verified the design and checked the manufacturability (to the required tolerances) and availability of the part (or process), shall endorse the document. Where electrical specification notes are called-up within the mechanical drawing, these shall be verified by the cognizant electrical engineer.

7.13.3 Requirements documentation and files

A complete and comprehensive definition of our requirements must be made available to the chosen supplier. The structure is as follows.

7.13.3.1 2D “control” drawing

This document is the main control and “pointer” to all the sources of information: the supplier will need to manufacture, assemble, and inspect the part to company’s satisfaction. Initial sample inspection report (ISIR) outlines the contractual obligations with specific regard to part quality and design ownership (to company), which the supplier must meet. Our drawings and specifications, which accompany the purchase order must *never* be on supplier’s headed paper. Except for standard “off-the-shelf” commercial items, modified commercial items, catalogued electrical connectors, fasteners, and others, the design belongs to Co.

7.13.3.2 Typical content of the control drawing

The following list displays the typical content of a control drawing:

- A statement that the 3D file takes precedence
- The name and location of the 3D CAD file

- The material and any regulatory such as UL listing requirements
- Amount of regrind permissible for plastics
- Part marking requirements and location:
 - Recycling materials identifier
 - 10-digit part number for which the last two digits must be changeable
 - Date clock for injection molded plastics
- The appearance-significant surfaces with texture specifications, location of gates and ejector pins, and other tool-related information for plastics parts
- Terms and conditions of tooling, default tolerances not to be shown on the 2D drawing and part qualification
- With assembly drawings, a table with item number, description, and number-off per subcomponent
- The location and file number of an artwork, or graphic if the part is to be printed
- Only those dimensions to be inspected for part qualification should be shown on the 2D control drawing
- A statement that RoHS (restriction on hazardous substances) specification applies
- Sufficient 2D views sometimes an isometric of the part to:
 - Make it easily recognizable to procurement staff
 - Show the minimum number of inspection dimensions and set-up datums as deemed necessary by the design engineer to qualify the part

Note that in most cases the 2D control drawing should *not* be a fully dimensioned drawing.

7.13.3.3 Datum and tolerances

ISIR pass or fail criterion' datum dimensioning should be employed to avoid any misinterpretation. Since Co uses global sourcing policies, the datum principles outlined in any of the following standards are acceptable:

- ISO 1101
- ASME Y14.5M, ANSI Y14.5 82M, or ASTM Y14.5 96M GD&T
- BS 8888 or BS 308: parts 1, 2, and 3

The underlying objective is for the design engineer to attempt unambiguous communication with any anonymous-remote tooling engineer or inspection facility with whom our business is placed. Datums are chosen to communicate the functionality of the part, whilst at the same time allowing practical, simple setup on any coordinate measuring machine. Careful thought must be exercised by the design engineer with every tolerance dimension added to the 2D control drawing. Tolerances should be as wide as possible, while still retaining the functionality of the part.

Widespread and lethargic use of tolerances without thought to the absolute use of the part must be discouraged. Corrections, later to specifications, to match acceptable ISIRs cost serious use of precious resource. "Right-first-time" is the objective. The thought process should be:

- Do I need the tolerance?
- Can I get it? Is it achievable?

7.13.3.4 Creation source and format

The 2D control drawing must originate from the 3D CAD model. Sometimes, for rationalization purposes, dependent on the manufacturing process, the dimension on the 2D control drawing will *not* absolutely equal the 3D “perfect” file dimension. For instance, a 3D modeled size of 6.97 may be rounded off to 7.0 on the 2D control drawing. This is typical for sheet metal parts and is left to the discretion of the designer, provided the tolerance called-for encompasses the as-modeled 3D dimension. Final file format passed out to suppliers and stored on electronic files accessible to procurement and quality assurance (QA) staff must be in Adobe Acrobat, that is, pdf file format.

7.13.3.5 Assembly drawings

Each assembled part should show a leader, which refers to a sequential item that is numbered 1, 2, 3, and so on. The item number should be in a circle. A table should be included to define each subcomponent clearly and the quantity required. Where the supplier is to source the assembled subcomponent, and no Co specification exists, a comprehensive description of that component must be supplied. An example is furnished in [Table 7.1](#).

7.13.3.6 Drawing number

The number of the drawing shall equal the part number allocated under the item creation note (ICN) system, currently in place within the engineering data center at Co. These follow a class-code system, and are all a 3000-series number. The part number is a 10-digit number shown as follows: **3XXX XXXX XX**.

7.13.3.7 Title policy

Titles on 2D control drawings shall never include the product names announced in the marketplace for the product. The title of the drawing shall *not* exceed 26 characters

Table 7.1 Assembly drawing description

Item No.	Co document	Description	Qty.	CAD file name
1	3871-0452-04	Molding, Front Cover, Sz7	1	3871-0452_Mld_Frnt
2	—	Screw, Torx-Head; M8x12; Steel Property Class 8.8; Zn. Plate 8 µm; RoHS 7022-0071 applies.	6	M8x12 Torx Screw
—3	7020—9803	Artwork, Elev. Soln.	ref	—
4	6521-9533-06	Plate, Ultrasonic Rivet.	2	6521-9533_Plt_Rvt

RoHS, restriction on hazardous substances.

including spaces. Naming policy should normally be a noun followed by a descriptor if necessary, for instance: “Molding, Support, Size1” or “Plate, Support, Rear, Sz6” Assembly Drawings should begin with the word “Assembly,” for instance, “Assembly, Enclosure, 240V.”

7.13.4 3D model

This file is an absolute perfect representation of the part in 3D and in its mid-tolerance condition or intended interference. In the case of plastic parts or pressure die-castings, it contains all the draft angles necessary to eject the part from the mold or die. With many toolmaking CAE packages, the tool designer will use this file to make the tool cavity or punch.

Mechanical engineering designer must have knowledge of and apply sufficient clearance for the production process chosen for the part. The range of processes, covered in the manufacturing of company’s parts, is too wide and diverse to cover in this document.

7.13.4.1 Clearance allowance

Clearance information must be stated, for instance: plastic part “A” must fit into plastic part “B.” On the master assembly CAD model, sufficient clearance between A and B must be accommodated to allow for manufacturing tolerances due to:

- toolmaking tolerances,
- shrinkage and warpage, which is dependent on polymer and process parameters and shot-to-shot variation.

Critical tolerances need to be agreed with and called-up on the 2D control drawing. Default tolerances for dimensions *not* called-up on the 2D control drawing need also be allowed for. These are referred to in the tooling terms and conditions.

7.13.4.2 Format

3D models must be constructed using CAD and its version number. Subsequent updates will be communicated by company.

7.13.5 Material specifications and supporting documentation

7.13.5.1 7000-XXXX series documents

To support the need for standardization of materials, processes, regulatory requirements, supplier contractual obligations, primarily with respect to tooling, and qualification procedures, a set of 7000-XXXX series pdf files need to support and be called-up within the 3XXX-XXXX-XX; 2D control drawing, which forms the basis of the supplier deliverables. Where no 7000-series specification exists maybe some new process or material, then this needs to be created within the notes on the 2D control drawing.

7.13.5.2 Typical 7000-series documents

The following list exhibits a few 7000-series document titles:

- 7022-0017, PC/ABS; Pale-Gray
- 7022-0016, Terms and Conditions; Tooling, Thermoplastic parts
- 7022-0071, RoHS Compliance requirements
- 7022-0061, Lubricant, Tin-lead Electrical Contacts

7.13.6 Specification: written construction guidelines

The specification for a material or process should always be written to capture the overall minimum engineering requirements, which are important to the design or functionality of the part. Where possible, the specification should never point to a single-process or single-source-of-material. The supplier who reads the company's specifications must be under no illusions that the engineering team consider this process or material to be the only one, which can fulfill the needs of the design. The design engineer, during the development stages of the project, is the best person to capture these minimum basic needs. The company's purchasing teams must have the widest possible freedom to source the part. Following a statement of the minimum engineering or physical properties requirements, the specification should give the purchasing authority a selection of "qualified or approved sources" which meet the specification but always finish with the words "or Company approved equivalent." Where only one supplier can currently meet the specification, the rider should still always be added "or Company approved equivalent."

7.14 Heat sink example

7.14.1 Scope

This document outlines our requirements with respect to the content and amount of information company require with the quotation for the provision of extrusion tooling and machining for aluminum heat sinks. Terms and conditions are to be read in conjunction with company's standard terms of supply. This document will take precedence where any conflicts occur.

7.14.2 General conditions

The tools and tool drawings will become and remain the property of company when the final payment is made. The "tools" include all jigs and fixtures, trim tools and casting dies required to manufacture the final part.

In cases where the supplier wishes to maintain the tooling over the life of the product, definitive plans need to be submitted to company to ensure supply continuity.

Potential suppliers who tender for these parts need to return a signed quotation.

The "Acknowledgement of Order" with the chosen supplier needs to repeat the supplier's acceptance to the company's relevant standard or list each of the exclusions agreed to by company at the quotation and negotiation stages.

In any dispute, “Contract-Law” of the local jurisdiction applies.

On tools of our ownership, should we wish to move the tools for any reason, these will be made available by the supplier or extruder for removal upon a minimum of 48-h notice. Any outstanding moneys, parts, or materials against which company has made a commitment will be settled in a manner mutually agreed by both parties.

Tools of our ownership should also be clearly marked “Property of Company.”

7.14.3 Tool and part design and manufacture integrity

The supervision and control of the tool designers and the toolmakers to supply a quality product is the prime responsibility of the part supplier, whether it be machinist or extruder, not his subcontractors. These responsibilities include fitness for purpose, minimum extrusion distortion, final machining operations such as surface flatness and hole tolerances produced as agreed and agreed quality of flash-trim, and stains or blemishes on any agreed appearance surfaces. It is also the supplier’s responsibility to assess the part design at the outset and provide a written commitment on tool life.

Current CAD system at company is CAD type and version. The extruder and machinist shall confirm their ability to receive, interpret, and work with 3D dimensionless files and 2D control drawing from this system, assuming responsibility for any CAD conversion errors in the design of the tools should they use alternatives to design the tools and produce the finished part.

The 2D control drawings are supplied by company to outline critical tolerances, significant surfaces, and material primarily for inspection purposes such as ISIR.

Dimensions or tolerances *not* shown on the 2D drawing default to the 3D CAD model. Unless otherwise stated these are listed in [Table 7.2](#).

7.14.4 Schedule integrity

The supervision and control of the tool manufacture and design, final extrusion, post-machining, and schedule commitments remain the prime responsibility of the heat sink end-supplier. A comprehensive plan including people, time, activities-breakdown, resources, materials preferably in Microsoft Project with measurable benchmarks shall also be supplied no later than the date the order is to be placed.

Table 7.2 General quality tolerances

From (mm)	To (mm)	Tolerance (mm)
0	10	±0.25
10+	80	±0.35
80+	150	±0.45
150+	300	±0.55
300+	400	±0.65

The supplier should note that the tool payment will not be made until the written plan with the specified content is received by company.

If tooling-resource “window” forecasting is a problem in estimating schedules, the supplier should assume that the initial tool and part order will reach him, 4 weeks after the quote. This assumption should be clearly listed in the quote.

If the tool order is to be placed later than this, company shall recheck the tooling “window” available with the supplier.

During the progress of the tooling and initial extrusion trials, the supplier must agree to supply to company written updates via email in time intervals not exceeding 1-week periods that the tooling and trials are still on target to meet agreed plans. The reports must establish recovery plans for slips that may have occurred in the intervening time between submissions.

With high fin-to-gap ratio heat sinks, submitted plans shall include a risk assessment of die failure. With such high-risk dies, schedules shall show recovery plans with “backup” dies.

7.14.5 Tooling quote integrity

Unless otherwise agreed, tooling expenditure will be as follows: 50% with initial order and 50% on sample delivery with associated ISIR.

With the quote, company needs to receive the following items in the cost breakdown of the total tooling quote:

- The tool manufacture cost.
- The estimated tool life and the cost for ongoing tool maintenance. These costs must include the submission of quarterly tool condition reports to company.
- The cost of all auxiliary tooling.

The following items need also to be included in the total tool pricing, but not necessarily shown as separate line-items:

- Sampling costs. The costs to provide a minimum of 5 m of samples at each change and resampling stage. These samples must include an extrusion with final machining operations complete. Costs must also include all initial sample inspection results (ISIR).
- All tool insurance costs and storage at the extruder premises, shipment, and others.

On placement of a written order, the agreed price will be the fixed and final price. In the event of any design change or any other additional costs incurred, these costs must be agreed in writing with company before any liability is implied or accepted for any additional cost or change to the project time scale.

In way of further definition regarding tool design changes discovered by the supplier or his subcontractors after the order has been placed, company will not accept responsibility for charges which arise due to a “extrudability” issues.

Examples of these are changes requested to alter wall thickness, add radii, special-jig costs to correct distortion, part cost increases to machine some feature not identified in the original quote, and others unless these specific areas on the part geometry are referred and agreed to in the initial tender.

Part cost quotations and assumptions from the supplier, that is, the extruder shall accompany each quote. Costs and assumptions need to be broken down as follows:

- Assumed extrusion weight usually given by company from the CAD file.
- Base material cost per ton of material and state exact country-specific grade and standard.
- Amount of scrap assumed.
- Cost of any trimming and deflashing.
- Cost of machining features, each feature to be itemized separately.
- If applicable, any other finishing process.
- Shipment packaging costs and define proposed method.

On tools of our ownership, the tool general arrangement (GA) drawings must be viewed and agreed by company prior to work commencing on the tooling.

Tools shall be maintained during their normal useful life at the part supplier's expense. The part supplier will take all reasonable care in maintenance and use, during the agreed lifespan of the tooling. The part supplier or extruder will insure the tooling held on his premises against a total loss, for the full value of the tooling.

The mutually agreed lifespan of the tooling shall be a prime requirement of the tooling quote before company become responsible for any repair or renewal costs. The final negotiated figure must be communicated in writing to company.

7.14.6 *Payment terms*

Unless otherwise agreed, payment terms are as follows:

- Tooling cost will be covered by paying 50% with initial order followed with the remaining 50% on receipt of agreed samples and ISIR. Any part cost payment will be made once initial sample quantities have been received along with inspection data (ISIR).
- Samples must be of sufficient quality to allow the qualification process to begin. In this context, all the geometrical features on the 3D CAD model must be present to allow assembly of electronic components and mating parts.
- No severe voids will be permissible. Dimensions out with tolerance and degree of distortion permissible for the first-design-verification build will depend on the "usability" of samples.

7.15 Tool example

7.15.1 *Scope and purpose*

This document outlines specific requirements regarding the design, manufacture, and supply of mold tooling for thermoplastic and rubber components produced by the injection-molding process. This document is intended for tooling orders placed directly with toolmakers or companies who manage and supply injection mold tooling.

The primary purpose of this document is to ensure:

- Tool orders placed direct with external toolmaking facilities yield quality parts to specification.
- All suppliers, being asked to quote, are notified “up-front” of the company’s complete set of requirements.
- Tools fit available at mold manufacturing presses and equipment available at company’s qualified mold shop.
- Avoid possible communication errors, where tool orders are placed independently of the trade molder.
- Stress the importance of functionality and schedule.
- Reach agreement on tool guarantees and tool maintenance, where usage is remote from the toolmaker.

The overall requirements are based around quality tool standards within the industry. The requirements of the document are the default condition but need to be read in conjunction with any commercial agreement negotiated for any specific project.

Excluded from the scope are injection mold tools produced from aluminum, tools for gas-assist technology, in-mold-decoration, powder injection, or co-injection technology.

Note that this document assumes that the company will place tool orders through qualified mold shops.

7.15.2 General requirements

The tools, tool drawings, 3D CAD files, specifications, and electrodes made to manufacture the tool will become and remain the property of the company once final payment is made.

These terms and conditions will accompany the initial request-for-quotation (RFQ) and subsequent tool orders from company. No subsequent “Acknowledgement of Order” or small print modifications received from the supplier shall override these conditions.

In any dispute, “Contract-Law” of local jurisdiction applies.

In the unlikely event, that company needs to interrupt or halt the tool manufacture for any reason, the completed portions of the project will be made available for removal on payment for all completed portions. Under these circumstances, company will reach a mutually agreeable settlement for payment of all outstanding moneys, incurred by the tooling supplier, related to design work, parts or materials already purchased and labor costs already expended.

Each tool shall be clearly marked with the following data in English:

- “This Mold is the Property of Company”
- Part description: from 2D control drawing
- Part number(s): first eight digits only extracted from 2D control drawing
- Shot weight in grams: per part
- Number of impressions
- Injection or runner system type: for example; hot runner system

- Max ejector stroke (mm)
- Mold dimensions (mm): length, width, depth
- Total mold weight (kg)
- Date of manufacture: should be the expected month and year of first mold trials
- Manufactured by including the toolmaker's logo

7.15.3 Function

The tooling supplier shall accept responsibility for the tooling in terms of fitness for purpose and the ability of the tool to mold the part as specified.

Prior to the start of tool design, tool supplier shall obtain for each part the particulars of the intended mold press from the company's qualified molder. If valve gates, hot runner systems, or other special equipment are required from the tool design, checks must be made to ensure the molder has the necessary controllers, accessories, and other equipment for the types chosen.

Tool designer shall work only to the specific grade or grades of polymer called-up on the company part specification. Special attention must be paid to the flame-retardant chemistry. Tool designer shall obtain these data sheets and processing information direct from the polymer manufacturer. Design of the cavity, gates, and runners to generic-polymer information held within certain plastic flow analysis programs is not permissible, unless specifically checked against the specific grade called-up in the company design specification.

Unless otherwise agreed plastics flow analysis is required on all parts. Complex parts also require distortion and warpage analysis. All analysis results to be submitted to company.

Company's enclosure designs are UL strength critical. Tooling designer shall use shear rates to size gates. Shear rate limits for flame-retardant polymers are of prime importance in the nozzles. Highest volumetric flow rate, which the molder may apply, shall be considered. Tool designer shall consult polymer supplier for onset shear rates reliance on standard limits given in-flow analysis programs are not permissible.

There are two major considerations:

- Reduction in IZOD impact strength due to high shear. Company may require checks for molecular degradation in finished moldings. In general, increases in melt volume rate from virgin material, which exceeds 10%–15%, is not permissible.
- High values of shear are associated with gate blush. On appearance-significant parts, shear rates should be limited to 70% of the onset shear rate. All analyses, polymer supplier values, and calculations are to be submitted to company prior to finalizing design of gates.

Choice of plastic mold steel will reflect the type of part to be molded and should be agreed with company. [Table 7.3](#) summarizes various requirements and demands to be considered, with respect to the steel properties and considers the different situations in which tools are used:

Mold steel specifications vary worldwide. Details must be provided in the quote. Tool life with adequate maintenance and proper use, materials, parts, and technologies chosen for the construction shall yield at least the production quantities listed in [Table 7.4](#).

Table 7.3 Steel properties

Toolmaker	Molder
• Machinability • Spark erosion • Polish ability • Photo and chemical etching • Dimensional stability • Quality of goods	• Tool life • Wear resistance • Corrosion resistance • Surface quality • Hardness, toughness • Thermal conductivity

Table 7.4 Tool life expectancy

Material	Production quantity (moldings per cavity)
Unfilled, halogen-free, flame-retardant thermoplastics	600,000
Filled (glass-reinforced) flame-retardant thermoplastics	300,000
Elastomeric and rubber	600,000

Dependent on the application and annual part quantities, company may consider its competitive edge in the use of certain high-conductivity alloys where the return-on-investment is justified. Toolmaker should incorporate these options in the quote, if the benefits can be justified by, for instance:

- Faster cycle times
- Uniform mold temperature thereby limiting distortion on complex parts
- Better part quality
- Low maintenance cooling channels

Manufacture of the tool shall not proceed until the GA, tool steels, materials, ejection system, nozzle ring, gates, and runner system have been approved by company and its qualified molder.

For uniformity of appearance across various global products texture on tools shall employ Mold-Tech or equivalent specifications and technologies. Actual MT number on appearance-significant surfaces will be called-up on the 2D control drawing, or part specification.

In all circumstances, company’s 3D files, 2D control drawings, and specifications define the final requirements for the part. “Checking” drawings or “requirements-verification” drawings returned by the prospective supplier on their headed paper or internal work sheets will be acknowledged as “received only,” that is, the accountability for the accurate production of the part, to specification remains the responsibility of the tooling supplier. Company retains part design rights.

The structure of company’s information part transfer consists of a 3D CAD file and a 2D control drawing. The 3D file is a “perfect” representation of the part, usually at its mid-tolerance condition as considered by the company’s design engineers.

Table 7.5 General tool tolerances

From (mm)	To (mm)	Tolerance (mm)
0	10	±0.25
10+	80	±0.35
80+	150	±0.45
150+	300	±0.55
300+	400	±0.65

The 2D control drawing is a 10-digit part number which points to the 3D file and conveys critical tolerances, datums, significant surfaces, material specifications, and other information, which need to be submitted on the ISIR. This drawing has a limited number of tolerance dimensions. Dimensions *not* shown on the 2D drawing automatically default to the 3D CAD model. Unless otherwise stated, applicable tolerances are listed in [Table 7.5](#).

Welding of tools is not permissible, without prior written consent from company.

7.15.4 Schedule

Toolmakers shall understand the importance of making a commitment. Secondary only to functionality, company considers the toolmaker’s ability in planning skills as uppermost. Normally this will be the subject of “due-diligence” survey at the toolmaker’s premises to absorb the design, manufacturing, and tool qualification procedures in-place to control and monitor progress.

Toolmaker shall provide a project manager, able to provide daily support during the project. Project manager must be able to speak English and provide response to emails within 24 h.

A published, detailed schedule with measurable benchmarks shall be supplied. This deliverable is a necessary requirement before the first portion of tool payments is made. During the initial quotation stage, if available resource “window” fluctuations are a problem, the toolmaker shall assume that the tool order would reach him, 4 weeks maximum after the initial quotation was furnished. If the order is provided later than this, company shall recheck the tooling “window” available with the toolmaker.

Matched CAD systems between the part designer and tool designer are a distinct bonus on time-critical programs. Concurrent engineering and simultaneous engineering as the tool design enters the optimization stages will yield high probability of “right-first-time.” In this context, preference will be given to those tool design facilities using an approved 3D CAD system. If possible, modification requests by the tool designer back to company should be the modified 3D part. This modification can be checked by company’s engineers on the master-product-assembly-model, saving new product development time in the process.

Project manager shall undertake to update progress of tooling plan every 7 days and inform company. Preferred arrangement is that company has access, via password, to the toolmakers website to check progress of the published plan and other project management documents. Toolmaker's plan shall also list the assumptions and timings beyond the first stage. Distinct external dependencies, which need to be communicated in a timely manner, are the following:

- Sufficient polymer quantity and source for trials plus any preproduction runs required by company. This is important as lead time for flame-retardant color-compounded resin can be up to 16 weeks.
- Equipment, facility, and staff availability to do the ISIRs.
- Where inserts or special fasteners are used, agreement with the trade molders on the preferred source.
- The availability of any special ultrasonic-horns, should welding be required in the part design.
- Agreement with company or the trade molder on the delivery of surface-printed parts.
- Company engineering staff for parts approval on site or remotely.
- Trade molder staff for tool acceptance trials.
- Tool shipment, insurance, and packaging method.

7.15.5 Quotation integrity and completeness

Tool quotes shall include breakdowns and definitions to preserve quotation integrity and completeness. This includes a comprehensive description of the tool. This is mandatory, since the functionality, quality, and final cost of injection-molded parts are determined by a complex coupling between polymer properties, mold geometry, and process dynamics. Toolmakers able to contribute optional tooling approaches and offering various trade-offs will be given preference from a technology perspective. For cost-effective tool design proposals company's purchasing teams shall indicate on the tooling RFQ the anticipated part volumes and product life.

Minimum tooling definitions must include:

The gating system including number and location of feeds, hot or cold runner, hot bush, hot tip or valve gate, and other pertinent features of the tool.

The exact make of the hot runner system or valve gate if recommended.

Type of ejection: conventional pin, hydraulic and if the injection-side is being quoted.

Side cores and lifters: mechanical cams or hydraulics.

Source of standard tooling parts: DME, Hasco, or other ejector pins, moving cams, frames, and for other parts.

Number of cavities.

Mold steel and the international standard complied with AISI, DIN, JIS, or others and finished hardness. A breakdown defining which elements of the tool are being referred to shall also to be detailed in the quote as per [Table 7.6](#).

Company reserves the right to demand the source and trade name, with certificates-of-conformance (COCs) for the purchased tool steels. Where heat treatment or nitriding is also under consideration, COCs must also be allowed for.

Concurrence with this specification or list the noncompliance aspects.

Table 7.6 Tool hardness

Part	DIN	AISI
Cavity	1.2738HH	Prehardened HRC 36/38
Core	1.2738HH	Prehardened HRC 36/38
Inserts	1.2343	Hardened HRC 48/52
Side cores	1.2343	Hardened HRC 48/52
Cavity and core plates	1.2312	HRC 30/33
Frame (bolster)	1.1730	

Tool design costs and the time allocation in working days to design the tool. If a suite of tools is involved, relative to a single RFQ, quotation of total time for all tools is necessary. This may only be necessary on projects, where the company internal degree of part design uncertainty is high and several options are considered.

Time input and output parameters of plastics-flow-analysis need to be included in the quotation.

Minimum of five samples at each change and resampling stage from the first (T1) to the last, that is, third (T3).

All initial sample inspection results (ISIR) together with the mold-set parameters under which the samples were obtained to produce all dimensions within tolerances on the 2D control drawing.

The cost of shipment by courier air-mail express of the samples.

Tool marking costs must also be included.

Tool shipment costs shall include all electrodes manufactured to produce the tool. Under certain circumstances, company may employ one of its shipping agents to perform this task; however, quotes for shipment shall still be submitted as a separate line-item on the initial quotation.

The supply of all tool drawings in 3D CAD, all material specification, and associated 2D or 3D details to manufacture the tools. This must be a complete set of information capable of replicating the tool at any future date. This CAD file or package must incorporate all changes during the tool development phase and reflect the tool status at the point of shipment to the company-designated molder.

The cost of chemical etches to company specification. Where this cost is not available at the time of the initial quote, an estimate, based on current experience, should be supplied. Under certain circumstances, with less-appearance-significant parts, and on small surface areas, company may accept a spark-finish approximation to the texture specification. This is dependent on appearance plaques and the lifetime durability guarantee remaining in place.

On placement of a written order for new tools, the agreed price will be the fixed and final price. In the event of any design change or any other additional costs incurred, these costs must be agreed in writing by company prior to any liability is implied or accepted. In way of further definition regarding changes found to be necessary during the tool trial stages:

Company will not accept responsibility for charges which arise due to issues associated with toolmaker errors, insufficient draft or polishing, addition of “moving-half-snatch-features,” or similar issues.

Unacceptable sink mark correction, extreme distortion, flatness, or weld lines unless these specific areas were identified at the plastics-flow-analysis stage or at the tool GA approval stages.

7.15.6 Qualification

Polymer variations in stabilizers, fillers, pigments, and flame-retardant chemistry can all affect the validity of part qualification. Tooling supplier shall ensure that the identical grade of color-compounded polymers, called-up on the part specification, are used for tool qualification. Alternatives are not permissible. Tool supplier shall also ensure sufficient lead time is allowed for the sourcing and supply of sufficient quantity of resin.

Where inserts or other additional fixed articles are called-up on the part specification, tooling supplier shall agree with company and the trade molder the exact source of supply of identical parts. In these cases, pull-out forces or torsional strength needs to match the overall molded-part qualification.

Pad or silk-screen printed artworks on molded parts will normally be the responsibility of the trade molder.

A requirement of the company is to accurately document a set of process parameters which enables the tool to move from the original press used for tool qualification to the trade molder's press and reproduce the part consistently. Secondary requalification work at the molder's premises must be kept to a minimum. It is accepted that machine screws, screw diameters, stroke length, and hydraulics or electrics can vary between presses. Therefore, process setups must indicate machine definition and a general setup specification for an appropriate modern injection-molding machine.

Molding repeatability is based on four key processing variables:

- Plastic temperature
- Plastic flow rate
- Plastic pressure
- Cooling rate and time

To keep variables to a minimum, where feasible, tool qualification mold shop shall choose a press and a screw-size to be the best possible match to the press-particulars indicated by the production trade molder for the part.

Dimensions to be inspected for the ISIR are on the 2D control drawing. Where necessary, additional checks for suspect dimensions should be taken from the 3D part file. Measurements and cosmetic considerations should be taken 12 h minimum after molding.

7.15.7 Warranties

Unless otherwise specified in the project commercial agreement, tooling supplier shall warrant the tool or tools for the mold-shot delivery life. For each tool, tooling supplier

shall provide a scheduled and systemized mold maintenance program. Company recognizes that to be cost-effective, mold cleaning and detailed inspection must be performed and documented:

- At specified cycle frequencies
- Using specific instructions for varying levels such as in-press, wipe down, general, major
- After troubleshooting mold and part defects
- After repairs have been made
- After any reengraving process which might take place after the tool is shipped

Typical specifics required are:

- Instructions on how and frequency
- Specific zones of tool for visual inspection
- Residue buildup in vented and nonvented areas of tooling
- Plating wear and track marks
- Evidence of plate-out stains for flame-retardant polymers
- Documented observations and records
- In-press servicing procedures and frequencies
- Absolute maximum cycle count before major overhaul
- Grease levels on gear racks, sliding cam blocks, internal pins, bushings, and other critical parts
- Water line and bubbler contamination or blockage
- Manifold seepage
- Rust and corrosion from water leaks or internal condensation

Warranty shall itemize what items of the tool if any are to be excluded. If these include standard purchased items used in the mold industry, sufficient information should be supplied in the tool design documentation to identify source, maker's part number and date of procurement or tool fitting.

Toolmaker shall propose preferred method of "policing" regular maintenance program:

- Periodic inspection reports
- Document submissions
- Photographs
- Appointed representative for inspections

7.15.8 Payment terms

Unless otherwise agreed, tooling payment terms and deliverables are as follows: one-third with tool order and receipt of project plan. The second third within 30 days of receipt of invoice, five samples together with a complete ISIR, and the matching mold setup conditions. Company will *not* begin the approval process without these data. Final third is paid 30 days from receipt of the tool and invoices for the following:

- Final approval of textured samples
- Complete set of tool drawings in 3D and 2D CAD files

- Final tooling sign-off and set of electrodes manufactured to produce the tools
- Electronic copy and detailed schedule of systemized tool maintenance program

In certain time-critical projects, company may request to run small batch, early production moldings at the mold shop used to qualify the fully approved and textured tools. Under these circumstances, final one-third tool payment will be honored on the deliverables. If certain parts require pad or silk-screen printing, remote tooling supplier may need to agree best logistics and print-jig solution to obtain preproduction parts.

7.16 Review

Successful technical standardization is a cornerstone of successful new product development and introduction in the electronic enclosure, housing, and package segments of an industry according to [Kang and Motohashi \(2015\)](#). This chapter provided a short review of the origins and development of standards and the process that produce them, that is, standardization.

First, the use of the word standard was defined in this context and was pointed out that standards are instruments of consistent measurement ([De Vries, 2013](#)). These measurements could take place in many economic transfer dimensions, but this chapter focused on technical aspects exclusively. The interaction of standards and the law was discussed in the conceptual framework of net benefit and stakeholder support.

Four standards development pathways were described in accordance with [Weiss and Cargill \(1992\)](#). These are the NASB, externally funded, association managed, and internationalized versions. Prioritization and selection activities as well as participation in a TC were explicated.

Importantly, stages of a general technical standards development were explained as per [De Vries \(2013\)](#). The process starts with a proposal, which may or may not warrant an approval from the NASB. Assignment of the project to an existing TC or constitution of a new TC was described next. Drafting of any technical standard is an enormous undertaking; however, it must not produce a finished standard, because public comment must be solicited, received, and appropriately dealt with prior to balloting the TC and the ultimate publication of the standard.

This process must always be followed at the various levels that standards are created, including corporate standardization practices ([Jakobs, 2017](#)). Four examples were incorporated to highlight a few of the many possibilities for corporate-level technical standardization. A material, mechanical, heat sink, and a tool example were furnished to complete the review of standardization activities.

7.17 Hot tips

Standardization establishes a “level playing field” for the competition. Therefore, it behooves participants to understand its rules.

- Standards development process is based on three internationally recognized principles: openness and transparency, consensus building, and balanced representation.

- The most important is to exert appropriately indirect influence by mastering the concepts of net benefit and stakeholder support.
- The four development pathways need to be understood to select, recommend, and propose the most fitting approach to solve a standardization issue.
- Understanding and implementing the eight standardization steps are critical at every level including corporate standardization activities.

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8.1 Introduction

This chapter focuses on intellectual property (IP) and it is not to be confused with ingress protection in this handbook's context. Understanding both concepts is critical for the success of an electronic enclosure new product development effort. It is helpful to see standardization as the prerequisite to join the competition (Farrell, 1989) and IP as the unique selling point or sales differentiator (Collier and Iheanacho, 2002). Sales and marketing professionals in addition to the whole school of economics believe that it is this differentiation that allows companies and individuals to earn extra return on their investments in the form of maximized profits according to Hahn (1959). Therefore, Shiva (2001) asserts that it is critical to understand IP from a business perspective as it relates to enclosures, housings, and packages.

Mandel (2011) highlights that fundamentally, IP refers to an intangible asset that is the creation of the human mind. Hence, the use of the word “intellectual” is warranted, emphasize Chisum et al. (2011). Such a creation becomes a property if and when a relevant right in a particular territory is assigned, assert Machlup and Penrose (1950). The importance of these rights is today understood universally, but it was not always so according to Sell (2003). In fact, May and Sell (2006) explain that the concept of intellectual property was recently created. The recognition of IP started during the scientific revolution in the early 18th century. So, the idea that an intellectual output is a property that could be owned, sold, and bought much like any other property has only been practiced for less than half a millennium (Maskus, 2000b; Chon, 2005; Drahos, 2016).

A time-limited monopoly granted in exchange for teaching the public of the underlying idea is the fundamental concept of IP (Easterbrook, 1990; Cornish et al., 1999; Hovenkamp, 2016). Drahos (2016) explicates that this means that once the protection expires, any entity could potentially reproduce the invention. Thus, Gibson (2016) asserts that the entire community benefits. This process was seen as a way to reward inventiveness and foster innovativeness (Dratler, 2017). Etzkowitz and Leydesdorff (2014) highlight a debate about these issues both in academia and industry alike. At any rate, it behooves to grasp these concepts for any practitioner aspiring to be successful in a global market (May, 2013). Generally, IP includes five major categories: copyrights, trademarks, patents, industrial design rights, and trade secrets according to Bently and Sherman (2014). All of which are important from the electronic enclosure, housing, and package perspective. However, four of these categories in Table 8.1 could be compared globally in accordance with Myers (2017).

Importantly, intellectual properties are intangible creations for which a monopoly is granted by law of a geographical entity such as the United States, the UK, or any other

Table 8.1 Comparison of IP categories

	Patents	Copyrights	Trademarks	Trade secrets
Application	Invention of products, designs, and processes.	Creative works.	Designs, phrases, symbols, or words that identify the source of the products or services.	Secret knowledge that provides an advantage for the holder.
Examples	Products features, design, software, and manufacturing processes.	Drawings, recordings, videos, photos, software, websites, writings.	The name of a company, logo, and a phrase that are printed in all company literature.	Secret formulas, manufacturing processes, business information such as list of customers.
Legal rights	Prevents others from manufacturing, utilizing, or selling the invention.	Prevents unauthorized reproduction, distribution, display, performance, and creation of derivative works.	Prevents third parties from utilizing similar trademarks and thereby, prevents mistaken identification of the products or services.	Prevents unauthorized use or dissemination of the trade secret.
Weaknesses	High cost of both registration and enforcement.	Does not prevent third parties from utilizing the underlying ideas or concepts.	Does not protect functional designs.	Does not prevent discovery by “fair means” such as reverse engineering practices.
Registration	Required in all countries.	Registration is not required but has some benefits.	Required in most countries.	No registration is available.
Geographic Limitation	Issuing country only.	Recognized globally but not equivalently.	Country of registration.	Recognized globally.
Duration	10–20 years.	Varies.	Indefinitely.	Indefinitely, or as long as the information is kept secret.

jurisdiction (Moore, 2017; Biagioli et al., 2015; Hart et al., 2013; Granstrand and Holgersson, 2015). Granting of these rights is not terrestrially comprehensive in nature, and this fact creates major issues (Duffy and Hynes, 2016; Grimpe and Hussinger, 2014; David and Halbert, 2015). In other words, there is no universally accepted way of securing global intellectual property rights, and this creates problems in a globally connected commercially aware world according to Ernst (2016).

Generally, Nard et al. (2017) explain that two steps are needed to protect most intellectual property rights. First, the creator or owner must establish the relevant IP rights. This step often involves registration or similar action. Second, the owner must take steps to enforce the acquired rights in case of an infringement.

8.2 A brief history of intellectual property

May and Sell (2006) explain that intellectual property (IP) can trace its origins to the creation of two important laws. The Statute of Monopolies (1624) and Anne (1710) are arguably the origins of patent law and copyright, respectively, within the English-speaking world according to Prager (1944). These two statutes established the modern interpretation of the important concept of intellectual property. The *Monthly Review* used this term first in 1769.

Gallini and Scotchmer (2002) elucidate that the general purpose of intellectual property law was to provide minimal protection to encourage innovation almost always limited in time and scope. The concept's origins can potentially be traced back to Jewish law, which includes several considerations, state Sherman and Bently (1999). Sell and May (2001) explain that the effects are strikingly like those of modern intellectual property laws.

Sell (2003) explains that intellectual property also encompasses trademarks and trade secrets in addition to copyrights and the various patents. Yet, the foundations for intellectual property were laid by the latter two. Hence, a brief historical review must focus on these.

8.2.1 Patents

Historically, patent law was based on custom and common law in England, and importantly not on statute (Pottage, 2010). Mathias (2013) explains that patenting has begun as the Crown granted a de facto time-limited monopoly as a form of an economic incentive primarily to ensure an ever-increasing industrial production. Davies (1934) believes that the first patents were gifts from the Crown. Therefore, patenting was not process based. There were no judicial reviews and oversights. Considerations were lacking and no actual law developed around the idea of patents according to O'Connor (2012).

Practical process originators should have been the guilds. Epstein (2008) explains that they were mandatory associations that held monopolies over industries. Guilds in turn were controlled by the Crown. However, Mokyr (1992) argues that because

English guilds were unable to control industrial production successfully by the 14th-century England's economy was far behind that of the continent.

Klitzke (1959) elucidates that Edward II began to remedy this situation. He encouraged foreign inventors to settle in England, by offering "letters of protection." These protected settlers from irritation caused by the guilds on the condition that they train local apprentices to pass on their knowledge. Hence, the current idea behind patents was born according to Hulme (1896).

The first documented letter of protection was given in the year 1331. The first letters, however, did not grant a full monopoly according to Frumkin (1947). Practically, the protection letters acted much the same way as the EU today, according to Shiva (2001). They allowed foreign workers to live and practice their trade in England with minimal level of harassment.

After 118 years an exception to the rule happened. Klitzke (1959) asserts that a complete monopoly was issued to a fellow named John of Utynam on April 3, 1449. In effect, the letter granted him the first full patent in England. Hulme (1896) underlines that this patent was, however, issued a quarter of a century later than the first issued by the Italian states.

Granting of patents became a common practice in England by the 16th century (Long, 1991). Ruddock (1946) notes that the next milestone was reached in 1537 when Antonio Guidotti, an Italian silk merchant, sent a letter to Henry VIII's private secretary. Guidotti asked Thomas Cromwell's assistance to secure a royal letter of patent protecting the silk monopoly for up to 20 years. Cromwell secured the patent. Henry's son Edward VI continued this habit by granting a patent to Henry Smyth. Smyth claimed the introduction of foreign glass-working techniques according to Davies (1934).

The patenting process continued with Queen Elizabeth. Federico (1929) explains that formal procedures were set out in 1561. These new procedures formalized issuance of patents to new industries. They also allowed the granting of monopolies. The granting of these patents was as popular as it is today due to its almost unlimited potential for raising revenue. Ramsey (1936) advises that a patentee was expected to pay dearly for the patent. This worked much better than raising taxes because disfavor of the public was directed toward the patentee. Hence, Angeles (2011) observes that the government of the day managed to levy a tax without the associated blame.

Over time, the patenting practice became more challenging, according to Mossoff (2000). The original practice of granting temporary monopolies on new industries became distorted and morphed into granting long-term monopolies of common commodities such as salt and starch. Therefore, patenting led to a disagreement between the Crown and the Parliament. After much debate in 1601, it was agreed that the power to administer patents was vested in the common law courts (Dean, 2002). Simultaneously, the Queen revoked some of the most damaging monopolies according to Calabresi and Leibowitz (2013).

However, James I continued to create monopolies by granting patents, explains Boyle (2003). White (1979) explains that under the Chairmanship of Sir Edward Coke, the Committee of Grievances abolished many monopolies due to public pressure. A statute prepared by Coke passed the House on May 12, 1621, but was defeated

by the House of Lords. However, [Kyle \(1998\)](#) writes that the Statute of Monopolies, 3 years later on May 25, 1624, was passed by the Parliament. Thus, the age of modern patenting has started, according to [Nard \(2014\)](#).

8.2.2 Copyrights

[Patterson \(1968\)](#) explains that the exclusive right to print and censorship responsibility of literary works rested with the guild of printers named the Stationers' Company in England. Copying restrictions were in place since 1662, which were established by the Licensing of the Press Act ([Griffin, 1999](#)). Importantly, the Act was not permanent and it had to be renewed biannually ([Holdsworth, 1920](#)). As part of the guild's responsibility the Stationers' Company enforced the Licensing of the Press Act ([Patterson, 2002](#)).

However, [Feather \(2006\)](#) argues that censorship administered by the Stationers' Company led to public unrest instigated by some of the affected authors. [Holdsworth \(1920\)](#) explicates that these authors and their supporters sought to prevent the Act's reauthorization ([Bettig, 1992](#)). [Hughes \(2009\)](#) explains that this campaign culminated in the Parliament's refusal to renew the Licensing Act in 1694. Thereby, the Parliament effectively ended the Stationers' monopoly and press restrictions.

During the next decade, the Stationers' Company supported the introduction of many reauthorization bills, but Parliament failed to enact them. This apparent failure prompted the Stationers' Company to advocate licensing authors rather than publishers. In this new format Parliament considered the bill and added substantial amendments. [Feather \(1980\)](#) explains that ultimately, in the year of 1710 the British Parliament passed the Statute of Anne. Subsequently, Royal Assent was granted on April 5. This bill became known as the Statute of Anne simply because it was passed during the reign of Queen Anne. However, the law is also known as the Copyright Act 1710. This was the first statute to incorporate copyright regulation into the government domain so that judicial bodies, instead of private parties, would regulate conduct of this field, according to [Joyce et al. \(2016\)](#).

The Act prescribed a copyright term of 14 years. In addition, it incorporated a provision for renewal for a further 14-years term. This meant that only the author and their chosen printers were allowed to publish the author's creations during the stipulated period ([Feather, 1987](#)). This statute successfully transformed the publishers' private law copyright practice into a public law grant system. Once enacted, copyright belonged to the authors rather than to the publishers. Statute of Anne also influenced development of copyright laws in several other nations and thereby established the utilitarian underpinnings of the international concept of copyright law, according to [Litman \(1986\)](#).

After 28 years, all possibility of copyright protection would expire in accordance with the Statute of Anne ([Feather, 1987](#)). Therefore, the previously protected material would become part of the public domain. [Patterson \(1965\)](#) argues that this fact prompted a period of instability known by historians as the Battle of the Booksellers. Despite some challenges the Statute of Anne remained in force until 1842 when the next Copyright Act replaced it.

8.3 Objectives

Idris (2003) states that with the one notable exception of trademarks, the objective of intellectual property (IP) law is to encourage economic progress. Drahos (2016) explains that IP law does this by facilitating an exchange of temporally limited exclusive rights for complete disclosure of inventions and creative works. Hence, society and the right holder mutually profit (Stiglitz, 2007). Thereby, inventors and authors supposed to be incentivized for the continued creation and disclosure of their work according to Besen and Raskind (1991). Hovell (1982) points out a serious shortcoming of this logic that right holder benefits while the inventors and authors can rarely hold onto their rights. Beall (2012) believes that the IP system is broken and cites as evidence the author who gives away her copyrights to her publisher in exchange for a miniscule potential royalty payment, or the inventor who transfers her patent to her employer in exchange for a low salary and the hope of continued employment as an example provided by Merges (1999). Samuelson (1987) worries that the invention could be so important that the right holder will benefit throughout the protection period while the employee has long since been made redundant. However, Drahos (2016) points out that economic progress was made in the process albeit without fairness.

Generally large corporate entities benefit from this system the most (Demsetz, 1974; Hettinger, 1989; Griffith et al., 2014; Moore, 2017). May and Cooper (2017) assert that the benefactors desire absolute protection. However, they also argue that IP is desirable because it encourages innovation and creativity. Therefore, more extensive the IP protection should equate to increased progress. The stated logic is that creators' incentivization will be inadequate unless the probability of a full value capture is facilitated. Therefore, Hughes (1988) and Helpman (1992) argue that the absolute protection for full value concept equates intellectual property with real property to allow adoption of its laws and ideological stance.

8.3.1 Financial incentivization

Granting of exclusive IP rights afford protection that in turn allow owners to benefit from a property they have acquired (Shavell and Van Ypersele, 2001). Thus, exclusive rights provide a financial incentive. Chang (2001) asserts that the debate is not about the incentivization but its intended purpose. Goldfarb and Henrekson (2003) observe that protection allows investment in IP and recovery development costs and associated profits. Profitability confuses advocates of reasonable justification theories (Lemley, 2004; Fisher, 2001; Hettinger, 1989; Hughes, 1988).

Park and Ginarte (1997) highlight that estimating IP's contribution to economic progress is a difficult predicament. The United States Patent and Trademark Office (USPTO), however, issued an approximation that the worth of IP to the US economy was slightly more than \$5 trillion according to Leydesdorff et al. (2014). Further, the USPTO estimated that an additional 18 million American jobs were created in 2013 because of IP investments. The European Union (EU) and the United Kingdom

have furnished similar figures. Yet the UK Intellectual Property Office made a statement, explain [Mhiripiri and Chari \(2017\)](#) that:

There are millions of intangible business assets whose value is either not being leveraged at all, or only being leveraged inadvertently.

Thereby, substantially undermining credibility of the financial motive theory and thus support for exclusive IP rights ([Nard et al., 2017](#)).

8.3.2 Increased economic growth

[May \(2006\)](#) elucidates that protection of IP rights is essential to maintaining economic growth and was enshrined in the World Intellectual Property Organization (WIPO) treaty and other related international agreements. According to the WIPO Intellectual Property Handbook, there are two objectives for the manifested IP laws:

- First, to assert the economic and moral rights of creators.
- Second, to promote creativity.

The WIPO emphasizes dissemination and application of IP to encourage fair trading ([Drahos, 2002](#)). The WIPO asserts that this would contribute to social and economic development according to [De Beer \(2009\)](#). [McManis \(2009\)](#) emphasizes that the Anti-Counterfeiting Trade Agreement (ACTA) states that

effective enforcement of intellectual property rights is critical to sustaining economic growth across all industries and globally.

[Castellaneta et al. \(2017\)](#) estimate that two-2/ of the value of corporate businesses can be attributed to IP assets in the United States. IP-intensive industries are estimated to generate 72% more value added per employee than their nonintensive counterparts. [Fagerberg et al. \(2017\)](#) highlight that a joint research project of the WIPO and the United Nations (UN) measured the impact of IP systems on six countries and found a positive correlation between the strength of the IP system and economic growth.

8.3.3 Morality

[Drahos \(2016\)](#) elucidates that there are many advocates of the moral arguments for IP despite the complex relationship between IP and human rights. [Dove \(2016\)](#) emphasizes that according to Article 27 of the Universal Declaration of Human Rights,

everyone has the right to the protection of the moral and material interests resulting from any scientific, literary or artistic production of which he is the author.

Thus, Article 27 fuels IP justification attempts in accordance with [Smith \(2016\)](#) that could be categorized as part of one of four theories:

1. Lockeans believe that IP is justified as an outcome of hard development work.
2. Utilitarians argue that IP is a stimulant that increases progress and incentivize people to further innovation and creativity.
3. Personality theorists assert that IP is simply an extension of an individual.
4. Equivalency theorists observe that IP is the same as real property.

These categories will be further explored to provide important insights into the four theories:

1. Natural Rights and Justice Model:

[Gordon \(1993\)](#) states that this argument is fundamentally based on Locke's concepts. He stated that a person has a natural right over the outcomes of his or her labor, explains [Buckle \(1991\)](#). Separating these products from the originator is viewed as unjust. However, [Hettinger \(1989\)](#) admits that Locke had never argued that his natural rights and justice concept applied to IP. Further, Locke's fundamental argument that laborers have the right to control that which they create might be irreparably flawed according to [Drahos \(2016\)](#). [Moore \(2017\)](#) explains that the argument that a laborer owns his or her body and therefore the right of ownership automatically extends to everything a laborer creates is inaccurate at best. Thus, the IP extension is also flawed.

2. Utilitarian-Pragmatic Model:

[Baron and Baron \(2003\)](#) explicate that this theory's core idea is to emphasize that prosperity is positively correlated to protection of private property. Advocates of this theory assert ([Resnik, 2003](#); [Moore, 2002, 2017](#); [Fromer, 2012](#)) that the innovation regime and large number of inventions in 19th-century United States are the results of the patent system. Utilitarians claim that by providing innovators with an acceptable return on investment (ROI), IP maximizes social utility ([Granstrand and Holgersson, 2015](#)). [Menell \(2016\)](#) enlightens that the underpinning presumption is that IP promotes public welfare. [Cotter \(2015\)](#) demonstrates that utilitarians also argue incentivization. Systems of protection such as IP optimize utility according to this theory. However, [Steidlmeier \(1993\)](#) points out that the major flaw in this argument is that the incentivization is acting on the wrong actor that is on the owner of the IP, rather than on the creator of IP. Hence, the utilitarian's argument is also fundamentally flawed.

3. Personality Model:

[Hughes \(1988\)](#) asserts that this theory is most easily summed up by a quote from Hegel:

Every man has the right to turn his will upon a thing or make the thing an object of his will, that is to say, to set aside the mere thing and recreate it as his own.

[Von Lewinski \(2008\)](#) argues that European IP law is forged by this notion that ideas are an extension of their creator. Personality theorists assert that a creator is inherently at risk of dispossession and alteration ([Kur et al., 2013](#); [Waelde et al., 2013](#); [Muzaka, 2016](#); [Grosheide et al., 2014](#); [Smith, 2017b](#)). IP protects personality-based moral claims. The personality model is also flawed via the Lockean disposition according to [Williams \(2015\)](#).

4. Equal Model:

[Spooner \(1855\)](#) claims

that a man has a natural and absolute right—and if a natural and absolute, then necessarily a perpetual, right—of property, in the ideas, of which he is the discoverer

or creator; that his right of property, in ideas, is intrinsically the same as, and stands on identically the same grounds with, his right of property in material things; that no distinction, of principle, exists between the two cases.

This argument equates IP with real property. Additionally, [Rand et al. \(1986\)](#) argued in a logical sequence that the protection of IP is basically a moral issue. The fundamental belief is that the human mind itself is the source of all wealth and survival. Therefore, all property is intellectual property. Thus, to violate IP is not unlike violating any other property rights according to their argument. The equivalency theory is currently in favor ([Drahos, 2016](#)), but it does have its shortcomings ([Fang et al., 2017](#); [Stiglitz, 2014](#)). [Reichman and Sell \(2014\)](#) assert that IP is not like other property; their comparison is centered around a physical object, a hammer, and therefore, they state that this argument is also flawed.

In conclusion, the objectives of IP can easily be summarized as based on financial incentivization and economic growth. Indeed, all morality-based justification theories are flawed according to [Moore \(2017\)](#). Thus, their real, albeit unintended purpose is to subject the concept of intellectual property to a long and arduous debate. Knowing the points of this debate is, however, useful as it eventually might change, undermine, or simply eliminate the current long-standing protections afforded by various legislative instruments ([Drahos, 2016](#)). Therefore, this debate can have a profound effect on electronic enclosure, housing, and package development practices.

8.4 Intellectual property debate

The last innovation wave created a new environment with computerization and the implementation of the global network known as the Internet ([Weiser, 2003](#)). [Jewkes and Yar \(2013\)](#) warn that this wave allowed digitalized intellectual properties to be copied and distributed with incurring miniscule or no costs at all. As such, this debate centers around the use of the term as a foundation for creation of a universally accepted mental model ([Gentner and Stevens, 2014](#); [Baratgin et al., 2015](#); [Gauffroy and Barrouillet, 2014](#); [Garnham, 2013](#)), influencing support and behavior of IP ([Cialdini, 1987](#); [Cialdini and Goldstein, 2004](#); [Nolan et al., 2008](#)). In addition, critics see IP overreaching its originally intended boundaries. IP creators and owners in the electronic enclosure, housing, and package areas need to understand the major themes of this debate in order to approximate its temporal and spatial effects ([Roin, 2014](#)).

8.4.1 Labeling

Proponents of this debate argue, advises [Sell \(2003\)](#), that the term intellectual property is semantically invalid. In other words, they argue that adding the words property and rights to intellectual is invalidated by the new label's, that is, IP rights' ability to contradict practice and law ([Coombe, 1998](#); [Biagioli et al., 2015](#)).

Further, they argue that this term creates a mental model that is universally accepted due to constant repetition and thereby unduly influences and extinguishes legislative reforms ([Arapinis and Condello, 2016](#); [Del Mar and Twining, 2015](#)). Debate

supporters also argue that copyright, patent, trademark, and other laws should not be combined together as they are unrelated (David and Halbert, 2014; Roin, 2014; Nard et al., 2017). The creator of the Free Software Foundation, Stallman (2006) admits that the label intellectual property is commonly used but advocates its rejection because it

systematically distorts and confuses these issues, and its use was and is promoted by those who gain from this confusion.

Further, he also claims that the term IP operates as

a catch-all to lump together disparate laws” ... “laws originated separately, evolved differently, cover different activities, have different rules, and raise different public policy issues.

And he adds that the continued use of this label creates a significant bias by firstly confusing these government-granted monopolies with ownership of physical things and secondly by inducting a comparison with property rights. Stallman advocates referring to a copyright, a patent, and a trademark in the singular, and he warns against creating a collective term. Similarly, Boldrin and Levine (2009) use the term “intellectual monopoly” to provide a clearer definition of the underlying concept. They also argue that intellectual property is very different from property rights (Boldrin and Levine, 2013; Boldrin, 2009). Stallman (2006) argues by citing the Lockean theory that

if copyright were a natural right nothing could justify terminating this right after a certain period of time.

Lessig (2002) also criticized the comparison with physical property. He argues that such a comparison fails because physical property is generally rivalrous, but intellectual output is not. This means that if a copy is made, for instance, of a song, listening to the copy does not prevent the songwriter also listening to his or her original. These arguments generally support piracy and theft according to Johns (2010).

8.4.2 Substitution

Bosworth (2014) asserts that “intellectual property” has on many occasions been referred to as “intellectual rights.” Rights are a traditionally broader concept than property. Rights have included moral and other personal protections. These cannot be bought or sold. Use of the term “intellectual rights” has declined rapidly since the 1980s. At the same time use of the term “intellectual property” has steadily gained ground. “Monopolies on information” and “intellectual monopoly” have been used often along with arguments against the misuse of “property,” “intellect,” or “rights,” most notably (Boldrin and Levine 2009), thereby creating an alternative terminology.

8.4.3 Objections

Critics of intellectual property often point out the harm intellectual monopolies cause, for instance, in granting pharmaceutical patents (Horton et al., 2014; Blackstone et al., 2014). They claim that IP is preventing progress, the benefits are assigned to members of powerful interest groups and generally to the detriment of the masses. In other words, Fromer (2015) argues that the public interest is harmed by IP. In additions, engineers and scientists expressed concern that patents are discouraging technological development in the newest wave of innovation, that is, nanotechnology (Sargent, 2016; Khan, 2014). Moser (2012) based on her historical analysis highlights that intellectual property laws may generally be harmful with respect to innovation:

Overall, the weight of the existing historical evidence suggests that patent policies, which grant strong intellectual property rights to early generations of inventors, may discourage innovation. On the contrary, policies that encourage the diffusion of ideas and modify patent laws to facilitate entry and encourage competition may be an effective mechanism to encourage innovation.

Drahos (2016) also notes:

Property rights confer authority over resources. When authority is granted to the few over resources on which many depend, the few gain power over the goals of the many. This has consequences for both political and economic freedoms with in a society.

The WIPO (WIPO, 2008) recognizes that conflicts exist between intellectual property rights and other human rights. Helfer (2003) mentions that the UN Committee on Economic, Social and Cultural Rights argued that IP tends to be governed by economic goals. In their view, IP should rather be viewed as a social product and made subservient to human rights laws. The Committee observed that when governments fail to do so they risk infringing upon the essential human right to food and health in addition to other benefits (Xanthaki, 2007).

Landes and Posner (2009) explicate that IP creates artificial scarcity and further it does infringe on the right to own a tangible property. Kinsella (2013) uses the following scenario to argue this point:

Imagine the time when men lived in caves. One bright guy—let's call him Galt-Magnon—decides to build a log cabin on an open field, near his crops. To be sure, this is a good idea, and others notice it. They naturally imitate Galt-Magnon, and they start building their own cabins. But the first man to invent a house, according to IP advocates, would have a right to prevent others from building houses on their own land, with their own logs, or to charge them a fee if they do build houses. It is plain that the innovator in these examples becomes a partial owner of the tangible property (e.g., land and logs) of others, due not to first occupation and use of that property (for it is already owned), but due to his coming up with an idea. Clearly, this rule flies in the face of the first-user homesteading rule, arbitrarily and groundlessly overriding the very homesteading rule that is at the foundation of all property rights.

8.4.4 Expansion

Bently and Sherman (2014) explain that expansion of IP duration and scope is another source of criticism. In addition, Foster (2005) highlights that IP protection has been sought for the entire domain of the newest innovation wave: biotechnology and nanotechnology. Patents have even been granted for living organisms thereby creating a potential expansion in IP scope.

The increase in copyright term extension highlights continued expansion in duration in accordance with Joyce et al. (2016). Part of the problem is a lack of registration or copyright notice requirements. This situation had led to new issues. Belleflamme and Peitz (2014) highlight the apparent increase in orphan works. The copyright owner cannot be contacted for these works, creating cascading problems for creative industries.

Correa (2007) observes that this expansion has been driven by international trademarks harmonization efforts. The primary instrument is the Agreement on Trade-Related Aspects of Intellectual Property Rights also known by its acronym TRIPS (Correa, 2000). This agreement was ratified in 1994 and formalized regulations for IP rights. Importantly, Matthews (2003) emphasizes that any sign that is capable of distinguishing the products or services of one business from another is capable of constituting a trademark in accordance with TRIPS. This has important consequences for electronic enclosures, housings, and packages.

However, Bradner and Contreras (2017) observe that objections are most often made on one dimension of IP without considering the complex interwoven pattern of technology development and its influence on economic growth. Others like May (2013) and Drahos (2016) concur.

8.5 Intellectual property rights

(Maskus, 2000b) elucidates that intellectual property rights comprise copyrights, geographical indications, industrial design rights, patents, plant variety rights, trade dress, trade secrets, and trademarks. There are also more specialized exclusive rights attached to the general category of intellectual properties, such as circuit design rights (Cui et al., 2011) and supplementary protection certificates for pharmaceutical products (Correa, 2000). However, by far the most important in terms of enclosures, housings, and packages are patents according to Hughes and Drury (2013).

8.5.1 Patents

A patent is a form of exclusive right granted by the relevant government to an inventor (Gans et al., 2008). A patent affords its owner the right to exclude all others from importing, making, offering to sell, selling, and using an invention for a stipulated period of time (Hall et al., 2005; Boldrin, 2009). This protection is granted in exchange for the full public disclosure of the invention (Lichtman et al., 2000; Baker and Mezzetti, 2005).

Singh et al. (2016) explain that the fundamental idea is that once the stipulated protection is lapsed a qualified member of the public should be able to reproduce the previously protected invention without any difficulty. This, of course, is counter to the interest of the inventor, so an effort is made by patent attorneys in particular to offer a vague enough description to gain a granted patent, while hindering entry by any future competitor according to Baker and Mezzetti (2005).

There is no universally standardized procedure for securing patents (WIPO, 2008). Requirements vary according to national laws and international agreements. This fact, according to Cahoy et al. (2016) creates an untold number of difficulties for inventors in a globally connected world. Sheldon (2015) explains that usually, a patent application must include one or more claims that satisfactorily define the invention. In addition, a patent claim defines a specific property right Bradner and Contreras (2017). Weaver et al. (2017) state that an invention is a solution to a specific technological problem and it could be an enclosure, housing, or packaging issue in the context of this handbook series. This may be a product or a process issue. Normally it has to fulfil three minimum requirements in accordance with Park (2008):

- novelty, it must be new,
- not obvious, in other words it must have an inventive step, and
- usefulness, there needs to be an industrial applicability.

The TRIPS of the World Trade Organization (WTO) declares that patents must be available in any member states for any invention, in all fields of technology, provided they meet the three minimum requirements stated above (Secretariat, 1999). Nevertheless, practical patent process harmonization is still very far off, even between WTO member states. Scherer (2015) highlights that the agreement also establishes that patents must provide protection for a minimum of 20 years.

8.5.1.1 Law

Süzeroglu-Melchioris et al. (2017) opine that explaining the relevant patent law is firmly in the domain of a qualified and preferably very experienced patent attorney. However, a few basic points should be well known by the electronic enclosure, housing, and package industry according to Drury (2001).

Importantly, Ginarte and Park (1997) explain that a patent does not provide a right to create, utilize, or trade an invention. Instead a granted patent legally provides the exercisable right to exclude all others within a specific jurisdiction from creating, utilizing, trading, offering for sale, or even importing a patented item for the entire term of a particular patent according to Powell (1917). Pressman and Tuytschaevers (2016) highlight that the temporal limit imposed is usually 20 years from the recorded filing date subject to the on-time payment of renewal fees that are also called maintenance fees.

From an economic and practical standpoint, however, Lallement (2017) asserts that a patent is a legal instrument that confers upon its proprietor

a right to try to exclude by asserting the patent in court.

Therefore, [Risch \(2014\)](#) concludes that the concept of patent trolling is completely erroneous. [Osenga \(2014\)](#) agrees and adds that legal action is the only reason for the existence of patents. [Cheng et al. \(2017\)](#) observe that many patents are never tested in court. This does not oppose the previous statement, rather it strengthens it. It betrays the fact that the legal system achieved its fundamental purpose of defending the rights of the innovator ([Gwynne, 2014](#); [Lee, 2015](#); [Bartmann and Schulz, 2016](#); [Ford, 2017](#)).

Paramount is the fact that many granted patents turn out to be invalid once their proprietors attempt to assert them in court according to [Eisenberg \(2007\)](#). [Allison et al. \(2003\)](#) explain that a patent without court history is always less valuable than one, which has been tested and found to be valid. [Solomon \(2017\)](#) elucidates that this is another reason why patent trolling statements are simply the result of not understanding the legal system or simply trying to mislead the public with the goal of eroding a strong patent system and exchanging it with a much more vulnerable one where innovations are much less protected from infringement.

[Sichelman \(2017\)](#) highlights that a patent is a limited property right a government provides to inventors in exchange for their covenant to share all pertinent details of their inventions with the public. Therefore, a patent may be assigned or transferred, licensed, mortgaged, sold, given away, or simply abandoned similarly to any other property right ([Taylor and Inman, 2017](#)). Hence, [Dratler \(2017\)](#) believes that intellectual property rights are an especially fitting term for patents.

Perhaps surprisingly to many, even a granted and court-tested patent does not necessarily afford its current owner the right to exploit the patented invention ([Vermont, 2006](#)). That is because many inventions are improvements of prior inventions, observes [Gordon \(2000\)](#). [Haustein and Neuwirth \(1982\)](#) note that this is especially often the case at the first half of any innovation wave. [Kitch \(1977\)](#) explains that prior inventions often still be covered by another valid patent. In such cases, the proprietor of the improvement patent can only legally utilize the improved invention if and only if the prior patent holder gives permission ([Allison and Lemley, 1998](#)). [Grushcow \(2004\)](#) opines that in a competitive economy, such permissions are not easy to secure without significant financial disbursements.

[Halewood \(1997\)](#) warns that many countries incorporate a “working provision” that requires exploitation of the invention in its jurisdiction. The consequences of noncompliance with these provisions might invalidate the patent. [Champ and Attaran \(2002\)](#) note that many patentees are stunned by a court decision to award a compulsory license to a party simply wishing to exploit a patented invention. In such cases, proprietors could challenge the court’s decision, but evidence must be provided that compliance with the working provisions was achieved.

There are many ways for third parties to challenge validity of a pending or even issued patent directly at the issuing agency, which is usually the national patent office ([Morgan and Stoner, 2004](#)). [Janis \(2004\)](#) explains that the patent validity challenges are often referred to as opposition proceedings. It is, however, often better to initiate these challenges in court according to [Devlin \(2008\)](#). Fundamentally, a

successful challenge must prove that the patent in question should not have been granted.

There are four fundamental grounds for challenges in accordance with [Bar and Costello \(2017\)](#):

1. the claim is not patentable,
2. the claim does not cover something new,
3. the claim was obvious to the relevant experts at the recorded time of the patent application,
4. fraud was committed during the application or patent prosecution.

[Shapiro \(2000\)](#) elucidates that the patent office or court might rule that a patent is valid in its entirety, that is the challenge was not successful; the patent can be found to be invalid in whole, that is the challenge was successful; or the patent can be found invalid in part for any of the above grounds.

8.5.1.2 Ownership

[Schwartz and Goldman \(2001\)](#) state that natural persons and business entities could also submit a patent application in many countries. However, only the inventor or inventors may apply for a patent in the United States ([Jaffe, 2000](#)). [Leontief \(1963\)](#) points out that rights are regularly assigned to business entities once the patent is issued. [Belenzon and Berkovitz \(2010\)](#) believe that many patent debates center around the frequent practice of these assignments. Many employment contracts require inventors to assign their patents to their employers according to [Cherensky \(1993\)](#). [Galasso and Schankerman \(2015\)](#) assert that negotiating power asymmetry is the issue in these debates.

Ownership of an invention may automatically pass from the inventor to their employer by many European countries' legal process in accordance with [Meireles et al. \(2016\)](#), if

- the invention was made as part of the inventor's employment duties,
- an invention could reasonably be expected to result from employment duties, or
- the inventor had an obligation to further the interests of the company.

Granting a patent means in practice that the inventors, their successors, or their assignees have become the proprietors ([Jell, 2012](#)). The local laws govern the share of patent exploitation in cases where a patent is granted to more than one proprietor ([Merges and Locke, 1990](#); [Nagaoka et al., 2010](#); [Belderbos et al., 2014](#)). [Tsukada and Nagaoka \(2015\)](#) explain that this area can hold some surprises as well. Each proprietor may freely license or assign their rights in a few countries ([Gorbatyuk et al., 2016](#)). Yet, other countries prohibit such actions without the explicit permission of all proprietors ([Nagaoka et al., 2010](#); [May, 2006](#); [Idris, 2003](#)).

The ability to assign ownership rights creates liquidity in a patent and classifies it as a property ([Kruppert, 2017](#)). [Odasso et al. \(2014\)](#) highlight the practice that many inventors can obtain patents for the explicit purpose to sell them onto third parties. The

acquiring parties then own the patents and naturally have the rights to prevent others from exploiting the inventions (Nicholas, 2014). Powell (1917) asserts that these rights are no different from that of the original inventor.

8.5.1.3 Costs

Patenting costs vary from country to country. In addition, Harhoff et al. (2016) explain that the total cost of patenting might also be dependent upon the type of patent and complexity of the invention. The costs of patenting include:

- preparing and filing a patent application,
- prosecuting the application until issue, and
- maintaining the patent.

The average cost of obtaining a European patent and maintaining the patent for a 10-year term was over €30,000 in 2005 according to the European Patent Office according to De La Potterie and Mejer (2010). Malewicki and Sivakumar (2004) note that the cost of patent prosecution was estimated to be from \$5000 to \$50,000 per patent in the United States at the turn of the millennium. Litigation increase costs significantly.

8.5.1.4 Alternatives

There are two major alternatives to patenting: issuing a defensive publication (Barrett, 2002) and maintaining the invention as a trade secret (Friedman et al., 1991). Holgersson and Wallin (2017) opine that both approaches are deemed to be riskier than patenting and hence the evergreen popularity of patenting.

A defensive publication's purpose is to establish prior art and thereby assigning the invention into the public domain according to (Barrett, 2002). This can be done by publishing a detailed description of the invention without seeking a patent. A defensive publication prevents others from patenting the invention. This goal is, however, not always accomplished and costly litigation must overturn the issued patent without any possibility of recouping those costs. Therefore, Holgersson and Wallin (2017) highlight that this strategy is very risky.

Invention-related information is often kept confidentially according to Dass et al. (2015). A trade secret is information that is kept confidential and provides a competitive advantage to its holder. Usually, Menell (2017) states that trade secrets are protected by nondisclosure agreements (NDAs). NDAs supposed to prevent information leaks. Milgrim and Bensen (2016) explain that one of the obvious advantage of holding a trade secret that the value of a trade secret does not end after 20 years but it continues until it is made public. In addition, a trade secret does not require payment of fees or completing arduous amount of paperwork (Robertson et al., 2015). It also has an immediate effect. This is, however, also a very risky approach primarily because of trade secret susceptibility to legal means of reverse engineering according to (Holgersson and Wallin, 2017).

8.5.1.5 Benefits

Eaton and Kortum (1996) explicate that patenting provides incentives to develop efficient research and development programs. Primary incentives embodied in the patent system in accordance with Baldini et al. (2007) include the following:

- incentives to invent;
- to disclose the invention;
- to invest the capital necessary
 - to experiment,
 - to produce, and
 - to market the invention; and
- to improve upon earlier patents.

Bhattacharya et al. (2014) state that patenting also allows an inventor to exploit the exclusive right status and thus become a licensor. Such an inventor or innovating firm must secure the funds for both the patenting process and the defense of the patent (Azoulay et al., 2015; Martínez et al., 2016). Therefore, Chinying Lang (2001) asserts that patenting allows the inventor to accumulate capital from licensing income rather than manufacturing and distributing. Thus, the innovation becomes the inventor's sole focus and specialization. Therefore, Ernst (2003) argues that a better ROI can be secured by the markets on such highly specialized activities.

8.5.2 Copyright

Joyce et al. (2016) explain that a copyright is a form of intellectual property that provides exclusive rights to the creator of an original work. Yuan (2006) points out that these rights are for use and distribution and limited temporally. Copyrights are also territorial in nature, which creates issues in a globally connected world as copyright laws vary by country according to Davies and Schriker (1994).

Samuels (2002) explicates that copyright encompasses a wide range of creative activities, be it intellectual or artistic. Burk and Cohen (2001) highlight that these rights are exclusive but not absolute as limitations are imposed such as the concept of fair use. A paramount limitation is that a copyright does not cover ideas only their manifestations (Senftleben, 2004).

Leaffer (2010) elucidates that many jurisdictions require that copyrighted works must be in a tangible form. Liu et al. (2005) inform that copyright is often shared among members of a group of creators such as authors. In such cases each creator holds a set of rights to use, distribute, or license the outcome. They are collectively referred to as rights holders.

Copyrights include the following in accordance with Cohen (1997):

- use,
- sell or surrender these rights to others,
- distribution, importing, and exporting,
- reproduction,
- public performance or display,

- transmit or display by means of radio or video,
- control over and creation of derivative works, and
- moral rights such as attribution.

Adilov and Waldman (2013) explain that temporality of a copyright varies by territories but usually spans the author's life and an additional 50–100 years. This means that a copyright extinguishes 50–100 years after the author dies, which is a temporally much greater protection than the usual 20 years afforded by patenting (Reese, 1995; Chafee, 1945b; Strong, 2014; Darling, 2015; Rosignoli, 2017).

Many nations require the completion of certain formalities to establish valid copyright (Ginsburg, 2009; Pallante, 2013). However, many others recognize copyright in any form of completed works, without a formal registration process (Gervais and Renaud, 2013; Van Gompel, 2013; Karp, 1994; Perlmutter, 1994; Sprigman, 2004; Samuelson, 2007). Fundamentally, Cornish et al. (1999) explain that copyright is enforced in civil courts. However, a few jurisdictions also apply criminal penalties (Moohr, 2003, 2004). Almost all jurisdictions incorporate some limitations into their copyright laws according to Senftleben (2004). Generally, these allow fair use, providing users with certain albeit very limited rights (Burk and Cohen, 2001).

Development of digital media and Internet technologies during the last innovation wave has created an impetus for reinterpretation of these exceptions (Memon and Wong, 1998; Rosenblatt et al., 2001; Couldry, 2012). Peitz and Waelbroeck (2004) highlight that new technologies created difficulties in enforcing copyright. Yu (2003) emphasizes that these challenges were used as a platform from which to shape a largely philosophical debate with the explicit purpose of demolishing or minimizing these rights. However, Choi and Perez (2007) add any form of business activities depending upon copyright for a steady flow of revenue stream have countered these arguments and instead advocated the extension and expansion of copyright. For instance, Litman (2017) asserts that the motion picture and music industry sought and created additional legal and technological barriers.

8.5.2.1 Law

Exclusive when associated with copyrights means that while the copyright owner is free to exercise rights granted under copyrights, all others are prohibited without issuance of an appropriate permission (Landini, 2012). Thus, Patterson (1991) asserts that copyright is a “negative right.” Breyer (1970) concludes that exclusivity serves to prohibit rather than to permit. Copyrights prohibit listeners, readers, viewers, and publishers various ways to reproduce, that is, to copy (Elkin-Koren, 1997). Therefore, Leafner (1993) suggests that it is important to realize that copyrights in and of themselves do not permit or even encourage their owners to do something. Merges et al. (2003) highlight that copyrights act similarly to patents and other intellectual property rights. Hence, grouping them together from a practical point of view is amply justified according to Davis and Miller (2000).

Yen (1997) states that esthetic features must be separable from utilitarian features in order to gain copyrights. Gorman (2001) advises that if separation of features is not possible, other forms of intellectual property protection should be secured.

Copyright protection varies in length of time in different jurisdictions (Yuan, 2006; Adilov and Waldman, 2013). Temporality depends on several factors, including creation type, that is a music, painting, sculpture or a literary work, falls under different classifications according to Pila (2010). Also, could be important whether the work has been published (Tyerman, 1971; Denicola, 1980). In addition, Condry (2004) informs that many jurisdictions take a different view if the work was created by individuals or corporate entities. However, as a general rule of thumb the most common copyright length is the life of the creator and an additional 50 or 70 years (Landes and Posner, 1989; Patry, 1994; Leaffer, 2010; Joyce et al., 2016). Yar (2005) highlights that the United States is different in this respect. The stipulated term for copyright is counted from the date of creation or publication and the length of protection is dependent on classification. Landes and Posner (2003) state that copyrights usually expire at midnight on December 31 of the expiration year.

Like all laws, copyright laws are subject to change by legislation (Litman, 1989; Ginsburg, 1999; Senftleben, 2017). Joyce et al. (2016) explain that this includes temporality adjustments. The 20th century has seen a number of adjustments made around the world and as a consequence, remainder of copyright time assessment has become a challenge according to Rothman (2014). Cornish (2015) warns that most nations have extended the length of their copyright protection terms in many cases even retroactively. While international treaties dictate minimum copyright terms, sovereign nations are free to mandate longer than the minimum stipulated terms (Harris, 2013).

8.5.2.2 *Treaties*

The 1886 Berne Convention established mutual recognition of copyrights (Solberg, 1925). Chafee (1945a) elucidates that the Berne Convention made it possible that copyrights do not have to be asserted or declared. They are automatically in force at the time of creation (Brown, 1985). This means that, for instance, an author need not register or make an application for copyright protection in any of the countries that are participating in the Berne Convention (Brassil et al., 1999). Hirtle (2015) explains that an originator of a creative work is automatically entitled to all copyrights as soon as a work is written or recorded on physical medium and to all derivative works unless the author explicitly disclaims them or until the copyright expires in accordance with the Berne Convention. The Convention also created an equal playing field, that is foreign authors are treated equivalently to domestic authors according to Jacobs (2016).

Interestingly, Bently and Sherman (2000) state that the United Kingdom signed the Berne Convention in 1887. However, significant areas of the Convention were not implemented until the Copyright, Designs and Patents Act of 1988 was passed according to Taylor (1989). Hatch (1989) clarifies that the United States also signed the Berne Convention in 1989. The delay was due to the fact that the United States and Latin American countries entered into the Buenos Aires Convention in 1910 according to Rinaldo (1974). Finkelstein (1953) informs that this Convention mandated a copyright notice on the creative work such as the statement “all rights reserved.” In addition, the

Buenos Aires Convention permitted shorter and renewable copyright terms (Henn, 1953). In 1952, the Universal Copyright Convention was created, adds Finkelstein (1953). Jacobs (2016) opines that this was another watered-down version of the Berne Convention. Reichman (2000) advises that today the principals of the Berne Convention are all incorporated into the WTO's TRIPS agreement that was created in 1995. Thus, copyright protection is mandated by the Berne Convention globally (Brassil et al., 1999). Therefore, copyright laws today are standardized to some extent but many important details are still left to the administering jurisdiction's discretion according to Harris (2013).

8.5.2.3 Ownership

Ownership of copyrights could be a lucrative business proposition (Rohter, 2013). However, Flint (2014) asserts that one of the difficulties of copyright law is that possession of copyright often defaults to the employer rather than to remain with the creator of the creative work.

For instance, Taylor (1989) explains that the UK Copyright, Designs and Patents Act 1988 stipulates that if a work is created in the course of an employment then the copyright is automatically transferred to the employer. The enabling provision is labeled "Work for Hire" (Joyce et al., 2016). Ginsburg (2016) suggests that exceptions could be made by contractual agreements.

Fundamentally, Joyce et al. (2016) explicate that the first owner of a copyright is the creator. This could be an author, a painter, a sculptor, and others. Gadd and Gadd (2017) demonstrate that joint copyright ownership is possible if more than one person created the creative work. However, Belderbos et al. (2014) assert that there are some criteria that must be met.

8.5.2.4 Eligibility

Copyright protection might apply to a range of artistic, creative, or intellectual works (Joyce et al., 2016). Fishman (2014) worries that there is little standardization in the range and various jurisdictions are free to set their own criteria. Generally, the range includes the following categories listed in Table 8.2 in accordance with Cohen et al. (2015).

In some jurisdictions, graphic and industrial designs have diverging, while in others overlapping legal requirements according to Pahl and Beitz (2013). Drury (2001) warns that these need careful analysis in terms of electronic housings where industrial design can be critical.

8.5.2.5 Assignment

An entire copyright, most of the copyright such as all but moral rights, or some aspects of it such as reproduction alone may be assigned or transferred (Bently and Sherman, 2014). For example, Acquadro and Conway (2014) enlighten that an author will often sign contract with the publisher in which the author agrees to transfer all copyright in the handbook in exchange for royalties. Posner (2014) suggests that the idea is that the

Table 8.2 Copyright range

Copyright range
Choreography
Computer software
Dissertations
Drawings
Industrial designs
Literary works
Motion pictures
Musical compositions
Paintings
Photographs
Plays
Poems
radio and television broadcasts
Sculptures
Sound recordings
Theses

author and original copyright holder benefits, or at least expects to, from the publisher’s production and marketing capabilities far beyond those of the individual author.

Bruni (2014) asserts that since the last innovation wave, books might be copied and distributed at minimal cost through the Internet, inducing many authors to keep their copyrights and turn to self-publishing. However, Posner (2014) also points out that the publishing industry attempts to provide promotion and marketing for the author so that a book in question can reach a much larger audience. Hunter (2017) advises that a copyright holder, such an author, need not transfer all rights completely, although sadly most publishers will insist. Anand and Khanna (2000) believe that it is a better deal if the author grants another party a nonexclusive license to copy and distribute the book in a territory and for a predetermined period of time.

8.5.3 Industrial design rights

Design rights have a long and illustrious history (Cornish et al., 1999). Fellner (1989) states that industrial design protection was first provided in the United Kingdom. The Designing and Printing of Linen Act of 1787 was the first protective legislation

according to [Sherman and Bently \(1999\)](#). Registering for an industrial design right is both related to patents and copyrights ([Hunter and Wood, 2016](#)).

Industrial design rights are part of the intellectual property rights portfolio ([Bently and Sherman, 2014](#)). [Beckerman-Rodau \(2015\)](#) explains that they are often labeled “design right” or alternatively called “design patent.” Industrial design rights afford protection to objects that contain a visual design that is not purely esthetic and as such would not qualify for a copyright protection according to [Du Mont and Janis \(2016\)](#). [Tjalve \(2015\)](#) explains that an industrial design consists of a particular composition or configuration of color, pattern, shape, or a combination thereof usually in a three-dimensional form encompassing the claimed esthetic value. [Anwar et al. \(2015\)](#) add that an industrial design can also be a two- or three-dimensional regularly repeating pattern used to produce a product.

The Hague Agreement governs the International Deposit of Industrial Designs ([Johnson et al., 2014](#)). [Senfleben \(2015\)](#) states that this is a WIPO-administered treaty. [Johnson et al. \(2014\)](#) highlight that an international registration is possible by following a standardized procedure. [Bently and Sherman \(2014\)](#) point out that novelty is the all-important and most difficult-to-meet criteria. [Schartinger and Barber \(2016\)](#) explain that there is a choice to be made, either file an application with a national office or enter an application for a single international deposit with WIPO. The design will then be protected in the stipulated or desired number of countries ([Sherman and Bently, 1999](#)).

8.5.3.1 Europe

[Torremans \(2016\)](#) explains that registered and unregistered community design rights are available within the EU. These provide a complete coverage of the EU. A 25-year protection could be secured for a registered community design ([Christie and Gare, 2016](#)). This protection is subject to the on-time payment of renewal fees. These must be made once every 5 years. The unregistered community design rights protection lasts for a much shorter period of 3 years ([Kur et al., 2013](#)). This period starts once the design is made available to the public. Infringement occurs if the protected design is copied.

8.5.3.2 The United Kingdom

The United Kingdom protected only textile patterns between 1787 and 1839 ([Ashby and Johnson, 2013](#)). However, [Denicola \(1982\)](#) explains that the Copyright of Design Act, which was passed in 1842, increased the scope of the previous acts and allowed inclusion of other material designs. Metal and ceramic, primarily earthenware objects were included in addition to textiles. A diamond mark needed to be indicated on the designs to signal protection and indicates the date of registration ([Reichman, 1992](#)).

[Bently and Sherman \(2014\)](#) add that the UK law provides a national registered design right and an unregistered design right in addition to the EU protection. The unregistered right can last for up to 15 years, which is much longer than the EU-offered

3 years. An unregistered right exists automatically if certain requirements are met (Cornish et al., 1999).

Colston et al. (2010) advise that the registered design right can last up to 25 years, which is the same as the EU protection. Continuation of protection is subject to the on-time payment of maintenance fees. Importantly, from the electronic enclosure, housing, and package perspective a topography of semiconductor circuits is also covered according to Maskus (2000b). The IC layout design protection lasts 10 years.

8.5.3.3 *The United States*

US design patents filed before May 13, 2015, afforded a 14-year protection (Shultz and Saporito, 1996). Torremans (2016) elucidates that applications filed on or after May 13, 2015, last 15 years from the granting date. Design patents protect the ornamental features of the objects similarly to the EU and UK protection methods (Smith, 2017a).

8.5.4 *Trademarks*

Besen and Raskind (1991) highlight that trademarks are important from an overall business perspective. A well-recognized trademark can add good will as well as significant intellectual property value to a corporate appraisal (Hughes, 1988). However, Hughes and Drury (2013) believe that trademarks occupy lesser importance from the electronic enclosure, housing, and package perspective. Nevertheless, a brief discussion is included to provide a well-rounded review of intellectual properties.

According to Ginsburg (2004) a trademark is a unique expression, design, figure, symbol, or most often a sign that is also known as a brand, which differentiates products or services of a manufacturer or business from their competitors' offerings. The essential function of a trademark is like physical branding (Murphy, 1987; Krasnikov et al., 2009; Pike, 2015; Gibbons, 2016). A trademark is to provide a unique signature that exclusively identifies the source of products or services. Thus, a trademark is a badge of commercial origin (Sonmez and Yang, 2005). In other words, the purpose of a trademark is to identify a company as the exclusive source of its offerings.

The International Nice Classification of Goods and Services created 45 trademark classes (Mendonça et al., 2004). Goods are classified from 1 to 34, while classification 35 to 45 covers services. This classification attempts to create a uniform global trademark classification system according to Block et al. (2014).

8.5.4.1 *Law*

Emerson and Willis (2017) elucidate that despite of the existence of a global trademark classification system it is currently impossible to file and obtain a global trademark registration. In this, trademarks are like patents, copyrights, and the other intellectual properties (Merges, 2014b). Bently and Sherman (2014) highlight that trademarks are only protected within the geographic limits of the granting authority.

The "Madrid" system facilitates simultaneous trademark registrations in multiple jurisdictions (Elias and Stim, 2004). Choy et al. (2016) explain that this system

leverages the WIPO “international registration.” However, [Leaffer \(1998\)](#) points out that the international registration is obtained by first applying for a trademark protection in the company’s own jurisdiction. [Burmam et al. \(2017\)](#) believe that the Madrid system is an improvement on previous practices and allows a trademark owner to obtain protection in many jurisdictions. Therefore, the process of obtaining protection is simplified. Only one application needs to be completed accompanied with payment for one associated set of fees. Making changes such as names or addresses or the process of renewal is also simplified. Extension of coverage to additional member jurisdictions is also simplified and can be performed at any time after the initial registration ([Bently and Sherman, 2014](#)).

There is a Trademark Law Treaty that acts as a standard of procedural aspects of the registration process according to [Dinwoodie \(2016\)](#). However, still many differences remain between the various country’s application processes.

[Cook \(2013\)](#) highlights that the EU Trademark system, which was formerly called the Community Trademark system applies throughout the EU. Registration of a trademark must be made with the European Union Intellectual Property Office (EUIPO), which was formerly called the Office for Harmonization in the Internal Market (Trade Marks and Designs). Such an application provides a trademark registration, which is valid throughout all member states of the EU. Companies located outside the EU must have a professional representative during the application process with the EUIPO according to ([Kur, 2015](#)). Local companies can represent themselves. However, professional assistance is still recommended.

Well-known trademark status is granted to well-recognized international trademarks ([Lehman et al., 2002](#)). Importantly, a well-known trademark does not have to be registered in the location of an infringement action. [Schuyler \(1982\)](#) adds that this protection was established by the Paris Convention for the Protection of Industrial Property. According to [Secretariat \(1999\)](#) the protection was increased by the TRIPS. As a result, small- to medium-sized enterprises could join their bigger counterparts in pursuing global trademark protection so long as their trademark is classified as a well-known trademark. The advantage of this system is that it is registration free. Article 16.3 of the TRIPS Agreement provides the fundamental backbone of the protection. A well-known registered trademark is protected if at least one of the following conditions is met:

- the products or services are unique,
- the offending trademark would cause confusion in the marketplace, and
- the trademark owner’s interest is likely to be damaged.

8.5.4.2 Consumer protection

Historically, a trademark also fulfills consumer protection functions ([Schechter, 1927](#)). [Goldsmith \(2016\)](#) adds that trademarks serve as an identifier and as such prevent deceptions with regard to the origin and thereby the quality of a product or service. [Nugent \(2017\)](#) believes that it is for this reason that governments embrace the idea of registered trademarks.

Simon and Schmidt (2015) explain that trademarks incentivize manufacturers and others to provide consistency in their offers and thereby maintain their brand image. Therefore, Fishman (2016) asserts that liquidity of a trademark is dissimilar to other intellectual properties in that a trademark must be sold with the identified product or services, otherwise an “assignment-in-gross” is performed and it could lead to a loss of a trademark. Thus, trademarks are not divisible from the original goods or services.

Consumer protection is not the only reason for a government to be supportive of the idea of trademarks. Griffith et al. (2014) suspect that like the case with other intellectual properties, governments also raise additional revenues for their treasuries by granting a trademark.

8.5.5 Trade dress

Trade dress is another form of intellectual property. Trade dress is a legal term. O'Connor (2014) elucidates that it refers to the visual and esthetic characteristics of a product or its packaging that uniquely identify the source of the product to consumers. Dinwoodie and Janis (2014) explain that a trade dress protection can cover color, configuration, packaging, shape, size, and texture of a product.

An example of shape would be the iconic Coca-Cola bottle (Greene and Kesselheim, 2011). (Wong, 1997) explicates that the shape of the bottle does not have any functional attribute, but it instantly identifies the product within and as such it is an eminent example of an item covered by trade dress protection. Trade dress could become very important from the perspectives of enclosures and housing in terms of their “look and feel” that could be protected by this form of intellectual property according to Jamnia (2016).

8.5.5.1 The United Kingdom

Trade dress can be protected as getup, which in turn is protected by the law of passing off in the jurisdiction of the United Kingdom (Joyce et al., 2016). Passing off is available for protecting an unregistered trademark. This protection is available under common law. Wilke and Zaichowsky (1999) explain that passing off means to make a false representation that could induce a person to believe that the goods were supplied by another. In other words, creating fakes would be caught up in this heading. Interestingly, many things could be protected by trade dress, such as packaging, marketing techniques, business strategy, and even advertisement themes can also be protected under the auspices of passing off (Dinwoodie and Janis, 2014).

8.5.5.2 The United States

Gleiberman (1993) explains that the Lanham Act provides protection in the United States. Much like trademarks, a product's trade dress is also protected by a federal statute. O'Connor (2014) clarifies that the function of trade dress protection is to shield a purchaser from products that are imitations, in other words, to avoid a situation where

the purchase of one product is made in belief that it was another due to appearance reasons.

8.5.5.3 Formal registration

Lunney (2017) informs that trade dress may be registered with the USPTO. This could be done either in the Principal or the Supplemental Register. Registration is not required but offers advantages (Kopp and Langenderfer, 2014).

Graham et al. (2013) explain that a trade dress registration in the Principal Register carries the benefit of a US-wide “constructive use” and “constructive notice.” These prevent others from utilizing or even registering that trade dress without going through the formal process of contesting the registration. Importantly, a registration in the Principal Register becomes incontestable after 5 years according to Tushnet (2017). Thus, a registration eliminates many ways for issuing a legal challenge.

Cronin (2015) suggests that registering a trade dress in the Supplemental Register adds a further benefit. The Supplemental Register protects a trade dress in foreign countries. However, Seling (2017) points out that the protections offered are not equivalent to the US-based protections provided under the Principal Register.

8.5.5.4 Legal requirements

There are various legal requirements attached to successfully gaining trade dress protection in any jurisdiction (Beckerman-Rodau, 2002). Supreme among these requirements are the functionality (Cohen, 2009) and distinctiveness principles (Dinwoodie, 1996). Thus, Davis (1995) warns that it can be challenging to obtain appropriate protection for a trade dress.

8.5.5.5 Functionality

The prerequisite for a successful registration in the Principal Register or securing a common law protection provided by the Lanham Act is that a trade dress must not be functional (Graham et al., 2013). Du Mont and Janis (2016) explain that functionality in this context means that the configuration of colors, designs, materials, shapes, or textures that constitute a trade dress must not serve a utility other than creating an instant recognition in the purchaser’s mind.

For example, a particular mold texture could be protected under trade dress if it does not serve any function other than esthetics (Wong, 1997). Application of such texture could then, in theory, be also protected, which is an area intensely interesting from the enclosure and housing perspective.

The meaning of the word functional is context dependent (Bently and Sherman, 2014). For instance, the color red in a line on the box of an electronics packaging may not be functional and therefore the color selection is part of protectable trade dress, while the same exact color on a stop and start button would be functional due to the global recognition that the color red is warning the user and hence this color selection could not be protected under trade dress (Dinwoodie and Janis, 2014).

8.5.5.6 *Distinctiveness*

Dinwoodie (1996) explains that another prerequisite is distinctiveness. This means that a trade dress must instantly identify a product. Therefore, only product packaging would generally qualify.

Claimed trade dress in a product design cannot be intrinsically distinctive (Dinwoodie and Janis, 2014). Thus, a product design must acquire uniqueness through other means. Secondary meaning—based distinctiveness is interpreted as a trade dress that is not distinctive on its own, but the use of the trade dress has created a strong association between that trade dress and the source (Gallagher, 2015).

Related legal statutes are still evolving according to (Bently and Sherman, 2014). As it stands now, product packaging including electronic packaging, in very general terms, may be inherently distinctive according to Cho (2015). Nevertheless, the design or shape of the product itself, such as the enclosure or housing may not be inherently distinctive. Thus, O'Connor (2014) points out that they must acquire secondary meaning to be protected under the various provisions of trade dress.

8.5.5.7 *Protection for electronic interfaces and websites*

It must be stated that the exact boundaries of protection are still uncertain. However, Lee and Sunder (2016) explain that various courts are beginning to seriously consider trade dress protection for the “look and feel” of software. This is important as many enclosures and housings have unique embedded software displays that provide a unique experience to its users (Mehfooz and Bhalla, 2016).

8.5.6 *Trade secrets*

Menell (2017) elucidates that a trade secret is undisclosed information that is utilized as a competitive advantage. A few examples listed in Table 8.3 in accordance with Bone (2013). These must not be known or reasonably ascertainable.

Table 8.3 Types of trade secrets

Types of trade secrets
Compilation of information
Design
Formula
Instrument
Pattern
Practice
Process

There is no formally granted protection available for trade secrets. [Robertson et al. \(2015\)](#) advise that this means that each business must take measures to guard its trade secrets. An example of such trade secret is the formulation for Coca-Cola and in fact many other food and drink products.

Trade secrets attract other labels such as confidential information ([Patel et al., 2016](#)). Classified information, however, is not used as it is reserved for government secrets. These are protected by completely different sets of laws. There are countless trade secrets in the inner workings of enclosures, housings, and especially for packages ([Pres and Wende, 2017](#)).

8.5.6.1 Definition

Various jurisdictions define the term trade secret slightly differently ([Bently and Sherman, 2014](#)). However, [Pooley and Westman \(1997\)](#) explain that the three most important aspects are included in Article 39 of the TRIPS Agreement. Therefore, trade secrets must have the following characteristics:

- it is not known to the public,
- there is an economic benefit from its use and this benefit must be because of the held secret and not because of the value of the information itself, and
- its holder applies reasonable efforts to indefinitely continue its secrecy.

The United States defines trade secret in 18 U.S.C. § 1839(3) (A), (B) (1996) as also having three parts in accordance with [Dreyfuss \(1998\)](#):

- “information,
- reasonable measures taken to protect the information, and
- which derives independent economic value from not being publicly known.”

8.5.6.2 Value

Trade secrets are a vital, but often invisible part of a company’s intellectual property (IP) rights portfolio ([Idris, 2003](#)). The IP contribution to a company’s total value, usually measured as its market capitalization, according to [Maskus \(2000a\)](#) can indeed be very significant.

[Rivera \(2000\)](#) argues that the trade secret component’s contribution is extremely difficult to measure. This is partly because all intellectual property’s contribution is inherently hard to ascertain. It is also partly due to trade secret being completely invisible in most cases.

8.5.6.3 Protection

Trade secrets are not disclosed to the public ([Pooley and Westman, 1997](#)). This is in contrast to other types of intellectual properties. [Hannah \(2005\)](#) adds that trade secrets are usually protected by special procedures. These encompass legal, handling, and technological measures. The most common legal protection is to utilize NDAs. In

other jurisdictions work for hire and noncompete clauses might also be incorporated in addition to an NDA into the defensive arsenal (Godfrey, 2004).

Halbert (2017) highlights that protective measures effectively create a perpetual monopoly. Therefore, trade secret information is intrinsically much more valuable than a patent or a copyright (Maskus, 2000a). However, Seaman (2015) highlights that a lack of a formal protection regime associated with IP means that an independent third party can discover the trade secret without any potential penalties. This could be done in the enclosure, housing, and package areas through reverse engineering practices.

Thus, Klasa et al. (2016) argue that an effective trade secret arrangement means restricting access to a maximum of six individuals. Brown and Lumumba (2016) inform that an example of a product protected by a trade secret regime that is restricted to less than half a dozen people includes Coca-Cola.

Bently and Sherman (2014) advise that trade secrets may provide a significant advantage over other registered IP rights. That is because of associated temporality. Consider that the Coca-Cola company has secured no patents for the formulation of the Coca-Cola (Brown and Lumumba, 2016). Despite this it has been effective in protecting its market dominance than the 20 years of patent protection. Not surprisingly, Coca-Cola refused to reveal its trade secret even under judges' orders according to Hannah et al. (2014). As a consequence, Maskus (2000a) argues that trade secrets are the best IP treasures for the enclosure, housing, and package applications but an airtight protection regime must be developed to protect them.

8.6 Infringement, misappropriation, and enforcement

David and Halbert (2017) warn that trade in counterfeit patented, copyrighted, or trademarked products was valued at \$600 billion globally in 2011. This value accounted for roughly 1/20th of global trade according to Rojek (2017). Therefore, Chaudhry and Zimmerman (2013) advise that the violation of intellectual property rights is relatively common. Myers (2017) and Jiang et al. (2017) highlight that enclosure, housing, and package developers should bear this in mind when formulating an appropriate IP regime across their enterprises.

Infringement of patents, copyrights, and trademarks, and misappropriation of trade secrets attract civil or criminal penalties (Koyama and Hayashi, 2017). Pooley (2015) adds that punishment depends on the IP type, jurisdiction, and many other factors. There is no uniformity across the globe according to McJohn (2015).

8.6.1 Patent infringement

Merges (2014a) informs that patent infringement is most frequently caused by using a patented item without explicit permission from the patent owner. Selling a patented item without permission is slightly less frequent but often more damaging to the interest of the patent holder according to Mueller (2015). Kim and Song (2013) inform that

patent infringement cases are generally heard in civil courts. However, many jurisdictions incorporate criminal proceedings (Jiang et al., 2017).

A patent protection is based on the claims of the issued patent (Chiang, 2014). Allison et al. (2013) highlight that understanding many of the claims is not simple even for people within the industry let alone for users of the products. Hence, Graham et al. (2016) explain that to ascertain patent infringement is not a simple matter. In addition, safe harbor provisions exist in many jurisdictions (Kupecz et al., 2015). Russo and Johnson (2015) add that one example is to use a patented invention purely for research. The use of this safe harbor is limited in the United States to research that is done for purely philosophical purposes, such as a PhD study, and for data collection for drug approval according to Robertson (2014).

8.6.2 Copyright infringement

Gull and Flowers (2016) explain that copyright infringement is committed when an attempt of reproduction, distribution, display, or performance of a work is organized without permission from the rights holders. Guzman (2015) adds that making derivative works without permission is also an offence. Therefore, Loren (1997) highlights that permissions must be secured from the copyright holder. The copyrights owner is most often the publisher or other business interests (Saunders, 1993). Karunaratne (2012) cynically informs that infringement is often called piracy perhaps in an uncoordinated attempt to solicit the death penalty for such offenses. Smith (1992) underlines that a copyright is secured once a work is fixed. Lemley and Reese (2003) opine that enforcement of copyright is a responsibility of the copyright holder and many publishers have failed in their duties to pursue pirates successfully. Also, Joyce et al. (2016) warn that there are many limitations and exceptions to copyrights. For instance, Kelly (2016) explains that limited use of copyrighted work does not constitute infringement and are captured under the fair use and fair dealing provisions of most jurisdictions. However, details of those provisions vary tremendously across the globe (Cohen et al., 2015). Thus, Goold (2015) highlights that ascertaining infringement is a complex matter.

8.6.3 Trademark infringement

Tushnet (2016) elucidates that a trademark infringement transpires if one party copies and utilizes a trademark that is either identical or confusingly similar to a trademark that is owned by another party. Basically, Dogan (2014) summarizes that a trademark infringement is a deception that is related to products or services, which are identical or very similar to the products or services of the other party. Roberts (2017) highlights that a trademark receives protection without registration in most jurisdictions. However, registering a trademark offers legal avenues for enforcement (Blakeney, 2014). Infringement can often be heard in civil courts and in some cases even criminal proceedings could be initiated (Klein and Wueller, 2016; Lunney, 2016; Kiser, 2013; Dogan, 2014).

8.6.4 Trade secret misappropriation

Misappropriation of a trade secret is different from other IP violations (Lindsay, 2014; Menell, 2017). Handelsman (2017) explains that the nature of misappropriation is very different from infringement activities as trade secrets are kept invisibly, while the others are accessible to the public. Trade secrets are protected by the Uniform Trade Secrets Act of the United States (Dole, 2014; Png, 2015). In addition, the Economic Espionage Act of 1996 criminalizes misappropriation or theft of a trade secret (Halligan, 2014; Sandeen, 2016; Cohen, 2013; Kuntz, 2013).

8.7 Review

Development of a sound intellectual property (IP) rights portfolio is paramount from the electronic enclosure, housing, and package perspective (Idris, 2003). There are many seemingly isolated types of intellectual properties. As a result, Drahos (2016) demonstrates that the use of the IP label and its philosophical foundation is vigorously debated. Therefore, the enclosure industry needs to monitor future of this debate carefully.

Patents are by far the most frequently utilized IP instrument (Baker and Mezzetti, 2005). It has the longest history, therefore the most familiarity enables utilization of patents for IP protection purposes. However, there are other methods of protection available. For instance, copyrights applied to embedded software offer a much longer protection period than patents (Joyce et al., 2016).

Beckerman-Rodau (2015) asserts that industrial design rights and trademarks are also important. The former can protect some aspects of the enclosure or housing, while the latter provides over all brand image protection services. Trade dress is an emerging form of protection that could be incorporated into the IP defense shield (O'Connor, 2014).

Finally, Menell (2017) informs that the longest protection is offered by trade secrets. This form of protection, however, needs extremely careful planning and implementation to be effective. Once such a system is embedded the protection can continue forever, thereby this form of protection offers the longest and quite possibly the most effective electronic enclosure, housing, and package protection (Pres and Wende, 2017).

Infringement and misappropriation is big business and over 5% of the global trade engages in counterfeiting according to David and Halbert (2017). Enforcement most frequently is entrusted to the rights holders. Therefore, monitoring and vigorous litigation is necessary even if it is meant that pejorative labels such as “patent troll” might be earned in the process (Risch, 2014). IP rights are important for the survival of any business related to electronic enclosures, housings, and packages.

8.8 Hot tips

A well-designed intellectual property rights portfolio establishes differentiation from the competition (Fang et al., 2017). In addition, Reitzig (2004) an excellent IP rights

portfolio provides long-term and in a few cases unassailable competitive advantage. Therefore, it behooves electronic industry participants to understand its complex rules (Drury, 2001).

- Develop a well-designed and balanced IP rights portfolio.
- Incorporate your trademarks into your portfolio and monitor for similar new trademark registrations.
- Create a patent “wall” to protect your visible and reengineering prone intellectual properties.
- Understand your copyrights and do not infringe on others, especially be careful of your competitors’ rights.
- Exploit industrial design rights along with trade dress to create brilliant IP improvements.
- Create and implement a trade secret protection regime to substantially increase IP portfolio valuation.
- Monitor the intellectual property debate and implement changes fast.
- Fight infringements and misappropriations vigorously.

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9.1 Introduction

Sustainability is a composite word created from the combination of sustain and ability (Finkbeiner et al., 2010). Originally, Edwards (2010) explain that sustainability was applied in the ecological sense. Harte (1995) adds that in this usage sustainability describes a biological system that can exist indefinitely.

The word sustainability gained a more general interpretation in the 1990s according to Voinov and Farley (2007). Its original meaning was generalized to encompass the endurance of all systematic processes. Sustainability has become a buzz word (Bock, 2012; Pargman and Raghavan, 2014). French and French (2017) opine that it is currently the fashionable whip of industry and as such it is paramount to be able to navigate the alphabet soup that sustainability truly is within the electronic enclosure, housing, and package industrial segment.

Today, Zijp et al. (2015) observe that the idea is to manage and organize for sustainability. That means to create a sustainable development. Such a development in turn includes the four joining and often overlapping areas in accordance with Sneddon et al. (2006):

1. Culture
2. Ecology
3. Economics
4. Politics

Importantly, Jackson and Senker (2011) add that only number three is supposed to have a direct relationship with electronics. Yet, Petrick and Echols (2004) highlight that practicalities indicate that all four seem to bear heavily from a new product development perspective. In fact, Larson et al. (2017) elucidate that the four areas together create the business environment for all enterprises.

Sustainability is often utilized as an all-encompassing umbrella program of socioecological process, generally characterized by a relatively vague pursuit of a commonly left leaning ideal according to Richard (2017). Munda (2005) demonstrates that like all ideals, sustainability is no exception in that it cannot be attained fully, either temporally or spatially. However, Meijboom and Brom (2012) argue that it does indicate a direction and its proponents want to use it to persistently herd the global economy in their preferred direction. Proponents believe that this process will result not only in a sustainable system but also the very survival of humanity according to Rome (2015). Leemans (2016) warns that such grand and general visions, however, might find to be wanting. For instance, Daily and Ehrlich (1992) point out that due to its left-leaning heritage, proponents of sustainability

fail to propose a meaningful way to reduce not only humanity's carbon footprint but also the size of the global human population. Even curtailing population growth is firmly off the agenda (Bradshaw and Brook, 2014). Kennedy (2016) argues that it is no wonder that meaningful progress to protect the environment has yet to materialize in many areas.

Nevertheless, Ghimire (2013) explains that it could easily be agreed that a healthy environment is a prerequisite to the survival of humans and most other biological organisms. Therefore, Epstein and Buhovac (2014) posit that finding ways to reduce or perhaps to eliminate negative human impacts is a worthwhile activity. Thus, Lancaster (2016) highlights that chemistry in all its permutations is firmly targeted. This is important from all processes and materials selection from the electronic enclosure, housing, and package perspective according to Ashby and Johnson (2013).

Rapidly moving towards an ill-defined yet ever present sustainability challenge enlisted various international and national forums to support legislative activities (Bosselmann, 2016). Svensson and Wagner (2017) observe that successful legal activities outlaw certain activities and shape others such as consumerism, lifestyle choices, urban planning, and transport options. Hughes and Drury (2013) explain that these affect the utility of electronics and hence its various manifestations including its ever present "skins."

The sustainability ideal can morph into many shapes and forms. Most important among these in accordance with Gabrielson et al. (2016) are as follows:

- altering manufacturing practices to conserve natural resources,
- designing enclosures, housings, and packages in a flexible and reversible manner,
- reorganizing work practices, such as supporting telecommuting, green architecture, and other initiatives,
- reappraising economic activities and eliminating harmful chemicals from electronics, and
- utilizing science and engineering to develop new and green enclosure technologies.

Marten (2001) explains that sustainability could be interpreted as humanity's goal of reaching a human–ecosystem equilibrium that is named homeostasis. The process to reach the ideal is termed sustainable development. Importantly, Holden et al. (2017) elucidate that despite the huge popularity of the sustainability label, the possibility that the human population will achieve the ideal sustainability has been, and perhaps continues to be, questioned. This is especially so in light of continued and in many respects accelerating environmental degradation, unabated climate change, ever increasing overconsumption, by a seemingly unending and limitless population growth and its associated drastic economic growth in an essentially closed system that we all call home, planet Earth, according to Shiva (2016).

Bergman et al. (2016) believes that sustainability being vaguely defined allows various interpretations. It is also used in a trade war–like manner (Lang and Heasman, 2015) in, which the EU fires its directives at the imports (Korhonen et al., 2015), while the United States does impose its will in terms of legislative instruments like in the case of conflict minerals (Kim and Davis, 2016).

9.2 Conflict minerals

Conflict Minerals legislation is important in the world of electronics (Raj, 2010). Ochoa and Keenan (2011) explain that this is because all of the minerals regulated are used in the various enclosures, housings, and packages. Eichstaedt (2011) argues that it is important to understand the idea behind conflict minerals so a brief historical review is provided next.

9.2.1 The label

The word “conflict” followed by another designator such as “commodity” or “resource” was first used in the last decade of the last millennium (Bannon and Collier, 2003). Gilmore et al. (2005) opine that this new label was first utilized in relation to “conflict diamonds.” Bieri (2016) highlights that the popular media coined an even more vivid descriptor in “blood diamonds.” The movie of the same title did much to popularize this concept but provided no hint of direction as to the solution of the underlying problem according to Zwick et al. (2007).

Turner (2007) opines that the ideology of “conflict resources” has been gaining traction ever since. Brunnschweiler and Bulte (2009) observe that under the “resource” banner almost anything can qualify. Soon timber was enlisted. It was reported by Van Solinge (2008) that “conflict timber” financed hostilities in disparate countries such as Cambodia and Liberia. Koubi et al. (2014) argue that the logic is of course, somewhat fragile as wars will always need to be financed much like any other human activity and selling resources is one swift way to accomplish that goal. Should this avenue be closed another often much worse might emerge rapidly, observe Mukwege and Nangini (2009), at least in relation to the Congolese conflict.

UN General Assembly discussed “conflict diamonds” first, according to Pauwelyn (2002). Le Billon (2013) states that the UN Security Council increased the scope of discussion to include all resources that have originated from a conflict zone. However, Williams (2016) highlights that an internationally standardized definition is yet to emerge. Kim and Davis (2016) opine that such a definition is needed to facilitate a more systematic approach. The fundamental idea is to prevent abuses in a war zone by commercial entities (Vogel and Raeymaekers, 2016). Meierhenrich (2014) explains that this idea is once again seeming to dispute historical evidence of the many conflicts in human history. Nevertheless, Schoepfer et al.’s (2017) current working definitions center around the exploitation of “conflict resources.” Fichtelberg (2016) assumes that one of the goals of this ideal is to prepare a way for prosecution of war criminals and profiteering entrepreneur organizations and individuals. The following is a proposed definition of conflict resources in accordance with Global Witness by Mejía Acosta (2013):.

... natural resources whose systematic exploitation and trade in a context of conflict contribute to, benefit from or result in the commission of serious violations of human rights, violations of international humanitarian law or violations amounting to crimes under international law.

The Bonn International Center for Conversion has monitored and recorded “conflict resources” listed in [Table 9.1](#) by geographic regions since 1996 according to [Kingma \(2016\)](#).

9.2.2 *Developments*

Conflict resources are the outputs of primary industries that are sold to perpetuate a war effort ([Bannon and Collier, 2003](#)). Proponents cite anecdotal and statistical evidence that a “resource course” can prolong conflicts ([Ross, 1999](#); [Manzano and Rigobon, 2001](#); [Auty, 2002](#); [Papyrakis and Gerlagh, 2004](#); [Mehlum et al., 2006](#); [Robinson et al., 2006](#); [Humphreys et al., 2007](#); [Sala-I-Martin and Subramanian, 2008](#)). The most noted example popularized by the media has been the Democratic Republic of the Congo (DRC) according to [Montague \(2002\)](#). [Vlassenroot and Huggins \(2005\)](#) explain that the conflict zone is the eastern region of the DRC. [Turner \(2007\)](#) observes that armies, rebel groups, and others have profited from mining there. Meanwhile violence and exploitation grew according to [Mejer \(2010\)](#).

The four most commonly associated minerals with conflicts are also known as 3TGs. [Fitzpatrick et al. \(2014\)](#) explain that they are so labeled because of their initials.

- 1. The first “T” stands for tin, which is made from the ore of cassiterite.
- 2. The second “T” is for tungsten, which is made from the ore wolframite.
- 3. The third “T” is for tantalum, which is extracted from coltan.
- 4. The “G” is for gold.

[Maystadt et al. \(2014\)](#) highlight that all mentioned minerals are found in deposits around the eastern part of the DRC. It has been said that these minerals pass through a variety of intermediaries before being purchased by the smelters ([Autesserre, 2012](#)). These minerals, however, as [Raj \(2010\)](#) observes, are essential in the manufacture of a variety of electronics. [Young and Dias \(2012\)](#) add that these include many consumer electronics such as laptops, mobile phones, and others. Industrial applications are also

Table 9.1 Conflict resources

Conflict resources
Cocoa
Cotton
Diamonds
Fossil fuels
Poppy seeds
Rubber
Timber
Various metals

large users of devices that could potentially contain materials originally sourced from the DRC according to Taffel (2015). Hence, Kim and Davis (2016) advise that there is a need to be vigilant and the supply chain must be policed effectively. Rubinstein (2014) believes that diamonds and other “conflict resources” are not so significant from the electronic enclosure, housing, and package perspective.

9.2.3 Minerals

Parker and Vadheim (2017) explain that the four most prominent conflict minerals, for example, codified in the US Conflict Minerals Law, are cassiterite, wolframite, columbite-tantalite, and the ore of gold. Fitzpatrick et al. (2014) observe that these are all used as raw ingredients of the metals that utilized in components that are mounted on printed circuit boards (PCBs). Barume et al. (2016) elucidate that these are sometimes referred to as “the 3T’s and gold,” 3TG, or even simply the “3T’s.” Under the US Conflict Minerals Law, additional minerals may be added to this list in the future (Seay, 2012).

9.2.3.1 Tin (Sn)

Cassiterite is the main ore needed to extract tin (Gladwell et al., 1981). (Miller et al., 1994) explain that tin is essential to produce the solder on PCBs and in packages. This application gathers the most interest in a conflict minerals audit from an electronics perspective (Fitzpatrick et al., 2014).

Kerk et al. (1954) highlight that tin also has many other uses such as for the manufacture of biocides and fungicides. These are seldom a concern from an enclosures or housings perspective (Prendergast and Lezhnev, 2009).

However, Evans (1998) observes that tin is also used as an intermediate of polyvinyl chloride (PVC) and as an ingredient in high-performance paints. Therefore, Epstein and Yuthas (2011) warn that it might become a serious issue for original equipment manufacturers (OEMs). The former in wires and the latter in the coating of electronic enclosures and housings.

9.2.3.2 Tungsten (W)

Izumiya et al. (1998) explain that wolframite is an iron manganese tungstate mineral. This mineral along with scheelite is the most important source of tungsten according to Srinivas et al. (2000). Young and Dias (2011) observe that tracing tungsten is no simple task, given the existence of these two different sources.

Tungsten has a very high-specific gravity (Bleise et al., 2003). Lassner and Schubert (2012) explain that its great density is utilized in a variety of applications like ammunitions, industrial, fishing, dart, and golf club weights. A related electronics application is the vibration mechanism of mobile phones (Zheng and Ni, 2010).

Tungsten carbide has very high hardness and thus great wear resistance (Fang et al., 2009). These properties make it an excellent choice in applications like drill bits and other cutting tool surfaces.

Tungsten's very high melting temperature is utilized in electronics applications such as filaments, heating elements, and related applications (Langmuir, 1913). Xia et al. (2009) explain that tungsten is also used as an interconnecting material between the transistors and silicon dioxide.

Importantly, Wypych (2016) highlights that tungsten powder is used as a plastic filler that often ends up in enclosures and housings. Therefore, tungsten has many different application areas in electronic enclosures, housings, and packages, yet many applications are often overlooked when a conflict minerals audit is performed. Thereby, Jeffrey (2012) points out, creating a liability for the unsuspecting OEM.

9.2.3.3 Tantalum (Ta)

Columbite-tantalite is the generic name of the columbite and tantalite families of minerals, and they are also known as coltan in Africa (Ayres, 2012). These are difficult to test without sophisticated tests. This fact makes tracing coltan in the "real world" nearly impossible according to Young and Dias (2011). Coltan is the metal ore that is the source of tantalum.

Rowcliffe and Warren (1970) observe that tantalum carbide has very significant hardness, and as a consequence great wear resistance. López-De-La-Torre et al. (2005) explain that there are many cutting tool applications. It is also used in jet engine turbine blades. However, these are not important from an electronics perspective.

Freeman et al. (2007) elucidate that tantalum is used primarily in high-performance capacitors. These are more compact than alternatives and possess high reliability. Therefore, they are incorporated into a wide range of electronic applications such as airbags, antilock braking systems (ABS), digital cameras, global positioning systems, hearing aids, ignition systems, laptops, mobile phones, pacemakers, tablets, video cameras, video game consoles, to name just a few, according to Reynolds (2016).

9.2.3.4 Gold (Au)

Maystadt et al. (2014) explain that gold can be found in many areas of the world including the DRC. Applications utilizing gold include the storage of wealth, jewelry, dental products, and importantly electronics. De Haas et al. (1934) states that gold has very low resistance to the flow of electricity and thus it is an efficient conductor. In addition, gold resists corrosion (Hill, 1981). The combination of low electrical and excellent corrosion resistance makes gold a front runner in many electronics applications such as contact points (Okinaka and Hoshino, 1998; Bose and Bose, 1997). Sun et al. (2006) highlight that gold is also present in many chemical compounds used in the semiconductor manufacturing processes. This fact makes conflict mineral auditing an especially challenging predicament according to Epstein and Yuthas (2011).

9.2.4 Democratic Republic of the Congo

In theory, Pankhurst (2003) explicates that "conflict resources" is a general concept, but in practice this means that resources originating from one particular region of

the world are to be boycotted. This region is home to one of the deadliest war zone in the history of Africa, the Democratic Republic of Congo (DRC) and its neighboring countries according to [Tiwarei \(2015\)](#). [Berman et al. \(2017\)](#) explain that the idea is that by boycotting these minerals the economic means to wage a prolonged conflict will diminish and as such the conflict itself will automatically be solved. While this is an arguable concept, laws force electronic enclosure, housing, and package suppliers to obey its will without any potential evaluation of its sensibility or indeed its enforceability ([Parker and Vadheim, 2017](#)). Therefore, [Maystadt et al. \(2014\)](#) advise that learning about the geographic region and a brief review of the fluid situation on the ground is of some benefit.

Some state that the “real” conflict resource fueling the war in the Congo is gold rather than the 3T’s ([Vogel and Raeymaekers, 2016](#)). [Arikan et al. \(2015\)](#) explain that is because gold bullions are very difficult to trace but easy to sell. Certainly, argue [Vogel and Raeymaekers \(2016\)](#), gold is also relatively abundant in the Kivu region of the eastern DRC. Other conflict minerals pose a more difficult albeit manageable logistic challenge according to [Ross \(2004\)](#). [Montague \(2002\)](#) believes that these are exported from Congo and form the 3T’s described earlier.

Description of the armed conflict and mineral resource looting by various actors is beyond the scope of this handbook, but many sources of information could be found to portray the various perspectives ([Reyntjens, 1999](#); [Clark, 2002](#); [Nest et al., 2006](#); [Larmer et al., 2013](#); [Lake, 2017](#)). The immense scale of the conflict prompted the international community to try to orchestrate a bid to stop it according to [Reyntjens \(2009\)](#). [Seay \(2012\)](#) explains that implementing “conflict resource” legislation is one way to influence the outcome of this long prolonged and extremely bloodstained genocide-ridden war. [Turner \(2007\)](#) highlights that historians already differentiate between two periods but this has no major significance from an electronics perspective. Conflict resource restrictions aim to control the economies of the region and eliminate profitability and the need to control mines in the region according to [Woody \(2012\)](#).

9.2.4.1 Mines

[Geenen \(2012\)](#) highlights that mines in the eastern region of the DRC are difficult to access remote and due to the conflict dangerous regions. Armed groups reportedly control more than 50% of mining sites according to [Montague \(2002\)](#). These groups coerce civilians to work, extort tax, and engage in other illegal activities including war crimes ([Bannon and Collier, 2003](#)). Workers face horrendous conditions such as slavery, torture, and death from many sources ([Le Billon, 2013](#); [Berman et al., 2017](#)). Hence, [Autesserre \(2006\)](#) adds that the justification to try to stem the violence by the implementing a conflict resource elimination agenda is justified. The most important example was enacted in the United States ([Radley and Vogel, 2015](#)).

9.2.5 The United States law

Historically, [Raj \(2010\)](#) highlights that the conflict resources legislation originated with a focus on the electronics industry. [Whitney \(2015\)](#) states that anecdotal evidence

suggests that the birth of coltan control was due to the Congolese President's response to a question asked by an American politician. The question was:

Why the East Congo cannot be controlled?

Kabila responded:

The problem was the vast black market in minerals that funded the militias.

Thus, a Republican senator from Kansas, later governor of the same state, Sam Brownback, initiated the process. [Woody \(2012\)](#) states that he introduced the Congo Conflict Minerals Act in 2009. Importantly, [Seay \(2012\)](#) adds that this Act was going to force electronics companies to implement a verification and disclosure of their mineral sources, namely cassiterite, tantalum, and wolframite. However, [Prendergast and Lezhnev \(2009\)](#) explain that the Act was never considered as it expired in the Committee. Nevertheless, [Fein \(2010\)](#) emphasizes that the financial meltdown of 2008 provided a new opportunity in the unlikely candidate of the Dodd–Frank Wall Street Reform and Consumer Protection Act. This Act had nothing to do with “conflict resources,” but the concept of the Congo Conflict Minerals Act in 2009 was added as Section 1502, with the intention that the Securities and Exchange Commission (SEC) will police implementation of the Act. The United States Congress passed this bill and President Barack Obama signed it into law on July 21, 2010.

9.2.5.1 Auditing and reporting

[Woody \(2012\)](#) warns that companies not within the jurisdiction of the SEC will also be impacted by the auditing and reporting requirements. This is because Section 1502 distresses the entire supply chain ([Seay, 2012](#)). Thus, its scope includes privately held as well as non-US companies. The global reach of the Conflict Minerals Law is accomplished by containing two closely related requirements in accordance with [Sarfaty \(2015\)](#):

- establishing traceability by independent third-party supply chain audits and
- reporting of the audit results both to the SEC and the public.

Less than 1200 companies were required to submit full conflict mineral reports according to the SEC ([Fitzpatrick et al., 2014](#)). However, [Maystadt et al. \(2014\)](#) highlight that other estimates were much higher and indicated that 12,000 companies would be affected in the United States alone. This figure means that over 195,000 businesses have to implement supply chain traceability effort globally according to [Kim and Davis \(2016\)](#).

9.2.5.2 General applicability

Under the law, [Fitzpatrick et al. \(2014\)](#) explicate that companies must submit an annual conflict minerals report to the SEC if either of the following two conditions are met:

1. if the Exchange Act of 1934 requires the business entity to file reports with the SEC and
2. conflict minerals are needed to the proper functioning or manufacture of a product that the business entity is making or contract to be manufactured.

The second criterion is a combination of two separate concepts:

1. the utility of the conflict mineral in the output or manufacturing process and
2. the specification or supply chain control that the business entity possesses.

A business entity would automatically be deemed to contract an item to be manufactured if it:

- exerts any supply chain influence over manufacturing or
- offers a branded or generic product.

The business may offer the product under its own trademark or a different brand. This latter criterion supersedes the influence over the manufacturing process criteria. The business contract is the fundamental element in this determination. Thus, the law implies that retailers who are not engaged in manufacturing are also subject to the audit and disclosure requirements. Hence, electronics products are completely captured within the reach of this law.

9.2.5.3 Supply chain traceability

This law explicitly states the use of an “independent private sector auditor.” The SEC in turn has proposed two different levels of standard for performing the audits in accordance with [Timmer et al. \(2017\)](#):

- “reasonable inquiry” and
- “due diligence.”

Reasonable inquiry is the first step to decide if the business can formulate an assessment utilizing its own reasonable efforts. The outcome of this assessment must be reliable, utilizing trustworthy information to prove without a doubt the source and origin of its 3TG materials ([Fitzpatrick et al., 2014](#); [Kim and Davis, 2016](#)). In cases where the business entity is unable to reliably assess the source, the additional step of “due diligence” must be taken. This clearly means engagement of an independent private sector audit according to [Sankara et al. \(2015\)](#).

In addition, the statute states that the audits be

conducted in accordance with standards established by the Comptroller General of the United States, in accordance with rules promulgated by the Commission.

([Zaring, 2015](#)) warns that this specification hides an extremely powerful statement. It means that the exact SEC auditing standards apply to conflict minerals disclosures. Therefore, the SEC will have no discretionary powers accepting self-generated statements or certifications as a compliance with this law.

[Nadvi and Raj-Reichert \(2015\)](#) state that the Electronic Industry Citizenship Coalition (EICC) is a US-based trade association that organized independent private sector

audits to accomplish the conflict minerals supply chain traceability assessments. The fact that there is no official guidance on what is an acceptable audit scope or process complicates efforts. The law is ambiguous and allows businesses a certain degree of flexibility to satisfy requirement. While at the same time, the law preserves the SEC's rights to consider any disclosure or the process that produced it to be unreliable. Therefore, the report would not satisfy regulatory requirements according to [Arikan et al. \(2015\)](#).

The Organization for Economic Cooperation and Development (OECD) published its own guidance. This direction is becoming the de facto standard. However, there are significant inconsistencies and many conflict areas with the US standards. Therefore, business entities subject to the US jurisdiction cannot directly implement the OECD Guidance ([Fitzpatrick et al., 2014](#)). Thus, electronic enclosure, housing, and package specifiers or producers might experience significant legal compliance risks.

9.2.5.4 *Disclosure and reporting*

Business entities subject to the SEC supply chain traceability requirement are obligated to disclose conflict minerals utilized in their products ([Schwartz, 2015](#)). Conflict minerals could have been originated in the DRC or adjoining countries. [Brewer and Turner \(2015\)](#) explain that adjoining countries are currently defined as Angola, Burundi, Central African Republic, Congo Republic, Rwanda, South Sudan, Uganda, Zambia, and Zimbabwe.

[Griffin et al. \(2014a,b\)](#) explain that the law obligates reporting entities to provide a disclosure statement annually. This report must be issued even if none of the minerals were of DRC (or adjoining countries) origin and this information must also be stated in the report. An analysis with appropriate explanations of the country of origin must be furnished to support such a conclusion.

Business entities are required to state if conflict minerals were used ([Fitzpatrick et al., 2014](#)). Companies are also required to state if it is not possible to determine the country of origins of the minerals utilized. Irrespective of the determination, the outcome must be stated in the annual report.

Business entities must also make this information publicly available according to [Taylor \(2017\)](#). This could be accomplished by posting the annual conflict minerals report on an Internet site. However, the posting web address must also be furnished to the SEC. The same process must be used for all parts incorporated in a product.

9.2.5.5 *Deficiencies*

[Whitney \(2015\)](#) advises that this law has been the focus of well-deserved criticism: First due to the law's failure to address the root cause of the conflict and second due to the fact that transparency does not exist in the affected region. Therefore, [Parker and Vadheim \(2017\)](#) add that due diligence and legitimate mineral purchase cannot be expected in a hostile, often warlike environment. Third, the resulting effect has been criticized. Many legitimate mining cites were closed ([Ruggie, 2014](#)). These often provided the only source of income for the entire region. Thereby, [Vogel and](#)

Raeymaekers (2016) elucidate that devastating livelihoods for the very people, who can ill afford any more hardships. Thus, for instance, the Congo's legal exports of tantalum were reduced by 90% indicating a significant revenue erosion for the entire region (Fitzpatrick et al., 2014). Fourth, an investigation performed by the US Government Accountability Office (GAO) found that most business entities were simply unable to determine the source of origin of their conflict minerals according to Kim and Davis (2016). Last but not least, high-tech OEMs criticized the label: "NOT DRC Conflict Free" as a violation of the First Amendment of the United States Constitution (Schwartz, 2015).

9.2.6 Proposed law in Europe

Kumar (2017) states that the European Union, Parliament created a similar legislation during 2015. Some details still need to be agreed among the EU member states. However, the EU has already provided confirmation that a mandatory due diligence process would be implemented. All except the very smallest business entities would be affected. The focus would be the same tin, tungsten, tantalum, gold (Deetman et al., 2017; Manhart et al., 2017). In addition, their ores would also be monitored.

9.3 End of life

Goosey (2004) explains that end-of-life (EoL) is a supply terminology utilized with respect to a product. EoL means that the product's support is discontinued. Arguably, Sodhi and Reimer (2001) point out that this means the end of useful life has been reached at least from the OEM's perspective. Nakatani and Moriguchi (2014) highlight that at this point the OEM stops sales and marketing activities although these activities are usually stopped way before the EoL deadline. EoL time frame after the announced last production date depends on the product type. Rios et al. (2003) elucidate that different EoL examples include a toy that is usually supported only for a single season, which often measured in a few weeks, perhaps in rare cases a few months. Mobile phones might have an EoL in the order of 3–5 years, while automobiles might have an associated EoL of a decade or even longer. On the other hand, commercial aircraft and industrial machinery might be supported for a half a century or longer. Therefore, Sodhi and Reimer (2001) argue that the concept of EoL from the electronic enclosure, housing, and package perspective depends very much on the final market.

Product support also varies by markets (Rios et al., 2003). D'Antone et al. (2017) explain that electronics incorporated into an item with an expected lifetime of 10 years or more generally includes technical, spare parts, and service support. Jones and Zsidisin (2008) explicate that spare part EoL is price driven. That is because of ever increasing production costs. These costs rise when part manufacturing is reconfigured from a mass production and shifted into small scale batch production runs. Once the cost increases beyond a certain threshold, OEM support becomes uneconomic and EoL is reached.

9.4 Heavy metals

Kühn et al. (2016) highlight that often several hundred materials are employed to create a moderately complex electronic device. For instance, Fiete (2010) informs that a camera might contain 500 to 1500 components. Howard (2004) believes that many of these parts contain heavy metals. However, Salomons et al. (2012) note that there is no universally agreed definition of a heavy metal. As such, Sarkar (2002) asserts that heavy metals could be defined based on density, atomic number, or chemical behavior. In practice, Kühn et al. (2016) opine that the labels “heavy metals” and “dangerous substances” are often comingled. Nevertheless, beryllium, cadmium, hexavalent chromium, lead, and mercury are always associated with the negative connotations of the heavy metal label according to Salomons et al. (2012). Brominated flame retardants and PVC are also commonly grouped under the dangerous chemicals banner (Kühn et al., 2016). The above seven are the most important from an electronics perspective according to Ansems et al. (2002).

Huang et al. (2009) highlight that the list of seven substances causes significant pollution, manufacturing, and recycling problems. Järup (2003) points out that a major concern is the exposure of minors and expectant women to heavy metals such as lead and mercury. Bathla and Jain (2016) advance the view that these metals are toxic even at low levels of exposure. Their harm has been documented and includes children and fetuses (Caserta et al., 2013; Jedrychowski et al., 2015; Zeng et al., 2016; Sabra et al., 2017).

Alaee et al. (2003) observe that significant health hazards created by chemicals in electronics include brominated flame retardants. Morf et al. (2005) adds that these are utilized in PCBs, plastic enclosures, and housings. Birnbaum and Staskal (2004) inform that flame retardants do not break down fast or easily and over time they accumulate in the environment. Another problem is that long-term exposure can compromise the functioning of the brain and therefore lead to learning difficulties and loss of memory functions (Dingemans et al., 2007). Legler and Brouwer (2003) add that flame retardants can also interfere with hormone systems. Behavioral problems have been linked to prenatal exposures (Roze et al., 2009).

The once popular cathode ray tubes in TVs and monitors contained lead as did many paint formulations and batteries (Andreola et al., 2007). Childhood intellectual impairment has been linked with lead exposure (Schwartz, 1994; Health, 2005; Bellinger et al., 2017). In addition, Flora (2002) explains that lead can damage the blood and nervous and reproductive systems.

Kang and Schoenung (2004) inform that cadmium used in contacts, fastener coatings, rechargeable batteries, and switches accumulates in the environment. Cadmium is highly toxic according to Das et al. (1997). Kidneys and bones are affected by cadmium exposure (Järup et al., 1998).

Another heavy metal traditionally used in switches but recently utilized in lighting devices for flat screen displays is mercury (Babu et al., 2007). Gochfeld (2003) adds

that its use can damage the nervous system. This effect is particularly severe during early childhood according to [Counter and Buchanan \(2004\)](#).

[Von Burg and Liu \(1993\)](#) explain that production of metal housings used to utilize various compounds of hexavalent chromium. This type of chromium is toxic and carcinogenic according to [Costa and Klein \(2006\)](#).

PVC is a chlorinated polymer utilized in electronics ([Rouif, 2004](#)). [Titow \(2012\)](#) informs that the most common use is as insulation of wires and cables. [Menad et al. \(1998\)](#) observe that burning of PVC releases dioxins and furans. These are toxic and long lived in the environment and as a result even very low concentrations are a cause for concern ([Meharg et al., 1997](#)). [Ventrice et al. \(2013\)](#) opine that this fact stimulated the European Union (EU) to regulate their use along other chemicals.

9.5 Reach

EU regulation EC No 1907/2006 is the Registration, Evaluation, Authorization and Restriction of Chemicals, commonly known by its acronym REACH ([Bergkamp, 2013](#)). [Gergely and Gayral \(2015\)](#) inform that this EU regulation limits or bans the production and utilization of certain chemicals. Chemicals are listed as dangerous if their associated harm to human health and the environment is above a certain threshold value according to [Williams et al. \(2009\)](#). [Kelemen \(2011\)](#) believes that REACH is a complex EU legislation. [Williams et al. \(2009\)](#) opine that it is the strictest chemical substance regulation mechanism. [Barry and Kanematsu \(2016\)](#) observe that REACH has affected many industries globally, including electronics.

[Wallace et al. \(2015\)](#) inform that REACH established the European Chemicals Agency. This agency manages the administrative, scientific, and technical aspects of the regulation. Administration includes registrations. Over 150,000 chemicals are registered ([Biedenkopf, 2015](#)). REACH has a no data, no market policy ([Heyvaert, 2007](#)). [Gustavsson et al. \(2017\)](#) adds that this means that if a substance is not registered it is illegal in the EU.

[Zarfl et al. \(2012\)](#) highlight that REACH incorporated regulation for the utilization of chemical substances of very high concern (SVHC). These chemicals are listed due to their potential negative effect on health and the environment ([Hammerschmidt and Marx, 2014](#)). The European Chemicals Agency must be notified if the total quantity of the SVHC listed chemicals utilized exceeds one ton annually and the substance is present in excess of 0.1% body mass of the article according to [Van Leeuwen and Vermeire \(2007\)](#). [Gabbert et al. \(2014\)](#) inform that there are 168 SVHCs incorporated into the list for authorization. [Silbergeld et al. \(2015\)](#) highlight that certain uses of SVHCs are subject to prior authorization issued by the European Chemicals Agency. Applications must include provisions for SVHC replacements with an alternative of improved safety. The applicant must work toward finding a safer alternative if none exists at present. This policy is known as substitution ([Durin et al., 2017](#)).

9.5.1 Historical milestones

Walters (2017) opines that REACH has overhauled EU chemical policy. Hix (2013) observes that its creation was neither simple nor speedy. Koch and Ashford (2006) add that the European Commission formulated its chemicals policy in a white paper on the Strategy for a future Chemicals Policy, which was issued on February 13, 2001.

Bronckers and Van Gerven (2009) explain that the original legislative proposal was tabled more than 2 years after October 29, 2003, and was communicated to the European Parliament and the Council during November 2003. The new regulation passed its first reading in Parliament on November 17, 2005. The Council of Ministers reached an agreement on December 13, 2005. More than 4 years have passed since the first adoption of the white paper. The European Parliament approved REACH exactly a year after December 13, 2006. The Council of Ministers formally adopted REACH on December 18, 2006. All in the spirit of the festive season according to Bocquillon and Dobbels (2014).

Officially, expenditure versus profit was carefully analyzed (Hix, 2013). Cost of compliance was estimated to be €5.2 billion over 11 years according to Vaughan (2015). Plater et al. (2016) observes that profits balancing costs were estimated to be health benefits and direct healthcare-associated expenditures. However, Brouwer et al. (2014) explain that there were wide disparities in reported potential outcomes by various studies. Nevertheless, the regulation became law on January 20, 2009, almost 8 years after its initial concept was approved. This is a similar incubation period to an extremely large new product development undertaking according to Ward and Sobek Ii (2014). Its implementation was similarly lengthy to its development, but this Directive was fully implemented in 2015, some 14 years after the original idea was approved (Rudén and Hansson, 2010).

9.5.2 Justification

Justification of REACH is rooted in the shortcomings of previous EU regulations according to van Leeuwen and Vermeire (2007). In addition, Domingo (2002) highlights that there was a strong public perception of chemical risk not because of actual incidents but because of a general fear of the unknown world of chemicals. Therefore, a two-pronged approach was devised. Protection of health and the environment was used as a synergistic justification method. Use of this method enabled the acceptance of the REACH legislation according to Bergkamp (2013).

Woodhouse and Breyman (2005) opine that this double justification resonated with certain audiences such as the strong Green movement in Germany at the time. While these ideas are laudable the actual implementation seems to benefit certain groups much more than others (Hannigan, 2014). Such asymmetry provided a foundation for criticism. For instance, Entine (2011) informs that using phthalates and brominated flame retardants is deemed undesirable. REACH in effect banned these substances globally. However, Shaw (2010) highlights that replacements are not as effective and such create additional risks for humanity. In

addition, [Attina et al. \(2016\)](#) add that replacements are also more expensive and as such have a deleterious economic effect. [Entine \(2011\)](#) demonstrates that such a logical linkage was not studied, but similarly linked logic was used as a pillar of justification.

[Baker \(2008\)](#) explains that REACH is justified based on the following linked logic. Using potentially toxic substances in electronic devices may prima facie seem to be safe. However, there are numerous ways that chemicals can enter the human body and stay harmful in the environment. Substances can leave traces during use. For instance, leave droplets in the air allowing inhalation to take place. Once in the human body they can do very much harm. However, [Entine \(2011\)](#) asserts that many of the supposed entry paths have never been adequately investigated nor their effects proven.

Further, [Grossman \(2009\)](#) explicates the justification that was used. Even where chemicals might not do proven harm to humans, they can still contaminate air and water ways. Hence, nasty chemicals can invisibly enter the food chain and poison plants and fish animals. Therefore, they might be consumed by humans. Thus, these chemicals are dangerous.

Another justification strategy was to underline the unknown elements of chemistry and its relationship to human health and the environment ([Onianwa, 2015](#)). Minimal safety information exists for most chemicals used according to the European Commission. There were over 100,000 chemicals in use in the EU according to the survey of 1981. Yet only 3000 have been tested. Still over 800 are now known to be carcinogenic, mutagenic, or toxic. Such statistics were engaged to prove the fundamental logic behind REACH according to [Entine \(2011\)](#).

[Hartung and Rovida \(2009a\)](#) observe that the chemical industry tried to interject its argument. For instance, the rather toothless statement of continued use of many chemicals is justified because at low levels they are utilized and there is no proven harm to health. However, such statements were rejected citing the many substances that may accumulate in the body, thus reaching unsafe concentrations ([Kampa and Castanas, 2008](#)). In addition, they may also react with one another. Major concern is the production of new and unknown substances with elevated risks. Interestingly, [Edwards and Aronson \(2000\)](#) point out that the same issue clearly is present with medicines. Yet, the argument was accepted without further investigation. As a result, many dangerous chemicals were listed in Annex 1 of the Dangerous Substances Directive, which is now Annex VI of the CLP Regulation ([Monteny, 2005](#)).

9.5.3 Requirements

REACH has a three-tiered requirement system. It requires registration, evaluation, and authorization. REACH in accordance with [Rudén and Hansson \(2010\)](#) requires that:

- chemicals manufactured in quantities of greater than 1 ton to be “registered,”
- those manufactured in quantities greater than 100 tons to be “evaluated,” and
- SVHC must be “authorized.”

9.5.4 Information

REACH regulation requires transparent communication about chemical substances across the entire supply chain (Koch and Ashford, 2006). This requirement guarantees that customers, importers, and manufacturers are informed of health and safety issues associated with the chemical substances. Retailers are obligated to provide information about substances within their products. This must be done within 45 calendar days of receiving a formal request (Karlsson, 2010). According to REACH, retailers ought to drive manufacturers toward substituting less harmful substances in all products (Combes et al., 2003). The list of harmful substances is growing unabated (Entine, 2011). Haverland (2009) advises that this requires electronic firms to be vigilant and to constantly monitor announcements and substantive additions to REACH. This is best done via the European Chemicals Agency's website.

9.5.5 Registration

Registration is mandatory for any chemical substances manufactured or imported into the EU in quantities greater than 1 ton annually (Farn, 2008). A REACH requirement is to collect, collate, and submit data to the European Chemicals Agency (ECHA). This must be done on the hazardous properties of all chemical substances in this category. An exception was made from polymeric materials and nonisolated intermediates (Barry and Kanematsu, 2016).

9.5.6 Evaluation

Ågerstrand et al. (2014) highlight that evaluation is mandatory for any chemical substances manufactured or imported into the EU in quantities greater than 100 ton annually. Ågerstrand and Beronius (2016) add that evaluation provides the authority to ECHA to demand further information from registrants, and in a few limited cases from other supply chain members. Gustavsson et al. (2017) inform that there are two types of evaluation: dossier evaluation and substance evaluation.

Penman et al. (2015) explain that a dossier evaluation is conducted by ECHA to examine submissions for testing. ECHA must ensure that no unnecessary animal tests are carried out. Therefore, associated costs are also avoided.

ECHA performs a substance evaluation if a chemical substance presents a risk to health or the environment (Tischer et al., 2017). The suspicion is raised due to structural similarity to another already identified dangerous chemical substance. Therefore, all registration information is evaluated in every new case.

9.5.7 Authorization

Authorization is mandatory for any chemical SVHCs according to Basketter and Kimber (2014). This authorization requirement guarantees that risks from the use of such chemical substances are either sufficiently controlled or acceptable due to socio-economic circumstances and there are no available alternative substances or processes

(Giubilato et al., 2016). REACH enables restrictions of use to be implemented across the EU. Member States or the European Commission may present such proposals for consideration.

9.5.8 Information exchange

Lee et al. (2014) advises that manufactures or their importers must develop risk reduction measures. These must include all known uses of the chemical substance in the entire supply chain. REACH obligates users to provide details of their uses and all pertinent information to their suppliers.

9.5.9 Non-EU countries

Amenta et al. (2015) inform that many non-EU countries adopted and implemented REACH-related regulations. The Globally Harmonized System of Classification and Labelling of Chemicals (GHS) allowed a few countries to join a worldwide system of chemical registration scheme (Ribeiro et al., 2014). Serbia implemented the EU REACH system under the auspices of the EU IPA program. Switzerland has implemented REACH via a partial revision of the Swiss Chemical Ordinance Act. Turkey implemented REACH via its new Chemicals Management Regulation. China has chosen to comply with GHS according to Filipec (2017).

9.5.10 Issues

The primary criticism stems from the rather large costs to industry (Silbergeld et al., 2015; Iles et al., 2017). These costs are ultimately passed onto consumers according to Baudrillard (2016). Boström and Karlsson (2013) inform that REACH has also attracted tremendous criticism due to its inherent complexity. Thus, Vaughan (2015) highlights that there is a need to pay for REACH-related administration. In addition, Aulmann and Pechacek (2014) note that finding suitable replacements for banned substances is also a potentially expensive predicament. REACH was also criticized as restricting global trade (Karlsson, 2015).

Greens were also disappointed in REACH, inform Van Der Veen et al. (2014). The new law has attracted major concern because of its requirements for animal testing. Animal tests are now required but only allowed once per each new substance in cases where suitable alternatives cannot be used. The intellectual property owner must sell the associated rights of these results for a reasonable yet undefined price. This methodology raises questions of scientific validity as well as added unbounded costs.

Hartung is the former head of European Centre for the Validation of Alternative Methods (ECVAM). Hartung and Rovida (2009a) estimate that 54 million animals would be sacrificed for REACH. Their estimate shows that the associated animal testing costs approximately €9.5 billion. In a news release, ECHA criticized these assumptions (Hartung and Rovida, 2009b). ECHA's alternative assumptions included only one-sixth of the required animals (Rovida and Hartung, 2009).

9.5.11 Only representation

Non-EU companies offer “only representative” services according to [Motaal \(2009\)](#). REACH forbids registration of a substance if the “only representative” is not an EU-based entity. However, “only representative” status can be subcontracted to an EU-based business entity.

“Only representatives” must be EU-based companies and comply with Article 8 of REACH, which means that they must operate in a standardized and transparent way. Importantly, the “only representative” assumes all responsibility and liability for fulfilling the relevant obligations of importers in accordance with REACH for all the substances being imported into the EU by a non-EU entity ([Persson, 2007](#)).

9.6 RoHS

[LaDou \(2006\)](#) informs that the European Union Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment 2002/95/EC, also known as the Restriction of Hazardous Substances (RoHS), was approved by the Council on January 27, 2003. Directive 2002/95/EC was to be known as RoHS 1 ([Cho et al., 2012](#)). [Vandenberghe \(2008\)](#) explains that this Directive was amended and became 2008/35/EC and was approved by the Council on March 11, 2008. RoHS 1 was repealed on January 3, 2013 ([Achillas et al., 2013](#)). Directive 2011/65/EU was to be known as RoHS 2 ([Han et al., 2011](#)). This Directive was approved by the Council on June 8, 2011. Once again, a major review is being undertaken and entitled as the 2017 RoHS 2 scope review proposal.

[Goodship and Stevels \(2012\)](#) explain that these directives restrict the use of an ever growing but still small number of hazardous materials in the manufacture of electrical and electronic devices. [Widmer et al. \(2005\)](#) add that they are closely linked with the Waste Electrical and Electronic Equipment Directive (WEEE) 2002/96/EC. [Dimitrakakis et al. \(2009\)](#) highlight that this twin legislation sets collection, recycling, and recovery targets for electrical devices. They together form the foundation laws to solve the problem of electronic waste. The problem is exacerbated due to material toxicity ([Widmer et al., 2005](#)).

9.6.1 Lead-free

[Pecht et al. \(2004\)](#) state that RoHS is frequently referred to as the “lead-free directive.” [Shangguan \(2005\)](#) underscores that this certainly was its most disruptive element from an electronics perspective. [Ma and Suhling \(2009\)](#) explain that normal solder is composed of 63% tin (Sn) and 37% lead (Pb), which creates eutectic tin. However, the main ore of tin called cassiterite is a conflict mineral and as such tin is effectively captured by the US conflict resources law ([Fitzpatrick et al., 2014](#)), while the EU created the RoHS Directive with an effective date of July 1, 2006. Lead in any solder was forbidden from this day forward ([LaDou, 2006](#)).

[Suganuma et al. \(2009\)](#) advise that the first problem is that lead-free solder has a higher melting point than eutectic tin. Thus, components to be affixed with lead-free

solder need to withstand significantly higher temperature (McCluskey et al., 2006). However, there is a more insidious problem with lead-free solder in the form of tin whiskers. Sood et al. (2011) explicate that a famous example is the Toyota Camry electronic accelerator intermittent failure mechanism. This was investigated by NASA and the problem was traced to formation of tin whiskers according to Leidecker et al. (2011).

Lee and Lee (1998) defines whiskers as electrically conductive crystal structures made of hairlike tin filaments, which sometimes grow out of the metal's surfaces. They can grow a few millimeters in length. This is, however, long enough to short-circuit conducting wires and thereby disable proper functioning of vital components (Brusse et al., 2002). Chuang et al. (2007) inform that research has established that whiskers grow faster in vacuum than in atmospheric conditions. Brusse (2002) highlights that as such many satellite systems faced even more increased tin whicker problems. Large-value satellites have become inoperable due to misguided replacement of the solder material.

Daddona (2005) explains that pure tin produces whiskers. Traditional eutectic tin does not. Therefore, Subramanian (2007) informs that the space electronics industry has secured an exemption. They have kept using lead-tin alloys for space instruments. However, Puttlitz and Galyon (2007) assert that the general ban on lead in consumer electronics components has created difficulties for even space electronics. Since all consumer electronics industry has now replaced in lead alloys with lead-free solder, there are not many producers that can provide service for the space industry at a cost-effective manner.

9.6.2 Banned substances

Castell et al. (2004) highlight that each EU member state adopted RoHS. EU member states are responsible for enforcement and implementation (Cusack and Perrett, 2006). Shangguan (2005) informs that RoHS is frequently labeled as the "lead-free directive." However, Wäger et al. (2010) highlight that it currently restricts the use of the following 10 substances listed in Table 9.2.

Butyl benzyl phthalate, dibutyl phthalate, bis(2-ethylhexyl) phthalate, and diisobutyl phthalate were added as part of Directive 2015/863, which was published on March 31, 2015.

Polybrominated biphenyls and polybrominated diphenyl ether are flame retardants used in many plastics (Cusack and Perrett, 2006). Alaei et al. (2003) believe that the most important are ABS and polycarbonate. Morf et al. (2005) warns that these enclosure and housing materials must incorporate flame retardants to provide adequate fire safety in most electronics applications.

Salomons et al. (2012) explicate that hexavalent chromium is used in chrome plating, chromate primers and coatings, and in chromic acid. Most fasteners and other electronics components use hexavalent chromium for proper functioning (Li et al., 2012). Its replacement is not as straightforward as one would like to believe according to Wright and Elcock (2006).

Table 9.2 Hazardous substances

Hazardous substances
Bis(2-ethylhexyl) phthalate (DEHP)
Butyl benzyl phthalate (BBP)
Cadmium (Cd)
Dibutyl phthalate (DBP)
Diisobutyl phthalate (DIBP)
Hexavalent chromium (Cr6+)
Lead (Pb)
Mercury (Hg)
Polybrominated biphenyls (PBB)
Polybrominated diphenyl ether (PBDE)

As a rule of thumb, [Marinova et al. \(2008\)](#) advise that the maximum permitted concentrations in nonexempted products are 0.1% or 1000 ppm by weight. Of course, there is an exception for cadmium, which is in a much more restrictive category and therefore limited to 0.01% or 100 ppm by weight, add [Duarte et al. \(2010\)](#). [Lau et al. \(2010\)](#) highlight that the restrictions are in place for each homogeneous material in a device. This means that the limits do not take into consideration the mass of the completed product, or even its components. The limits apply to any single restricted substance that could theoretically be separated mechanically ([Goosey, 2007](#)). For instance, the sheath on a cable would form the base for the mass calculation or in another example the tinning on a component lead would serve the same purpose. This fact makes administration of this law relatively cumbersome, prone to errors, and misinterpretations according to [Cesaro et al. \(2017\)](#).

An illustrative example might serve to demonstrate the difficulties created by this law. A large smartphone or a tablet can be taken as an everyday device. Both are composed of a housing, circuit boards, various chips, rechargeable batteries, screws, washers, speakers, and many other components. The screws, washers, and even the housing might be made of homogenous materials. However, other components might comprise multiple subcomponents and these in turn might be constructed of many different materials. For instance, a PCB might include a multilayer board, several integrated circuits (IC), many resistors, capacitors, switches, and other basic components. A switch is also composed of a housing, some sort of a lever, a spring, a few contacts, pins, and others. Each of these components in turn might be made of different materials. A contact for instance, may include a copper strip with a surface coating. On the other hand, a speaker is usually composed of a permanent magnet, copper wire, vibrating element such as paper or another polymer and other substances. Here comes the catch! All materials that can be identified as homogeneous must meet the legally

imposed limit. Thus, if the housing was made of polycarbonate with less than quarter of a percent, say 2100 ppm (0.21%) PBB utilized as a flame retardant, which is a very low concentration, then the entire phone or tablet would fail the requirements of the Directive.

Wright and Elcock (2006) explain that medical devices, monitoring and control equipment were originally excluded. Thus, a loop hole was formed. The European Commission started a process in May 2006 recognizing this fact. Ultimately, Pecht et al. (2016) inform that a new legislation was created eliminating the medical devices, monitoring and control equipment exemption that became effective in July 2011.

Importantly, Andrews (2006) highlights that batteries are excluded from the scope of RoHS. Batteries are incorporated in the EC's Battery Directive (91/157/EEC) issued in 1991. Makuch (2003) explain that the first Battery Directive was concerned with trade barrier issues. However, the revised directive focuses on the harmful effects of battery waste disposal with regard to environmental improvements and protection (Wang et al., 2014; Lin and Chiu, 2015). Therefore, Turner and Nugent (2016) highlight that this Directive sets ambitious targets for automotive, consumer, and battery recycling. The actual manufacturer-provided collection target is 45% according to Fisher et al. (2006).

This Directive also sets heavy metal limits of 5 and 20 ppm for mercury and cadmium, respectively (Nnorom and Osibanjo, 2009). There are many exemptions, for instance, provisions are included for batteries used in emergency, medical, or portable power tools (Kim et al., 2012).

This Directive tries to restrict use of the major battery components. Winslow et al. (2018) advise that the Directive is targeting to recycle 75% of batteries that incorporate these hazardous materials. However, Recknagel et al. (2014) warn that limits of lead, lead-acid, nickel, and nickel-cadmium are not incorporated. Labeling information content is, however, mandated to facilitate recycling activities according to Rubik and Frankl (2017).

Salhofer et al. (2016) explain that this Directive controls equipment categories as defined by the WEEE Directive and are displayed in Table 9.3.

Importantly, Pecht et al. (2016) add that this Directive's scope does not extend to fixed industrial plant or tools. Horn (2016) explains that RoHS regulation applies to products made available within the EU. Origin information from the enforcement perspective is impertinent.

Nadvi and Raj-Reichert (2015) advise that the onus for compliance is placed on the company that makes the product available for the market. Compliance is not required of components and subassemblies. This regulation is firmly applied at a hitherto unrecognized homogeneous material classification level according to Mieke et al. (2015). This means that accurate information on all hazardous substance concentrations must be available across the entire supply chain (Lee et al., 2014).

Table 9.3 RoHS categories

RoHS categories
Automatic dispensers
Consumer equipment
Electrical and electronic tools
IT and telecommunications equipment
Large household appliances
Lighting equipment
Medical devices
Monitoring and control instruments
Semiconductor devices
Small household appliances
Toys, leisure, and sports equipment

9.6.2.1 Embedded substances

[Suganuma \(2001\)](#) informs that RoHS-restricted substances were deployed in many electronics applications. A few examples of lead-containing electronics components are listed in [Table 9.4](#) in accordance with [Li et al. \(2005\)](#).

[Ramachandra and Saira \(2004\)](#) point out that cadmium is also found in many of the components listed in [Table 9.4](#). Additional frequently used examples listed by [Mead \(2010\)](#) include nickel-cadmium batteries, plastic colorants, and many versions of photocells. Mercury is most commonly utilized in automotive switches and lighting

Table 9.4 Lead in electronics

Lead in electronics
Batteries
Camera lenses
Integrated circuits or microchips
Lamps and bulbs
Metal parts
Paints and pigments
Printed circuit board finishes, leads, internal and external interconnects
Polyvinyl chloride cables
Solders

applications according to Denton (2004). Hexavalent chromium is used for corrosion prevention in the form of metal plating (Eppensteiner and Jennkind, 2007), while diphenyl ethers-oxides and polybrominated biphenyls are important flame retardants (Alaee et al., 2003).

9.6.2.2 *High-tech waste*

Grossman (2007) explains that RoHS regulation was created to reduce hazardous materials in electronics. It was recognized that electronics obsolescence is accelerating and thus producing ever more waste including harmful substances (Widmer et al., 2005). Wath et al. (2011) highlight that this waste generally ends up in Third World Countries, which creates further long-term problems.

9.6.2.3 *Legal precedent*

RoHS is said to be justified based on over 50 years of toxicology research in the long-term effects of low-level chemical exposure (Awadalla, 2013). Grandjean and Landrigan (2006) explicate that relatively low concentrations of environmental toxins have been responsible for developmental, neurological, and reproductive defects. RoHS provides a new environmental legislative precedent in contrast to most statutes that seek redress for acute toxicity such as direct exposure to unusually large amounts of hazardous substances that were the proven cause of severe injury or death (Barba-Gutiérrez et al., 2008).

9.6.2.4 *Lead-free solder life-cycle assessment*

Ma and Suhling (2009) inform that the harmful effects of tin-lead and lead-free solder in bar and paste forms were studied and funded by the US Environmental Protection Agency (EPA). Gehin et al. (2008) state that a life-cycle assessment was published with respect to the most common uses in electronics. The tin-copper alternative scored best from the list of lead-free solders in bar form (Bradley et al., 2007). Kumar et al. (2008) explain that the bismuth–tin–silver alloy was best in paste form. All lead-free alternatives scored better than eutectic tin-lead solder (Kliopova and Laukytė, 2006). Herat (2008) asserts that this is not a surprising finding given the well-known toxicity of lead. Lead leaching from PCBs was the primary mode of identified transmission according to Park and Fray (2009).

9.6.2.5 *rominated flame retardant life-cycle assessment*

(Shi et al., 2009) highlight that brominated flame retardants (BFRs) ban has created difficulties for the supply chain. This ban is affecting plastics that contains a 0.1% or above BFR additive level. BFR level assessment is neither cheap nor simple (Kemmlin et al., 2009). Therefore, Choi et al. (2009) believe that suspected plastics with potentially high BFR concentrations became expensive to handle or discard. This includes most of the electronics enclosures, housings, and even packages according to Rakotomalala et al. (2010).

Pöhlein et al. (2005) elucidate that there are a few analytical techniques for measuring BFR concentration levels. X-ray fluorescence spectroscopy can pinpoint presence of bromine (Br). However, it does not indicate BFR concentration levels. Ion attachment mass spectrometry can be utilized to measure BFR concentrations in polymers. Chen et al. (2010) highlight that both methods are extremely expensive and put a potential analysis out of reach of the average plastics recycler. Thus, Sindiku et al. (2015) conclude that the BFR ban has significantly affected both new product development and recycling efforts globally.

9.6.2.6 RoHS 2

Gensch et al. (2014) explain that Directive 2011/65/EU is the second version of RoHS and therefore often labeled as RoHS 2. This Directive became EU law on July 21, 2011, with an effective date of January 2, 2013. Dalhammar (2016) adds that it is an evolutionary law in that it addresses the same issues as the first Directive. The substances are the same but some clarity is furnished. The Directive’s scope has crept in that the second version also covers additional electrical and electronic equipment, cables, and even spare parts according to Svensson (2016).

In addition, Horn (2016) highlight that the CE logo now indicates compliance with RoHS 2. Declaration of conformity is also detailed. Compliance must be demonstrated in sufficient detail. Noncompliance is a criminal offense. This Directive mandates production control and traceability via technical files like all CE marking Directives (Pecht et al., 2016). Humphrey (2017) explains that the difficulty is that to demonstrate conformity on the date of placing the product on the market is critical. An assessment must be made factoring in all exemptions on that date. According to Stark (2016) many electronics OEMs misunderstand compliance. Kanapathy et al. (2016) point out that this is because it is easy to make a noncompliant product by assembling compliant components only. Wang et al. (2017) warn that RoHS 2 also includes additional responsibilities for importers and distributors.

9.6.2.7 Additional substances

Ge et al. (2016) explain that Directive 2015/863 effectively bans four additional substances listed in Table 9.5. The maximum permitted concentrations in nonexempted products are 0.1%.

Table 9.5 Additional banned substances

Additional substances
Benzyl butyl phthalate (BBP)
Bis(2-ethylhexyl) phthalate (DEHP)
Dibutyl phthalate (DBP)
Diisobutyl phthalate (DIBP)

9.6.3 Restriction exemptions

Menon et al. (2015) advise that there are many exemptions numbering over 80. Some of these exemptions are wide-ranging. Therefore, Gensch et al. (2015) add that vigilance is required in all assessments. George and Pecht (2016) explain that exemptions automatically expire unless renewed. Kroupa et al. (2015) highlight that automatic expiry is set at either fifth or seventh year. Not surprisingly, most novice examiners get easily confused (Fortier and Pecht, 2017).

A few exemption examples in accordance with Deubzer et al. (2012):

Lead as an alloying element in steel containing up to 0.35% lead by weight, aluminum containing up to 0.4% lead by weight, and copper alloy containing up to 4% lead by weight.

Category 6c

Lead in high melting temperature type solders.

Category 7a

Lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, transmission, and network management for telecommunications.

Category 7b

Wright (2007) states that medical devices were exempted in RoHS 1. The second version of the Directive narrowed the exemption's scope and allows only active implantable medical devices in category 4h (Bhujbal, 2015).

9.6.4 Labeling and documentation

Fargnoli et al. (2013) warn that products within this Directive's scope must display the CE mark to show compliance. In addition, Barry and Kanematsu (2016) inform that the manufacturer's name, address, and a serial or batch number must also be displayed. More detailed compliance information can be located on the EU Declaration of Conformity for the product (Fargnoli et al., 2013). This is created by the OEM. Either the OEM or the EU representative is responsible for the design. Kroupa et al. (2015) highlight that the OEM must keep a technical file or technical records to demonstrate acceptable compliance.

9.6.5 Other standards

Pigosso et al. (2016) explain that new electrical and electronics equipment developers should be aware of other relevant environmental standards in addition to RoHS. Manufacturers often find that it is less expensive to create a single bill of materials for a global product instead of customizing the product to fit each region's specific laws. Therefore, Schaltegger et al. (2017) highlight that they develop their own standards.

Corporate standardization usually errs on the safe side and creates the most stringent supply chain regulation that creates over priced products that cannot compete effectively (Delmas and Pekovic, 2013; Epstein and Buhovac, 2014; Welford, 2016). Hence, Schaltegger et al. (2017) emphasize that great level of expertise and care must be exercised before an entire organization is committed to undermine its long-term competitive advantage by careless internal standardization.

9.6.6 Issues

Koh et al. (2012) inform that RoHS attracts its fair share of criticism. The two major criticisms are the negative effects on product quality and the exceptionally high cost of compliance according to Dietsche et al. (2016). In addition, Davies et al. (2015) assert that the fundamental point of RoHS is being questioned. Research indicates that the life cycle benefits of lead-free solder might have been overstated (Hendricks et al., 2015).

Herat (2007) highlights that RoHS restricts the use of lead and cadmium in electronics but does not address the most significant applications. Importantly, Ongondo et al. (2011) elucidate that only 2% of world lead consumption is related to electronics. Batteries are responsible for 90% of usage. Thus, Li et al. (2015) emphasize that batteries use 45 times the amount of the electronics applications. Therefore, George and Pecht (2016) believe that the cost to bear by the electronics industry is unfair.

McConnell et al. (2015) state that the most common lead-free solders have a 30°C higher melting point. However, Cheng et al. (2017) point out that wave soldering temperatures stayed the same at around 255°C. This means that lead-free solders have longer wetting times than eutectic solders, observe Zhang and Tu (2014).

Bent et al. (2015) believe that selection of RoHS compliant solders is not a simple matter. Xu (2014) advises that some formulations are stiffer with decreased ductility. This in turn increases the probability of cracking instead of deforming (Mahesan Revathi, 2015). Baksheeva (2015) observes that this behavior is markedly different from lead-based solders. As a result, Berni et al. (2016) emphasize that both thermal and mechanical analysis must be carried out simultaneously. Jacques et al. (2017) demonstrates that mapping thermal stresses over a mechanical finite element model is not a simple matter. Alexandridis et al. (2017) explain that this must be done to optimize component placement, selection, and thermal management on every PCB.

Fortier and Pecht (2017) assert that the transition to lead-free solder has affected long-term reliability of electronic devices and other systems incorporating electronics. These effects are especially important in mission-critical applications. The following lead-free solder issues are common and compromise reliability, thus perceiving quality in accordance with Puttlitz and Stalter (2004):

- Damage to PCB components
- Increased moisture sensitivity
- Warping or delamination of PCBs

9.6.6.1 Reliability issues

Tin whiskers growth is one of the most significant problem of lead-free, high tin-based solders (Tu and Li, 2005; Abteu and Selvaduray, 2000; Amin et al., 2017; Li et al., 2014; Illés and Horváth, 2014; Xue et al., 2014; Krammer et al., 2017). Dunn (2016) explains that tin whiskers are thin strands of tin that can grow to hairlike structures and make contact with an adjacent trace on the PCB, thereby creating a short circuit. Pinsky et al. (2016) warn that tin whiskers have been found to be the culprit in many electronics failure investigations. For instance, Daddona (2005) highlights that tin whiskers caused a nuclear power plant shutdown. In addition, Kostic (2011) informs that pacemaker incidents were documented. Wavrik et al. (2009) warns that mitigation of these well-documented problems is neither simple nor inexpensive. Kumar et al. (2008) inform that lead-free solder manufacturers offer tin–zinc formulations that produce nonconducting whiskers. Other formulations reduce whisker growth. However, Kato et al. (2016) assess that none of these approaches has been successful to eliminate whiskers growth in all circumstances.

9.6.6.2 Financial cost

Wilson et al. (2011) highlight that there are no de minimis exemptions. This means all must comply with RoHS, even small- and medium-sized business enterprises. Butler and McGovern (2012) believe that complying with RoHS due to its complexity is very costly. In addition, Ganesan and Pecht (2006) demonstrate that cost of product failures is significant. For example, Osterman (2006) adds that tin whiskers were responsible for a large number of Swiss Swatch failures. Swatch applied for an exemption according to Kumar et al. (2008). He continues that this request was denied.

9.7 WEEE

Bigum and Christensen (2011) inform that the WEEE Directive is a European Community Directive 2012/19/EU. Ziegler (2013) adds that the (WEEE) Directive became European Law in 2003. The major goal of the WEEE Directive is to set a collection, recycling, and recovery target for all types of electrical goods according to Cucchiella et al. (2015). Torretta et al. (2013) highlight that the minimum target rate was initially 4 kg per head of population per annum and this was increased to the current 2% of electrical and electronics waste equipment. 3,868,818 tons of WEEE was collected in 2015 (Salhofer et al., 2016; Parajuly et al., 2017; Lixandru et al., 2017; Bahers and Kim, 2018).

Butler (2008) informs that a crossed-out wheelee bin is the representative symbol of WEEE. A black line under the symbol indicates that goods have been placed on the EU market after the 2005 effective date. Clyncke (2014) adds that goods with the sign but without the black underline were manufactured between 2002 and 2005. These devices are treated as an “historic WEEE” and attract no reimbursement from the producer compliance schemes (Xevgenos et al., 2015; Friege et al., 2015).

9.7.1 Directive revisions

[Yamane et al. \(2011\)](#) highlight that the directive has been revised many times since its 2002 inception. 2006 and 2009 marked the first updates ([Dimitrakakis et al., 2009](#)). [Huisman \(2010\)](#) explains that after 9 years the Directive was unable to achieve its stated goals. Hence, [Botsford \(2010\)](#) adds that the law was amended yet again. [Dindarian and Gibson \(2011\)](#) inform that the European Parliament and the European Council agreed on amendments on December 20, 2011. This version became law on January 19, 2012.

[Huisman \(2010\)](#) elucidates that the changes primarily affect the method for calculating collection rates. The target was previously 4 kg per head of population annually. A revised method of calculation was introduced. However, [Haupt et al. \(2017\)](#) add that a transitional period of 7 years was also agreed to and the previous method was retained for the first 4 years until 2016. From 2017 the calculation of collection rates was revised to 65% of the weight of WEEE classified products entering the EU market ([Vanegas et al., 2017](#)). [Kalmukova et al. \(2017\)](#) add that the overall target for the entire EU is to recycle at least 2% of WEEE.

9.7.2 Member state implementation

Importantly, [Corsini et al. \(2017\)](#) highlight that responsibility for the disposal of WEEE rests with the manufacturers or distributors of the original equipment. [Dieste et al. \(2017\)](#) add that it obligates electronics companies to establish an infrastructure for collecting WEEE. The Directive states in accordance with [Atlason et al. \(2017\)](#) that

Users of electrical and electronic equipment from private households should have the possibility of returning WEEE at least free of charge.

[Dalhammar \(2017\)](#) highlight that this Directive prompted formation of “producer compliance schemes” in all EU member states. These schemes are operating with the support of manufacturers and distributors. They pay annual contributions for the collection and recycling of waste electronics. [Huang and Atasu \(2017\)](#) demonstrate that the electronics are sourced from household waste recycling centers and not directly from consumers.

9.7.3 Deadlines

[Turner and Callaghan \(2007\)](#) explain that the WEEE Directive obliged the 25 EU member states to adopt its provisions into their national law by August 13, 2004. Cyprus met this deadline but no others. One year after the original deadline past, on August 13, 2005, all member states complied except the United Kingdom. The WEEE Directive was finally adopted by the United Kingdom in 2006. Therefore, [Nugent \(2017\)](#) warns that deadlines appear to be rather flexible in the EU among the sovereign nation states.

9.7.4 Categorizations of WEEE

Hennebert and Filella (2018) observe that classification of WEEE can be made from several perspectives. Turner and Filella (2017) believe that temporality can be the first perspective. Johnson et al. (2016) add that there are historic and nonhistoric WEEE. Historic WEEE means that the electronic equipment was placed on the EU market prior to 2005. Franquesa et al. (2015) highlight that the WEEE Directive requires the last owner of the equipment to assure its recycling. Nonhistoric WEEE begins with 2005. This fact is demarcated as an underlining of the official WEEE symbol. Ylä-Mella et al. (2014) add that recycling any electronics displaying such a symbol is the responsibility of the manufacturer or its local distributor. They must assure collection and recycling of their devices. Cesaro et al. (2017) explain that another perspective is the official EU classification. This Directive created 10 major WEEE categories for reporting purposes shown in Table 9.6 in accordance with Wäger and Hischier (2015).

9.8 Review

There are a few sustainability-related legislations that demand awareness, monitoring for changes such as new or expired exemptions, understanding of its myriad of complexities, and ultimately full and proven compliance (Kiron et al., 2013). No electronic enclosure, housing, and package developer or manufacturer can afford to be found negligent in these areas (Griffin et al., 2014a,b; Hines, 2013; Hughes, 2016). Park and Roome (2017) warn that every one of these laws’ jurisdiction is limited, but in a globally interconnected economy, their true influence is indeed worldwide. Therefore, the most important initiatives have been reviewed.

Table 9.6 WEEE categories

WEEE categories
Automatic dispensers
Consumer equipment
Electrical and electronic tools
IT and telecommunications equipment
Large household appliances
Lighting equipment
Medical devices
Monitoring and control instruments
Small household appliances
Toys, leisure, and sports equipment

Conflict minerals legislation and compliance is important from an electronics perspective (Zhang et al., 2017; Dalla Via and Perego, 2017; Jameson et al., 2016). Bonevich (2013) explains that lead-free solders rely on tin, which is regulated by this law. Other elements are also important materials in electronics. 3TG is the label, which generally indicates conflict minerals according to Barume et al. (2016). These are tin, tungsten, tantalum, and gold.

The concept of EoL is important from a supply chain point of view (Govindan et al., 2015). Stark (2015) explains that significant hardware and software issues could manifest themselves if the new product development team does not prepare a workable strategy on how to overcome the disparity in various industries' EoL time frames. Kühn et al. (2016) emphasize that the heavy metals category is another area of concern that legislators have been regulating. Therefore, Chen et al. (2016) assert that knowledge of this area is a prerequisite in the electronics industry.

REACH is the overhauled EU chemicals policy according to Biedenkopf (2018). Rudén and Hansson (2010) explicate that understanding of the registration, evaluation, authorization paradigm of REACH is important. Avoidance of SVHC is paramount (Giubilato et al., 2016). Biedenkopf (2015) advises that knowing the rules of "only representative" services is a must for non-European OEMs and their supply chains.

Ganesan and Pecht (2006) inform that RoHS is not only the "lead-free" initiative. For instance, Cusack and Perrett (2006) add that the banned flame retardants were extremely important from an electronics housing perspective. Rakotomalala et al. (2010) believe that their replacement is neither simple nor cheap. Hua et al. (2009) highlight that hexavalent chromium is important with respect to fasteners and other metal surface treatments. Kanapathy et al. (2016) warns that compliance of a product cannot be assured by assembling compliant components due to the inherent complexities of RoHS legislation. Therefore, Iannuzzi (2017) emphasizes that high-quality expertise must be applied to assure compliance. WEEE adds another important criterion into the product development mix and it is intended to work in conjunction with RoHS according to Koh et al. (2012).

9.9 Hot tips

The electronic enclosure, housing, and package developer and manufacturer must create a robust process to deal with sustainability issues (Hallstedt et al., 2010). Importantly, Kanapathy et al. (2016) warns that the sustainability label camouflages a substantial compliance undertaking. Therefore, Rakotomalala et al. (2010) advise that this function must be resourced adequately. Pinsky et al. (2016) add that some of these initiatives also affect electronics reliability and require additional high-quality engineering effort to mitigate its consequences. The most important issues are as follows in accordance with Luzzini et al. (2015):

- Conflict resources, REACH, RoHS, and WEEE have global reach despite their limited jurisdiction.
- 3TG conflict minerals equal tin, tungsten, tantalum, and gold.

- Synchronize EoL time frames to avoid unexpected future difficulties.
- Understand the registration, evaluation, authorization paradigm of REACH.
- Avoid SVHCs.
- Compliance of a product cannot be assured by assembling compliant components.
- WEEE recycling targets and labeling compliance need to be planned for at the new product development stage.

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10.1 Introduction

Enclosures need to be specified correctly according to Drury (2001). Babiarz et al. (1999) inform that one way to do this is to use the IP and IK codes. However, Lee et al. (2018) explain that there are other dimensions that also need to be carefully evaluated to create a successful enclosure for any electrical or electronic equipment. Meller and DeShazo (2001) assert that environmental considerations are paramount in enclosures that are exposed to the elements. However, Kreeley and Coulton (2018) highlight that all enclosures are affected by the cooling effect or forming condensation if the environmental conditions deteriorate sufficiently. Enclosures designed for hazardous areas must be afforded special attention according to McMillan (1998). Important details are listed in the hazardous areas section. Hose-down areas (Moerman, 2011) and corrosive environments (Manahan et al., 2015) provide a special challenge to the practicing enclosure engineer. Gasket selection data are enclosed to assist with this task in accordance with Gnecco (2000) and Tong (2016). Extreme weather (Boggess et al., 2014; Berg and Krauß, 2010) and cold (Rowe et al., 2001; Keane et al., 2013; Jaguemont et al., 2016) along with long-term exposure (Paul and Bier, 2018; Méndez, 2017) information is provided to complete the environmental consideration framework.

10.1.1 The cooling effect

A standard enclosure is designed to allow rainfall to be channeled around protected and often gasketed areas. However, problems could occur in cases when the internal temperature is reduced rapidly (Sun and Zheng, 2006). Thomas (1976) recognized that in such cases the internal pressure in a high ingress protection (IP) rating enclosure is much lower than the external pressure. This presents a significant challenge as a suction effect is induced according to Griffin et al. (2008). This effect draws moisture through even many gasketed areas. Thus, moisture might find its way into the protected areas of the enclosure.

This effect is minimized by reducing the number of or eliminating gasketed areas in contact with rain (Association, 2007). This could simply be done by choosing an enclosure with gutters or fitting a well-designed rain hood (Association, 2011). Alternatively, the enclosure design might incorporate provisions for rapid pressure equalization. Ghirardi and Mills (1978) explain that this is done by controlled ventilation. Nevertheless, Mitolo and Montazemi (2014) add that this practice often reduces the associated IP rating.

10.1.2 Condensation

Vancauwenberghe et al. (1995) highlight that condensation creates major problems for the electrical and electronics industries. Water collecting in the bottom or lower portion of the enclosure must be avoided according to Thue (2016). In addition, moisture may also condense on the internal components (Vancauwenberghe et al., 1996). This in turn cause electrical “tracking” and “leakage” in the short term and degradation of insulation and component corrosion in the medium to longer term (Goudie et al., 1998; Amin and Salman, 2006; Tavner, 2008).

It is important to note according to Manahan et al. (2015) that condensation is frequently mistaken for water ingress. However, (Bergman and Incropera, 2011) demonstrates that it is caused by a difference in temperature (ΔT) between the outer and inner enclosure surfaces. You et al. (2017) explain that condensation generally forms on the same side as the prevailing wind. Ge et al. (2017) believe that there is no simple, special, or all-effective solution to this problem. Controlled ventilation, anticondensation paint, or heaters are all enlisted in this battle (Hao et al., 2014; Byrne, 2014).

Seinfeld and Pandis (2016) explain that water vapor is almost always present in air. Przybylak (2016) highlights that air becomes saturated if air is cooled and the “dew point” is reached. Further cooling below this temperature results in condensation according to Friedman et al. (1962). Therefore, Nasirabadi et al. (2016) conclude that a search for the cause of moisture in an enclosure on a “warm” that is above “dew point” day is futile. It means that the condensation has already evaporated. The problem will surely return as soon as the temperature drops below the “dew point” again.

10.1.3 Corrosive environments

In many applications enclosures will need to resist various chemical attacks (Levchik and Weil, 2006). This is important from the point of materials selection. Ashby and Johnson (2013) elucidate that a likely choice is stainless steel in addition to carefully selected plastics. Care must be exercised and only a materials expert can select the proper grade of material fine-tuned to an application according to Ashby (2000). Importantly, once the conditions change, for instance the processing plant changes products, the material selection is no longer valid. Hence, periodic reviews are necessary in corrosive environments highlighted by Hauge et al. (2016).

Wypych (2016) explain that most materials have good resistance to certain chemicals while attacked to a certain extent by all others. Therefore, Ashby and Cebon (1993) assert that expert advice must be obtained when finalizing material selection and construction methods. For instance, electronic components held within the enclosure may need significant protection from harmful gases (Wald and Jones, 1987).

Marine, Coastal, and Off-shore add the challenge of salt-laden atmosphere into the material selection mix according to Brun et al. (2016). Kobougias et al. (2013) explain that offshore specifications cover a wide range, from a very high IP rating enclosure on a ship’s deck through a relatively low rating enclosure usually found in any of the varieties of accommodation areas. Conseil et al. (2014) opine that many users have very

clear expectations and associated specifications. Still, if in doubt always contact a qualified expert assert [Jacobsen et al. \(2014\)](#).

10.1.4 Hose-down areas

[Moerman \(2011\)](#) highlights that hose-down areas require special enclosures. Hose-down enclosures are usually found in food, pharmaceutical, and other processing plants where the environment is subject to specific and demanding regulations according to [Buschart \(2012\)](#). These enclosures are chosen to be free of unnecessary surface treatment. The reason for this is to avoid contamination. For instance, [Moerman and Lorenzen \(2017\)](#) point out that flaking off paint could potentially enter the manufacturing process and thereby cause significant hazards, liability, and loss of production.

[Moerman and Wouters \(2016\)](#) explain that many users selected stainless steel designs, which have minimized external features. Such enclosures offer ease of cleaning according to [Manahan et al. \(2015\)](#). Nevertheless, many nonmetallic products offer the same or even improved benefits. However, [Ashby and Cebon \(1993\)](#) explain that stainless steel enclosures are popular in such applications perhaps because they promise to maintain the best appearance for a long time according to [Verran et al. \(2001\)](#).

[Sheldrake \(2016\)](#) explicates that in all cases special precautions and significant care must be taken with enclosures in a hose-down area. [Nagarajan and Welker \(1992\)](#) demonstrate that very high-pressure hoses can often exceed the IP rating of the enclosure. [Berrie \(2013\)](#) points out that this results in immediate and clearly unexpected water ingress. In addition, the previously described condensation can be a significant challenge especially in cool areas ([Lienig and Bruemmer, 2017b](#)).

10.1.5 Outdoor enclosures

[Mohla et al. \(1999\)](#) emphasize that attention must be focused on the prevailing weather conditions, including ranges and extremes of temperature when an enclosure is utilized outside. [Grondzik and Kwok \(2014\)](#) explain that thermal conditions will have a significant impact in the determination of the appropriate material. For instance, a decision to use plastics, aluminum, steel, or another more exotic material can only be made once the use temperature range is firmly established according to [Konh \(2017\)](#). [Jahan et al. \(2016\)](#) assert that the provision of additional equipment like heaters, thermal management systems, vents can also only be determined based on the functional requirement specification (FRS). Other issues also need enclosure engineering decisions such as special finishes perhaps in the form of an anticondensation paint according to [Hernández-Moreno and de la Torre \(2017\)](#).

There are many standard steel enclosures on the market. [Das et al. \(1997\)](#) explain that these usually are designed to meet industrial environmental demands. However, [Babrauskas \(2017\)](#) believes that failure to take account of all use conditions can invariably result in serious damage to the enclosure. Thereby, [Krause et al. \(2017\)](#) highlight that the safety of contents cannot be assured and reliability problems follow.

10.2 Enclosure specifications

Heberlein et al. (1996) explain that each specification has a different protection focus. Groh (2003) asserts that this results in the application of a different concept as well as zone suitability. Applicable codes, IP rating, impact resistance, potential material limitations are also listed in accordance with Horvath (2010). Examples of special requirements and application notes are also provided. The nonincendive focus is displayed in Table 10.7. Increased safety is shown in Table 10.8. Intrinsic safety characteristics are displayed in Table 10.9. The pressurized focus is shown in Table 10.10 while the flameproof concept is displayed in Table 10.11, oil immersion in Table 10.12, and powder and sand in Table 10.13 completes this review.

10.3 Ingress protection (IP ratings)

This section includes the relevant rules and examples of IP also known as IP ratings in accordance with Lienig and Bruemmer (2017a). Further information could be gathered by reading one of the geographically relevant standards (Lüthje, 2002).

10.3.1 Rules

The IP code is defined in the following standards: *BS EN 60,529: 1992 Degrees of protection provided by enclosures (IP code)*, *EN 60,529: 1991*, *IEC 60,529: 1989* and others (Eckhoff, 2006). These standards contain specification for degrees of protection provided by enclosures. Lienig and Bruemmer (2017b) explain that the IP or IP code provides a means of specifying the ability of an enclosure to protect its contents from intrusion by external objects. The standard applies to enclosures for electrical and electronic equipment with a rated voltage not exceeding 72.5 kV.

Mitolo and Montazemi (2014) explain that the 60,529 standard provides definitions, designation, and requirements for degrees of IP provided by enclosures for:

protection of equipment inside the enclosure against ingress of solid foreign objects; protection of persons against access to hazardous parts inside the enclosure; protection of equipment inside the enclosure against the ingress of water.

Table 10.1 European gas grouping classification

Group I	Mining only (underground firedamp methane)
Group II	Surface industry and “offshore” installations
Group IIA	Butane-like substances
Group IIB	Formaldehyde-like substances
Group IIC	Hydrogen- or acetylene-like substances

Table 10.2 International zone classification

Zone 0	Hazard is continuous or present for a long period.
Zone 1	Hazard is likely to be present.
Zone 2	Hazard is unlikely to be present or only present for short periods of time such as intermittently.

Arrangement of the IP code is displayed in [Table 10.14](#) in accordance with IEC 60,529:1989.

The letter “X” is used in cases if a characteristic numeral is not required. Double X that is “XX” is displayed if both numerals are omitted. Additional and supplementary letters might be omitted without replacement characters inserted. Letters need to be listed alphabetically if more than one supplementary letter is utilized. The relevant degrees of protection must be indicated by the original equipment manufacturer (OEM) if an enclosure provides different degrees of protection for alternative mounting arrangements. The degree of protection also needs to be specified in the instructions related to the relevant mounting arrangements.

Details for the marking of an enclosure are given in Clause 10. The meaning of the first characteristic numeral is shown in [Table 10.15](#) and the second characteristic numeral in [Table 10.16](#). Potential values for the additional letter are listed in [Table 10.17](#) and the supplementary letters are shown in [Table 10.18](#).

Table 10.3 Comparison of classification systems

ATEX, IECEx and US and Canada zones system		US and Canada class—division system	
Gas and dust group	Typical substances	Gas and dust group	Typical substances
IIC	Acetylene	Class I, Group A	Acetylene
IIB + H2	Hydrogen	Class I, Group B	Hydrogen
IIB	Ethylene	Class I, Group C	Ethylene
IIA	Propane	Class I, Group D	Propane
IIIC	Conductive dust	Class II, Group E	Combustible metal dust
IIIB	Nonconductive dust	Class II, Group F	Combustible carbonaceous dust
		Class II, Group G	Combustible dusts not in group E or F
IIIA	Combustible particles	Class III	Combustible fibers and particles

Table 10.4 Temperature code

Group II and III			Class I, II, and III		
Maximum surface Temperature of equipment [°C]	Temperature class	Ignition temperature of gas or dust [°C]	Maximum surface Temperature of equipment [°C]	Temperature class	Ignition temperature of gas or dust [°C]
400	T2	>300–450	450	T1	>450
300			300	T2	>300–450
			280	T2A	>280–300
			260	T2B	>260–280
			230	T2C	>230–260
	T3	>200–300	215	T2D	>215–230
200			200	T3	>200–215
			180	T3A	>180–200
			165	T3B	>165–180
			160	T3C	>160–165
135	T4	>135–200	135	T4	>135–160
			120	T4A	>120–135
100	T5	>100–135	100	T5	>100–120
85	T6	>85–100	85	T6	>85–100

Table 10.5 Approval agencies

Approvals	Agencies	Applicability
ATEX	Baseefa—British Approvals Service for Electrical Equipment in Flammable Atmospheres KEMA—NV tot Keuring van Elektrotechnische materialen LCIE—Laboratoire Central des industries Electriques	European Union
CSA	CSA—Canadian standards Association	North America
CUTR	FGUP certification Centre: SC VSI VNIIFTRI certification body: OS VSI VNIFFTRI	Russia, Belarus, Kazakhstan, and Armenia
FM	FM—Factory Mutual	North America
IECEX	CSA—Canadian standards Association Baseefa—British approvals service for electrical equipment in flammable atmospheres	International
INMETRO	INMETRO—National Institute of Metrology, Quality and Technology	Brazil
NEPSI	NEPSI—National Supervision and Inspection Centre for explosion protection and safety of instrumentation	China
SAA	SAA—Standards Association of Australia	Australia
TIIS	TIIS—Technology Institution of Industrial Safety	Japan

10.3.2 IP code examples

The examples displayed in Table 10.19 demonstrate the various potential arrangements of numerals and letters in an IP code marking in accordance with Wilkie (2004) and Calder et al. (2018).

Table 10.6 UL tests

Type 3: Concrete dust is circulated around the enclosure and hose tested
Type 4: 246 L per minute of spray for a minimum of 5 min from 3 to 4.5 m
Type 6: Temporary submersion in 1.8 m of water for 30 min
Type 6P: Temporary submersion in 1.8 m of water for 24 h
Type 12: dripping water and circulation of concrete dust
Type 13: 7.6 L per minute of a water with a wetting agent mix for 30 min

Table 10.7 Nonincendive

Protection focus	Nonincendive
Code	EX N, EXn
Principle of concept	Nonsparkling in normal use
Zone suitability	Zone 2
IP rating	IP54 (min)
Impact resistance	7 nm
Material limitations	None
Examples of special requirements	Portable equipment 1 m drop test
Application	Luminaries, motors, junction boxes

[Cole et al. \(2015\)](#) advise that it is important to note that care should be taken not to overspecify an IP rating for an application. This is because the cost of an enclosure increases rapidly with the rise in IP rating.

10.4 Mechanical impacts (IK code)

[Smith and Madden \(2008\)](#) explain that the mechanical impacts also known as IK code is defined in the standard *EN 50,102: 1995 Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK code)* and provides a means of specifying the enclosure's capacity to shield its contents from external impacts.

[Adams \(1994\)](#) elucidates that prior to the advent of EN 50,102 in 1995 a third numeral was added to the IP code to indicate the level of impact protection, for

Table 10.8 Increased safety

Protection focus	Increased safety
Code	EEx e
Principle of concept	Nonsparkling and nonincendive
Zone suitability	Zone 1 and 2
IP rating	IP54 (min)
Impact resistance	7 nm
Material limitations	None
Examples of special requirements	None
Application	Luminaries, motors, junction boxes

Table 10.9 Intrinsic safety

Protection focus	Intrinsic safety
Code	EEx i
Principle of concept	Electrical energy is limited below that which could cause an explosion
Zone suitability	“ia” zone 0,1,2 “ib” zone 1,2
IP rating	IP54 (min)
Impact resistance	None
Material limitations	None
Examples of special requirements	None
Application	Instrumentation, control, low power devices

instance, IP66(9). [Bolund \(2006\)](#) opines that abuse of this system was the main factor leading to the development of a separate standard. This system uses a separate two numeral code to differentiate it from the old approach. The standard was enacted in October 1995. Previous conflicting national standards were withdrawn by April 1997.

[Smith and Madden \(2008\)](#) explain that EN 50,102 specifies the way enclosures must be mounted during tests. In addition, environmental conditions, number of impacts and their distribution is also specified. The size, style, material, dimensions of the various impact hammers are elaborated to provide the necessary testing harmonization.

Table 10.10 Pressurized

Protection focus	Pressurized
Code	EEx p
Principle of concept	Pressurization prevents entry of the external gas and purging is necessary before power is switched on
Zone suitability	Zone 1 and 2
IP rating	IP40
Impact resistance	7 nm
Material limitations	Normally metal construction
Examples of special requirements	To withstand 1.5x max operating pressure with min 200 Pa
Application	Control panels, motors, computers, and instruments

Table 10.11 Flameproof

Protection focus	Flameproof
Code	EEx d
Principle of concept	Must be capable of containing an explosion
Zone suitability	Zone 1 and 2
IP rating	Suggest IP54
Impact resistance	7 nm
Material limitations	Generally cast alloys/iron
Examples of special requirements	Special consideration of flame paths at flange joints
Application	Motors, junction boxes, luminaries, and control devices

10.5 Cooling

[Esselen and Tischer \(1945\)](#) explain that cooling is utilized in a fantastic way in preserving food. Hot food is placed into a glass jar in most canning processes. A fitting lid is then placed on top of the jar with an integral seal. This seal's function is equivalent to a gasket's. The seal rests between the lid and the rim. The jar is then allowed to slowly cool to ambient temperature. The practical application of the physics principles is interesting indeed.

Table 10.12 Oil immersion

Protection focus	Oil immersion
Code	EEx o
Principle of concept	Immersing incandive devices in oil. BSEN 50015 does not allow sparkling devices.
Zone suitability	Zone 1 and 2 IEC 79-14 Zone1 BS 5345 part 1- zone 2
IP rating	Sealed and open reservoir enclosures are permitted
Impact resistance	7 nm
Material limitations	Normally metal construction
Examples of special requirements	Requires pressure relief value to IP23, over pressure test of 0.5 bar for 1 min
Application	Heavy current apparatus, transformers, and instrumentation

Table 10.13 Powder and sand

Protection focus	Powder and sand
Code	EEx q
Principle of concept	Covering devices with sand/powder quenches explosions caused by sparks or hot surfaces.
Zone suitability	Zone 1 and 2 IEC 79-14 Zone1 BS 5345 part 1- zone 2
IP rating	Factory sealed
Impact resistance	7 nm
Material limitations	Normally metal construction
Examples of special requirements	None
Application	Electronic assemblies, power supplies

Etzel et al. (2015) add that the cooling of the contents decreases the internal volume and thereby creates a vacuum in the jar. This vacuum pulls the lid into tight contact with the gasket and hence the jar rim to create a hermetic seal. Dudbridge (2016) observes that a large enough vacuum will be formed that will keep the lid tightly on the jar provided a hot food to ambient food volume contraction is sufficient and a properly formed jar seal is furnished. Most metal lids currently utilized are slightly domed to aid the consumer as a seal status indicator. A sufficient level vacuum in a sealed jar will pull the lid down to create a concave-shaped top. Fayer (2015) explains that losing the vacuum for whatever reason will cause the top of the lid to pop upward. This process is nonreversible and as such is utilized for quality control purposes (Saravacos and Kostaropoulos, 2016). However, Krause et al. (2017) conclude that this exact process plagues enclosures.

10.5.1 Airtight enclosures

Giraud et al. (2016) explain that sophisticated electronics are utilized in many types of outdoor equipment in large number of applications, for example, in outdoor lighting

Table 10.14 IP code arrangement

Code letters: ingress protection	IP
First characteristic numeral	Numerals 0 to 6 or letter X
Second characteristic numeral	Numerals 0 to 8 or letter X
Optional additional letter	Letters A, B, C, D
Optional supplementary letter	Letters H, M, S, W

Table 10.15 First characteristic numeral

IEC 60529 Clause 5		
First characteristic numeral	Against ingress of solid foreign objects	Against access to hazardous parts with
0	(Nonprotected)	(Nonprotected)
1	≥ 50 mm diameter	Back of hand
2	≥ 12.5 mm diameter	Finger
3	≥ 2.5 mm diameter	Tool
4	≥ 1.0 mm diameter	Wire
5	Dust-protected	Wire
6	Dust-tight	Wire

systems, solar energy systems, and telecommunications infrastructure equipment, just to name a few recent applications (Erol-Kantarci and Mouftah, 2015; Kolokotsa et al., 2016; Sharma and Saini, 2017). This means that more and more electronic equipment is being exposed to the environment and its often harsh conditions (Gilbrech, 2016).

Saxena et al. (2013) clarify that FRS must include the proper assumptions for the operating environmental conditions. Out of design range conditions can potentially damage sophisticated electronics according to Cressler and Mantooth (2017). Bollinger and Dijkema (2016) argue that this is because many electronic equipment is exposed to changing weather patterns outdoors. Blaj (2015) adds that a thunderstorm

Table 10.16 Second characteristic numeral

IEC 60529 Clause 6		
Second characteristic numeral	Against ingress of water with harmful effects	Against access to hazardous parts with
0	(Nonprotected)	Not applicable
1	Vertically dripping	Not applicable
2	Dripping (15 degrees tilted)	Not applicable
3	Spraying	Not applicable
4	Splashing	Not applicable
5	Jetting	Not applicable
6	Powerful jetting	Not applicable
7	Temporary immersion	Not applicable
8	Continuous immersion	Not applicable

Table 10.17 Additional letter

IEC 60529 Clause 7		
Additional letter (optional)	Against ingress of solid foreign objects	Against access to hazardous parts with
A	Not applicable	Back of hand
B	Not applicable	Finger
C	Not applicable	Tool
D	Not applicable	Wire

or even a subtle shift between a hot day and cold night can be a potential source of serious problems. [Khanna \(2017\)](#) emphasizes that other risks include exposure to harsh chemicals. Cleaning agents and various industrial liquids such as those utilized in high-pressure sprays to clean equipment can also cause significant issues ([Leith et al., 1996](#)). [Nakayama \(1986\)](#) observes that an indoor manufacturing facility should not necessarily be deemed safe for electronic equipment automatically either. Proper heat management is focused on the internal environment of the device according to [Jenkins and Berger \(1984\)](#). Many devices generate a significant level of heat during operation assesses [Reddy \(2014\)](#). Today, [Rashid \(2017\)](#) proves that electronics are designed to be deployed anywhere in the world. As a consequence, many or often all of the previously described situations are applicable to proper enclosure design opine [Shui et al. \(2018\)](#).

[Alshaer et al. \(2015\)](#) explain that many engineers without the benefit of specific enclosure engineering training design completely sealed enclosures in a somewhat misguided effort to insure absolute protection of the contained electronics. Their design efforts include robust housing material specifications, super sturdy seal materials for increased durability, and oversized bolts to ensure maximum tightness of the designed seal ([Kalbasi and Salimpour, 2015](#)). Therefore, [Yip et al. \(2017\)](#) conclude that many enclosures are effectively not only waterproof but airtight as well. This phenomenon of design excess is particularly relevant if the enclosure must be certified to

Table 10.18 Supplementary letter

IEC 60529 Clause 8		
Supplementary letter (optional)	Supplementary information specific to:	Against access to hazardous parts with
H	High voltage apparatus	Not applicable
M	Motion during water test	Not applicable
S	Stationary during water test	Not applicable
W	Weather conditions	Not applicable

Table 10.19 IP code examples

IP44	No letters, no options
IPX5	Omitting first characteristic numeral
IP2X	Omitting second characteristic numeral
IP20 C	Using additional letter
IPXXC	Omitting both characteristic numerals, using additional letter
IPX1C	Omitting first characteristic numeral, using additional letter
IP3XD	Omitting second characteristic numeral, using additional letter
IP23S	Using supplementary letter
IP21CM	Using additional letter and supplementary letter
IPX5/IPX7	Providing two different degrees of protection by an enclosure against both water jets and temporary immersion for a potentially “versatile” application

the National Electrical Manufacturers Association (NEMA) or relevant IP standards (Arce et al., 2017; Jespen, 2016a; Valdes et al., 2014). However, Hickey (2015) argues that many manufacturers have found out that successful certification does not guarantee lifetime performance of an enclosure system. Yung (2015) shows that unfortunately, once the enclosure is installed, it may begin to show evidence of water and particulates inside the housing. Yip et al. (2017) highlight that often this evidence is only found after failure of the enclosed electronic device. How could this be possible? After all, everything was overdesigned add Ma et al. (2015). Sachdeva (2015) elucidates that the perhaps surprising fact is that using watertight enclosures does not guarantee long-lasting protection and reliable performance. Isermann (2006) shows that this is because of the existence of pressure differentials (ΔP). Thus, over time this delta P can cause difficulty to detect leak paths. Therefore, all enclosure designs should be proactive and ought to address these issues at the conceptual stages of the new product development (NPD) rather than be reactive and address customer complaints originating from various applications, which are ultimately all the more expensive (Brusoni and Prencipe, 2001; Nielsen and Wenzel, 2002; Otto, 2003; Kumar and Phrommathed, 2005; Kline and Rosenberg, 2010; Pahl and Beitz, 2013; Weber, 2014; Wasson, 2015; Hubka, 2015; Morris, 2016; Bhamra and Lofthouse, 2016; Bhise, 2017; Tukker and Tischner, 2017; Mansor and Sapuan, 2018; Kimita et al., 2018).

10.5.2 Leakage

Michalski (1994) highlights that leakage-related field failures often occur precisely because of the oversized and airtight seals’ capability to prevent pressure equalization. It is a noteworthy point that the external pressure will fluctuate (Lutgens et al., 2001; Schneider and Hare, 1996). In cases when the external pressure is greater the enclosure

will try to equalize the pressure by drawing in air from the outside according to [Watt \(2012\)](#). However, [Racusin \(2016\)](#) adds that if the enclosure is completely sealed the pressure cannot equalize. [Tong \(2016\)](#) explains that this means that the pressure will be different inside the enclosure. More pressure inside will cause the enclosure to bloat. Less pressure inside will create a vacuum in the housing. Both situations lead to stresses on the enclosures and particularly on the seals. Effectiveness of the sealing surfaces might be compromised. Thus, [Malinowski and McCormick \(2002\)](#) show that despite the overdesigned enclosure and sealing practices the seal in service starts to allow water and other contaminants to enter the housing. Such a situation very often leads to failure of the enclosed electronics according to [Pecht \(2008\)](#). [Smith \(2017\)](#) highlights that predicting the timing of such failures is not a simple matter.

[Yang et al. \(2018\)](#) explain that an example can underscore the importance and the insidious nature of this phenomenon. A mission critical power electronic device was specifically designed to withstand tough environmental conditions. However, after only a few months in the field, the enclosures began to leak. Moisture entry was the cause of severe corrosion and caused failures. The engineering team soon determined that the leakage was due to seal failure. They insisted using tougher seals to eliminate moisture ingress. However, they eventually realized that this method only extended the time before the seals failed yet again. Their senior management decided to engage a world-class enclosure engineering consultant who quickly solved the problem by eliminating differential pressures and no failures have been recorded since.

10.5.3 Differential pressure

[Laloya et al. \(2016\)](#) elucidate that temperature changes (ΔT) are the most common root cause of pressure-related failures. The source of ΔT can be internal, external, or a combination of both ([Cho and Goodson, 2015](#)). [Whitaker \(2017\)](#) adds that electronics enclosed in the housing could potentially generate a significant amount of heat. Lack of proper heat management can result in serious reliability issue problems ([Owens et al., 2017](#)). [Bong et al. \(2017\)](#) observe that the generic solution to this type of problems is to facilitate adequate heat dissipation. Equally, a dramatic ΔT variation could be recorded even during a typical day, but especially during extreme weather events such as an unexpected thunderstorm ([Byers, 1951](#)). [Leo Samuel et al. \(2017\)](#) explain that proper weather and climate information is available to designers and the heating ventilation and air conditioning (HVAC) industry is very familiar with its use. However, [Ferreira and Kim \(2014\)](#) add that HVAC climate data are location specific so its direct use in conceptual electronics enclosure engineering is rather limited at present. [Yang et al. \(2018\)](#) believe that this might change in the future, especially for mission critical and customer configured electronic applications. Nevertheless ΔT variation is important as the following examples demonstrate.

[Cook and Polgar \(2014\)](#) inform that a new antenna was being developed for automated vehicle technologies. The vehicle antennas were mounted on externally. Therefore, the antennas were exposed and have experienced all types of weather conditions across the United States. The prototype antenna was housed in an injection molded PC/ABS thermoplastic enclosure incorporating IP67-rated gasketing. The cross-functional

NPD team found that sudden temperature drops created a sufficient vacuum inside the housing to overstress the seals. Thus, the gasketing system failed prematurely and allowed significant moisture ingress. The presence of moisture ultimately damaged the electronics to the point that the entire automatic guidance system had to shut down. Thereby, an overlooked issue in a small part managed to undermine the credibility of a large and important application. In fact, the NPD team was advised that the solution to their problem was to equalize the pressure without allowing moisture or particulates ingress. Of course, theoretical solutions might not be simple to implement but a practical solution is provided at the end of this section.

Tanyer et al. (2018) demonstrate that large ΔP can be created by changes in altitude. The rate of change could also be important. Most shipping containers are not pressurized. Therefore, many transporting situations create a significant ΔP . For instance, vacuum created by altitude changes makes it difficult to open the shipping container. This fact underlines the importance of this effect for enclosure engineers. A new apparatus was developed to meet exacting military specifications (Brulle, 2015). The FRS required that the enclosure open immediately after it hit the ground after being released from a reconnaissance aircraft. The internal electronics required protection from contaminants such as dirt, moisture, sand, and others. The enclosure engineer specified O-ring gaskets. These provided excellent seals. The pressure on seals increased from 135 mbar to almost 1100 mbar in 22 s. The associated ΔP would have prevented the enclosure from opening. Therefore, Owens et al. (2017) show that a pressure equalization strategy was incorporated at the conceptual stage of the NPD.

Henshall et al. (2016) observe that electronic apparatus is often permanently installed, for instance, solar energy enclosures, and as a result altitude change induced ΔP is a nonissue. However, many electronic enclosures are exposed to high-pressure cleaning sprays according to Lefebvre and McDonell (2017). Hose-down activities can generate a ΔP of over 150 mbar (Cook and Cullen, 2014). Lebeck (1991) asserts that this ΔP can be the cause of seal failure.

An enclosure engineer must not only think of the numerous openings in a large housing as weak points, which need gaskets. Other areas like indicator lights, screw heads, and wire conduits are also potential leak sources according to Venkatachalapathi and Mallikarjuna (2016).

10.5.4 Protection

Dev et al. (2016) explain that repeated and cyclic ΔP impart stress on seals and connection points. Stress causes strain and thus cyclic expansion and contraction ultimately, the root cause of seal failure. Simple solutions like drilling a hole in the enclosure might eliminate the offending ΔP but also create other unwanted issues. Baskin (2006) highlights that creating an opening in the enclosure provides an entrance for contaminants. Ingress of dirt, dust, water, and even insects, into an enclosure often compromise reliability of the electronics (Lelieveld et al., 1995).

Therefore, Honey (1998) concludes that most engineers would initially consider hermetically sealing the enclosure. They believe that this would provide the ultimate security for the protection of electronics. However, there are a few problems with

this type of solutions. Firstly, a hermetic sealing method would necessitate that only nonpermeable materials are used (Lewis, 1983). Therefore, implementation of this protection strategy would automatically exclude plastic components. Secondly, the enclosure is needed to be welded shut (Febo Jr, 2015). Therefore, maintenance of the electronics would become nearly impossible. Thus, this protection method is simply unrealistic for most devices. In addition, such devices would become prohibitively heavy and expensive. However, another frequently utilized option is the use of a potting compound (Lall et al., 2017). However, potting also excludes electronics servicing. Potting is also expensive due to the specialized processes, materials, and equipment that are involved in the implementation of this protection strategy.

As a result, most novice enclosure engineers recommend the use of larger seals (Gnecco, 2000), sturdier gaskets (Robinson et al., 1998), or simply more bolted joints (Meadows, 2017). Naturally, Taylor et al. (2017a) conclude that solutions like these will remedy the immediate problems of contamination and leakage. However, these are short-term solutions ultimately leading to an untimely failure. This is so simple because the essential problem of ΔP has not been adequately addressed according to Laloya et al. (2016). Ezolino (2016) underlines that the enclosure is of course more airtight and also much more expensive to manufacture without having addressed the root cause of the problem.

10.5.5 Equalization

Owens et al. (2017) believe that the solution to this important problem is pressure equalization. Therefore, vents must be incorporated into the design. There are a few materials that could be deployed in such a function. Sachdeva (2015) opines one of which is made of expanded polytetrafluoroethylene (PTFE). Such a vent allows elimination of the ΔP while simultaneously maintaining an excellent environmental seal. The proper vents are microporous membranes that are inherently waterproof (Holmes, 2000). Thus, Lüth (2013) explains that the microstructure of the material must be open enough to allow gas and vapor molecules to pass through. However, Ohring (2001) adds that the material must also have small enough openings to repel water, liquids, and particulates. Unfortunately, pressure equalization only solves cooling-related issues according to Siebert (2006). Linz (2011) highlights that there is another issue in the form of condensation.

10.6 Condensation

Park et al. (2013) inform that condensation mitigation in any enclosure is essential to prevent damage to the contained electronics. Electrical and electronic equipment, modules, and components are usually housed in an enclosure for the explicit purpose of protection from the environment state Jog et al. (2011). However, Conseil et al. (2014) demonstrate that even with a completely sealed enclosure ingress of moisture and water might be possible. Horvath (2010) warns that water inside an enclosure can and will accumulate. Minzari et al. (2011) observe that moisture might condense to

form small droplets on the components, which then coalesce into puddles. Water from the puddles ultimately seek out the lowest point in the enclosure. [Jacobsen et al. \(2014\)](#) caution that eliminating moisture and condensation is neither simple nor cheap. Enclosure engineers deploy a great variety of methods for this purpose. [Oh et al. \(2015\)](#) inform that even very small amounts of moisture or liquid water—based substance can often result in serious damage to components. Therefore, [Ambat and Møller \(2006\)](#) conclude that moisture and water ingress affects reliability of the system, degrades performance, and shortens expected life. Thus, a universal solution is preferred by the enclosure designers according to [Blackwell \(2017\)](#). Furthermore, [Lee and Peng \(2000\)](#) emphasize that such a solution should not only be effective but need to be relatively inexpensive. Thus, [Horváth \(2000\)](#) concludes that forming the right moisture and condensation prevention strategy early on in the NPD cycle has become critical.

10.6.1 Formation

[Zhan et al. \(2008\)](#) explain that water droplets condense out of moist air if the air is cooled below its saturation point. This temperature is also referred to as a dew point ([Johnson, 2007](#)). [Nath et al. \(2017\)](#) inform that water vapor directly condenses into frost if the condensing surface temperature is below freezing. [Herr et al. \(2001\)](#) highlight that condensation formation inside an enclosure creates many problems for electronic devices. [Song et al. \(2013\)](#) demonstrate that moisture ingress can lead to corrosion. Rust increases resistance, thus generating additional heat. Therefore, moisture leads to problems that are not too different from issues described in the heat management chapters. [Gillman and Le May \(2007\)](#) warn that corrosion can also lead to arcing, sparking, and shorting out of critical components.

10.6.2 Challenge

[Iwami et al. \(2013\)](#) believe that ideally, complete condensation prevention is achieved. However, many of the circumstances that ultimately lead to condensation are almost impossible to avoid entirely. [Gatzen et al. \(2016\)](#) inform that high-pressure sprays utilizing various soaps that also act as very good lubricants often penetrate around sealed components and gaskets with surprising ease. Enclosure attachments, extensions, and modules like pipes and conduits are seldom installed with the rigor applied by state-of-the-art enclosure design ([Jamnia, 2016](#)). Many fittings are simply not sealed properly. Additionally, [Manning \(2016\)](#) shows that condensation may form relatively far away in a conduit but ultimately drain into the enclosure. Leaks might also happen even if appropriate enclosure engineering practices are employed in the design process according to [Moerman and Fikiin \(2016\)](#).

Enclosures can and must be opened, for instance, for service, explain [Nasirabadi et al. \(2017\)](#). This provides an avenue of moisture entry if this happens in a wet or humid environment. Electronic components also generate a great deal of heat within an enclosure. The heat warms the air and therefore the air can hold even greater amounts of moisture. [Basyigit et al. \(2017\)](#) enlighten that at some point the enclosure surfaces cool below the dew point of the air, perhaps because of an equipment shutdown, or

perhaps lower night temperatures, or reduced external temperatures due to rain or other phenomena. Once the surfaces are at the dew point condensation will form. [Stosur et al. \(2015\)](#) demonstrate that large temperature variations also induce a ΔP that was discussed earlier.

10.6.3 Condensation prevention methods

[Amir et al. \(2015\)](#) inform that many condensation prevention and mitigation methods have been tried in the past to reduce the harmful effect of corrosion on enclosures and electronics equipment. [Mitchell and Cross \(2015\)](#) believe that some of these methods are relatively low-cost. Others are low-tech and easy to deploy. Yet, others [Bavarian et al. \(2016\)](#) highlight are extremely costly due to unbounded technological sophistication.

Wiping down the affected surface is a low-cost solution, observe [Jamil et al. \(2017\)](#). This could be done with a sponge or an appropriate lint-free towel. However, this method is generally considered to be an inconvenient and often even dangerous solution. In addition, this method is frequently only partially effective. Operators eliminate visible water that is the standing liquid from the lowest part of an enclosure. Unfortunately, the moisture-sensitive components remain wet. Therefore, the wiping method is largely ineffective ([Ali, 2016](#)).

Another method to eliminate visible puddles is to drill a small hole at the lowest point of the enclosure according to [Bhardwaj \(2017\)](#). This method is an effective way to drain standing water from the enclosure. Once again moisture located on the surfaces of sensitive components is ignored. Furthermore, [Allan \(1948\)](#) points out that this method also allows moisture-laden humid air to reenter the enclosure through the very holes that were just created. Thereby, this method is very successful in creating an unabated cycle of serious condensation. Additionally, [Cole et al. \(2010\)](#) emphasize that the enclosure's NEMA Type ratings are potentially sacrificed by holes that are not filled with an approved device in accordance with UL or CSA standards.

Medium cost methods often work by maintaining the enclosure's internal temperature well above the dew point. [Mistry et al. \(2016\)](#) explicate that this method works since moisture will not condense from air above its dew temperature. Various heaters are deployed for this purpose. More sophisticated heaters employ temperature control and monitoring. However, increased air temperature increases air's ability to store more moisture ([Lstiburek and Carmody, 1996](#)). [Wu et al. \(2015\)](#) caution that this could have the undesired and detrimental effects on heat-sensitive electronic components.

Various fans have also been deployed to create or increase airflow ([Subramanyam et al., 2004](#)). Increasing air circulation within an enclosure makes it tougher for condensation to form on many of the internal surfaces. [Vetelino et al. \(1996\)](#) explain that the problem with this method is that once the temperature dips below dew point condensation will form. Condensation will form first in the areas of the enclosure where air movement is restricted or minimized. Computational fluid dynamics (CFD) studies can pinpoint these areas in the early stages of NPD according to [Nasirabadi et al. \(2017\)](#).

Utilization of the previously mentioned hazardous location-style drains or breathers incorporate pressure equalization (Harriman, 1989). Haynes and Messec (1991) explain that drains and breather devices are certified for hazardous location requirements. However, Bandyopadhyay et al. (2010) warn that these requirements are not equivalent to UL 508A and CSA 22.3 enclosure standards. This means that these devices rarely pass a Type 4 water hose-down test. Paudel (2010) informs that the hose-down test is designed to guarantee that liquid will be kept out of an enclosure. In addition, these drains and breathers do not adequately address the issue of condensation forming on sensitive components (Payne, 2002). Therefore, hazardous location-style drain or breather installations often encounter performance- and corrosion-related issues as a consequence according to Ambat and Møller (2006).

Arora (2012) informs that high-price air conditioners or coolers can also be successfully employed to maintain specified temperatures. These devices can remove moisture from the enclosure. However, size, price, and complexity are issues that need to be mitigated by the enclosure engineer according to Kheirabadi and Groulx (2016). Therefore, Yang et al. (2018) conclude that these methods are often impractical and also cost-prohibitive for most of the common electronics enclosure applications.

10.6.4 Enclosure ratings

The Canadian Standards Association (CSA), NEMA, and Underwriters Laboratories Inc. (UL) are North American standard-writing organizations. Their standards and resultant ratings are harmonized and based on similar requirements of expected performance according to Arce et al. (2017).

Khalilieh (2016) explains that a common requirement by UL and CSA is to test enclosures by qualified enclosure engineers. Both organizations perform monitoring of approved manufacturing methods and material specifications conducted by their inspectors. However, D'Souza et al. (2017) highlight that NEMA does neither require independent testing nor monitoring. Thus, compliance with NEMA standards and ratings are up to the OEM. As a rule of thumb, an enclosure cannot be rated higher than its enclosed components according to Smeets et al. (2017). Therefore, Manahan et al. (2015) assert that both the enclosure and its contained components must be properly rated for an application in accordance with the relevant standard and the certification body.

Moisture can be removed from the enclosure by various means. Thermal methods trace their origins to refrigeration and air conditioning devices (Heremans, 2016). Utilization of such a device prevents condensation formation on the walls and components. Thus, thermal methods provide a level of prevention. However, if moisture can condense out then a way must be found to expel the liquid from the enclosure. A one-way drain is utilized to remove the accumulated water. Such a device is constructed to channel water away from the sensitive electronics and expel the liquid to the external environment. A one-way drain must also keep contaminants from entering the enclosure. Mistry et al. (2018) explain that a purge system can be utilized to maintain a greater pressure inside the enclosure than externally. This prevents moisture and dust entry. Thus, this method keeps internal components moisture free. However, a

purge system needs pressurized dry air for its functioning. Provision of such air might be relatively inexpensive on rare occasions, but in most cases it can be prohibitively expensive.

10.6.5 The solution

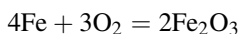
Joshy et al. (2017) explain that an all-inclusive solution can remove water and moisture from an enclosure. In addition, Arce et al. (2017) highlight that it is preferred that the method chosen retains the enclosure's integrity and certifications. This set of requirements calls for a device that equalizes internal and external pressures and allows water expulsion, while preventing contaminant entry and maintaining certification levels.

However, even with a device meeting all of the previously stated criteria, the ingress of humid air cannot be excluded while any covers are removed or an access panel is open according to Bryson and Battersby (2016). Therefore, Rafique et al. (2016) conclude that a combination of internal moisture removal and drainage system can provide the complete solution to condensation problems.

10.7 Corrosion

Understanding and minimizing the corrosion process in electronic components is an important area of enclosure engineering according to Slade (2017) and Thue (2017). Importantly, Li et al. (2005) emphasize that increased electronics packaging density increased sensitivity to corrosion to the extent that previously unaffected environments and applications suffer reliability problems as a result.

Niu et al. (2015) explicate that in principle, corrosion affects all electronic products. Leygraf et al. (2016) show that it is a complex chemical reaction that is oversimplified by Eq. (10.1).



Equation 10.1 Corrosion of Iron.

The main ingredients of corrosion, metal and oxygen, are well illustrated in Eq. (10.1), but there is no mention of either water or heat in this simple formula. Corrosion of a metal requires four elements in accordance with Perez (2004):

- an anode,
- a cathode,
- a metallic conductor, and
- an electrolyte.

Richey et al. (2016) explain that increasing the effectiveness of the electrolyte increases the rate of corrosion. Corrosion rates are determined by diverse factors. However, the following five factors are the most important in accordance with Slade (2017):

1. Oxygen
2. Temperature

3. Humidity
4. Salinity
5. Pollution levels

Generally, [Medgyes et al. \(2015\)](#) emphasize that corrosion is a slow process. Corrosion in an electronic enclosure often proceeds unannounced until a sudden and unexpected reliability problem manifests itself according to [Leygraf et al. \(2016\)](#).

10.7.1 Factors

[Slade \(2017\)](#) asserts that there is no corrosion, also known as oxidation, without oxygen. However, [Hooshyar \(2016\)](#) demonstrates that corrosion can even progress in an oxygen-deficient environment albeit at a much reduced rate. Therefore, in such environments the rate of the corrosion reaction and consequential metal destruction is slower.

[Chandler \(2014\)](#) describes an oxygen concentration cell formation if a metal is immersed in an electrolyte and one area contains more oxygen than another. The higher oxygen concentration area becomes cathodic relative to the rest of the surfaces. The formation of this cell results in very rapid progression of the corrosion process.

[Xu et al. \(2018\)](#) observe that corrosion reactions are electrochemical and as such the process accelerates with an increase of the temperature. Therefore, [Rao and Wang \(2011\)](#) conclude that corrosion is more rapid as power density challenges existing heat management in new electronics. The increase in the packaging and power densities of the devices has often resulted in an increased flow of cooling air inside the device. This increases considerably the contamination and gas contacts of the surfaces according to [Stratmann et al. \(1999\)](#). Unfortunately, the most common heat management device, the fan, exacerbates an already difficult problem. This is because fans introduce changes in airflow speed, temperature, and relative humidity. [Roberge et al. \(2002\)](#) explain that increasing any of these variables also increase the speed of corrosion and associated contamination of the surfaces. This in turn creates an even faster corrosion process ultimately resulting in premature failure of one or more critical components. Therefore, expert enclosure engineers minimize these variables based on CFD coupled with heat transfer and finite element analysis (FEA) studies according to [Nasirabadi et al. \(2017\)](#). While these are difficult to carry out successfully, their applied and carefully implemented results markedly increase electronics reliability according to [Suhir \(2013\)](#).

Humidity and its associated time-of-wetness variable play a significant role in determining applicable corrosion process rates ([Park et al., 2005](#)). In this context the time-of-wetness variable refers to the measured temporal unit that an exposed metal has contact with sufficient moisture quantities that sustain the relevant corrosion process. Therefore, [Goble \(2010\)](#) explains that the more moisture is present in the close proximity of the metal, the more corrosion will accelerate. Thus, [Holloway et al. \(2012\)](#) conclude that condensation and dripping water are especially hazardous corrosion promoters.

As a rule of thumb, to avoid accelerated corrosion, keep the electronics dust free and dry. This means no dripping water anywhere in the electronic enclosure and

that relative humidity must be below 40% and surface temperatures below 40°C, according to Uhlig (2011). Keeping all three variables within prescribed limits result in slow corrosion. In most cases the corrosion process becomes so slow that reliability will not suffer. However, Ambat and Conseil-Gudla (2016) argue that this means that the electronics must be kept in air-conditioned indoor facilities. Simultaneously keeping all three variables in check is very difficult outdoors.

IEC 60,721-1:1990 *Classification of environmental conditions, Part 1: Environmental parameters and their severities* and IEC 60,721-3-9:1993 *Classification of environmental conditions, Part 3: Classification of groups of environmental parameters and their severities, Section 9: Microclimates inside products* contains temperature and humidity specifications for the environmental classification of equipment, devices, and their internal components. The IEC 60,721-three to nine standard specifies microclimatic conditions within devices. The standard uses a microclimate definition to encompass the location where components have been installed.

There are other factors in addition to the five most important ones. For instance, Leygraf et al. (2016) inform that in free outdoor conditions there is a significant risk for increasing the corrosion process speed by sunlight. Long-term exposure to the sun's radiation spectrum decays most materials according to Chen et al. (2016). However, plastic materials suffer much quicker degradation than metals and as a result plastic materials must be carefully formulated with the right amount of ultraviolet (UV) stabilizers to be acceptable as an enclosure material.

Gaseous and ionic substances contained in air and dust particles can be found in most urban environments (Giorio et al., 2017). However, substantial traffic flows and industrial and power plants increase concentrations and thereby the risk of corrosion. Chemical salts also increase the rate of corrosion (Conseil-Gudla et al., 2017a). Salts do this by increasing the conductivity and therefore the efficiency of the electrolyte. The most common salt in the environment is sodium chloride. Sodium chloride is found in seawater. Salt deposited on exposed surfaces acts as a hygroscopic agent. This means that salt effectively extracts moisture from the air. Moisture in turn increases the rate of corrosion even in nonimmersed areas. Hence, well-documented salts influence corrosion. Gill (2016) explains that salt from the seawater can be found in the air as far as 50 km from the coastlines. However, chloride contents in the air drop fast. 250 m inland the measured concentrations are about 10% of the concentration levels measured on the beach. Storms often spread salt, sand, and dust, all of which are harmful to electronics. Saxena and Bhargava (2017) highlight that localized volcanic gas containing large amounts of sulfur and ash also cause problems including accelerated rate of corrosion. Gerengi et al. (2016) demonstrate that acid rain, which is a chemical by-product from heavy industries, promotes rapid corrosion. Carbon dioxide dissolves in moisture to accelerate corrosion if it gets in contact with a metal in the electronics enclosure.

Importantly, Liu et al. (2017b) highlight that vibration and ΔT cause fretting of the mating connector surfaces. This abrasion creates wear and fretting corrosion. This in turn increases contact resistance and thus causes reliability issues. Therefore, Brown (2017) emphasizes that mechanical vibration and temperature differences must be minimized to increase reliability of electronic devices.

Enclosure engineers must always be alert for corrosion as a potential source of reliability problems. For instance, agriculture and animal husbandry emit various gases and liquids. [Watson and Jn_and_Jüttner](#) inform that ammonia and thio-compounds such as hydrogen sulfide are the most problematic. These are the by-products of chicken coops, pigsties, and cow byres. Plants rotting in nature are also large emitters. Human excretion, such as sweat, saliva, and various skin conditioning products, can also cause surprisingly effective corrosion accelerants ([Mathiyarasu et al., 2006](#)). In addition, washing liquids, detergents, powders, and alcohol can also cause various corrosion-related faults in electronic devices according to [Selinger and Barrow \(2017\)](#). Human metabolism creates by-products such as carbon dioxide, methane, and aldehydes in breath and perspiration. These must also be factored in by the enclosure engineer. Tobacco smoke contains tar and other corrosion accelerator compounds.

[Cheng et al. \(2018\)](#) inform that electrical stress also speeds up corrosion. For instance, engineers of power electronics know that large current flow heats up the solder joint and gradually weakens it to the ultimate point of failure according to [Dusmez et al. \(2017\)](#). [Dai et al. \(2014\)](#) observe that in condensed wiring patterns high field intensity between the adjacent conductive paths increases leakage currents, which in turn accelerates the corrosion process. Metallic migration may also occur in microcircuits resulting in wire breakage due to high current density explicate [Jowett \(2016\)](#) and [Bhattacharyya \(2015\)](#).

10.7.2 Problem areas

[Ambat and Conseil-Gudla \(2016\)](#) explain that the corrosion problem affects both electrical and mechanical functionality in an electronic product. The corrosion process starts from manufacture of the components and often manifests itself in a gradual degradation of performance, while in other cases tough to diagnose and difficult to fix intermittent faults develop. The most common corrosion-related faults alter resistance and increase leakage currents. [Van Driel et al. \(2017\)](#) describe that associated faults can be observed in many areas including connectors, solder joints, EMC-related contacts and seals, discontinuity of conductive surfaces, the malfunctioning of switches, keyboards, and other input devices.

[Bagotsky et al. \(2015\)](#) inform that corrosion is also a significant issue in microcircuits, especially in high-power density components. The main problem is due to high operating temperatures—induced internal corrosion. This results in discontinuities of the conductive surfaces in extreme cases. An example is the wiring isolation difficulties in flip chips incorporating extremely dense external wire gaps related to corrosion according to [Sood \(2017\)](#). External contamination and moisture ingress were found to be the most frequent root causes. Therefore, [Talbot and Talbot \(2018\)](#) advise that cleaner manufacturing processes and better surface protection need to be achieved in order to solve this type of corrosion problems.

[Armarego \(2017\)](#) elucidate that packaging can create structures that have a great affinity to absorb condensed water by capillary action. As a rule of thumb, gaps that are less than 1 mm in any dimension create a capillary. The most common example of such a capillary is often created under parts and components mounted on the printed

circuit board (PCB). [Cook et al. \(2015\)](#) conclude that the corrosion process will progress rapidly if there are unprotected metal surfaces located in the capillary gap. The corrosion process might create connective bridges between leads and conducting paths ([Portan, 2016](#)). Generally, packaging structures create fundamental problems if capillary action is not addressed successfully.

Detailed tolerance reviews assist in alleviating gradual degradation of contact surface performance and associated faults. In addition, corrosion-related resistance increases and leakage currents need to be incorporated into any design review, especially where narrow spaces and dense patterns in the wiring exist. Improvements are usually achieved by electronic design modifications, pattern alteration, or selection of alternative connection technologies ([Hubka, 2015](#)). An important outcome of the design review is the identification of the proper electromechanical solutions, such as coatings and other protections for each relevant surface or area, so that the negative effects of corrosion and associated contamination can be eliminated.

[Seinfeld and Pandis \(2016\)](#) emphasize that the supporting enclosure engineering analysis must investigate the effects of changes in the components' parameters as a function of ΔT . Most important parameters change as a function of temperature and as such they must not be taken as constants. Thus, [Watson and Castro \(2015\)](#) warn that electronics engineers may specify components outside of their intended temperature capability range. This practice often results in significant operational faults at the extreme end of the performance spectrum. However, these faults just as often will disappear once the temperature range is within the manufacturer's specification regime. Therefore, [Baker et al. \(2017\)](#) highlight that a recurring no fault found condition might be experienced. Such can undermine customers' confidence in any electronic equipment ultimately eroding profitability of the OEM as well as the entire supply chain. Therefore, this analysis focuses its examination on the relevant device's performance capability within the specified temperature range. The engineering parameters are contained in the FRS.

[Ekvall and Andrae \(2006\)](#) assert that leadless solders created new corrosion problems and aggravated old ones. For instance, it is frequently found that PCB components do not wet properly ([Abtew and Selvaduray, 2000](#)). Use of an unsuitable flux or component lead coating material corrosion will jeopardize soldering integrity. Root causes of many soldering problems might be located if the circuit boards and components that progress through the supply chain are traced. [Cheng et al. \(2017\)](#) explain that complex soldering processes with many stages are also sensitive to corrosion. Such complexity often exists, especially if components are soldered to both sides of the PCB in more than one phase. Fluxes and the elevated temperature induce quick corrosion of the unprotected areas of the board. Thus, soldering properties are sacrificed in later stages.

[Watson and Castro \(2015\)](#) underline that another serious soldering problem is associated with the primary corrosion propagation agent: water. Many plastic packaging absorb water during shipment and storage. Moisture absorption diffuses ionic impurities and might cause significant package swelling. [Li and Wong \(2006\)](#) explain that the swelling is an indicator of moisture absorption and it is of a major concern as the volume of water expands 1200-fold during its vaporization as the temperature is rapidly increased from room temperature to the soldering temperature. Therefore, a swelled

package might explode during the soldering process. This is known as popcorning due to the resulting surface craters on the soldered area that somewhat resemble the surface characteristic of popcorn (Gallo and Munamarty, 1995; Munamarty et al., 1996; Gannamani and Pecht, 1996; McCluskey et al., 1997; Guo et al., 2015).

10.7.3 Water

It was discovered by Appleby and White (1992) that water film thickness plays a vital role in the initiation of corrosion on various steel surfaces. It was observed that if a layer of one–three molecules of water is adsorbed on the surface measuring 0.2–0.6 nanometers, corrosion will not be triggered. However, if the adsorbed layer thickness grows to over 20–50 molecules measuring 4–10 nm, corrosive reactions will become an inevitable certainty. Appleby and White believe that this initiation process can be generalized to other metallic surfaces.

Ambat and Møller (2006) explain that corrosion is always an electrochemical process, essentially a kind of electric circuit. A cell must be created by an anode, cathode, and electrolyte. If there is corrosion, there must be a flow of current between the cathode and anode sites. The circuit must be closed, and a driving potential that is voltage must also exist. Thus, all corrosion phenomena are accompanied by creation of a current. Voltage values of corrosion cells are in the order of 0.5–1.5 V with associated currents of 10^{-12} to 10^{-6} A. The corrosion will progress slowly if there is a voltage difference (ΔV) of less than 0.3 V. Thus, Bockris et al. (1980) summarize that corrosion detection by electrical means is difficult as picoampere currents must be measured within nanometers of space.

The anode in the circuit is the corrosion area of the base metal. The circuit is closed if the anode and cathode are immersed in a conductive solution that is in an electrolyte. This electrolyte is the conveyor belt that transfers oxidized metal ions from the corrosion area to the cathode. This process creates reduction species which are either nonmetallic atoms or metallic ions. Importantly, Popov (2015) describes that both cathode and anode sites must be immersed in the same electrolyte for the corrosion circuit to become operational. The most common electrolyte is water with added impurities. Hence, Nasirabadi et al. (2016) underline the importance of excluding water and moisture condensation from electronic enclosures.

Unfortunately, corrosion is only detected once corrosion products are visible (Leygraf et al., 2016). This is much too late to take corrective action from an electronic enclosure perspective. The reason for this is that operation of the electronics is affected way before corrosion products can be observed. Therefore, O'Connor and Kleynner (2012) believe that it is exceedingly difficult to prove that the root cause of an electronic malfunction is in fact water-induced corrosion.

10.7.4 Prevention

Li et al. (2015) believe that corrosion resistance could and should be improved. Several aspects are mentioned here to serve this purpose. Firstly, it is important to understand the fundamental principles of corrosion with regard to the actual application. Secondly,

a relevant corrosion resistance improvement method should be selected to eliminate or minimize environmental stresses. Thirdly, the design should be reviewed and the detail should be analyzed. For instance, a study of connector reliability should be carried out. [Mathia \(2010\)](#) explains that corrosion resistance could be increased by improving robustness, minimizing air flow for cooling purposes, maximizing moisture removal, limiting dissimilar material interfaces, and by the application of protective coatings.

10.7.4.1 Robustness

Corrosion that is oxidation changes properties of materials, components, and devices. However, [Ohring \(1998\)](#) suggests that most electronic devices would tolerate corrosion well if they could be made to fully function within a large temperature range. This would mean that these devices tolerate a large variation of component parameters. Thus, they would have large tolerances toward ΔT , corrosion, and other environmentally based variables. This, however, remains an idealized goal according to [Streetman and Banerjee \(2016\)](#).

In practice, corrosion processes impart slow and gradual changes to electronics components ([Fu et al., 2016](#)). This, in turn, slowly impedes the specified functioning of the device. The tighter the tolerances, the sooner this leads to malfunctioning. Consequently, the device will be more prone to corrosion sensitivity. For instance, if the electrical or mechanical functionality of a component requires very tight tolerances in signal quality, leakage currents, or impedances in the circuitry, the device will be very sensitive to corrosion. [Molina et al. \(2015\)](#) explicate that this is because corrosion alters electrical properties.

Resistance changes of switches, connectors, and solder joints; leakage currents between adjacent conductive paths; and insulation changes caused by corrosion must be included in the initial sizing of electronics ([Ambat, 2014](#)). Device tolerances must be calculated, and these need to be utilized to inform the enclosure engineers, corrosion experts, and component manufacturers to select the right level of protection measures.

Mechanical parts appear to be the most problematic. [Goldfarb \(2017\)](#) asserts that the greatest corrosion risks are connectors, switches, relays, mechanical, and solder joints. Also affected are displays and wiring patterns. On average, corrosion plays a significant part in more than half of all the faults occurring in power electronics ([Albrecht et al., 2014](#)). Minimizing the number of mechanical connections is a good start to increase robustness. This is especially true for unprotected connections. However, the FRS dictates the utilization of various electric connections. Many of these create increased levels of corrosion sensitivity according to [Woodgate \(2012\)](#). Examples are cable connectors, display connectors, EMC seals, keyboards, and plug-in modules. This means that by increasing component corrosion resistance fault tolerance of the entire system is increased.

10.7.4.2 Air cooling

[Raffel et al. \(2013\)](#) inform that contact with oxygen and dust particles increases with faster airflows. This means that the probability of a chemical reaction such as oxidation

otherwise known as corrosion is also increased. Electronic enclosures designed with protective inner covers for certain parts of the PCB were observed to have a drastic reduction of corrosion and other surface phenomena—driven degradation processes according to [Ohadi and Qi \(2004\)](#). For instance, one side of a device may look completely contaminated due to impingement of the airflow, while the reverse side appears very clean as it is protected from the airflow. Similarly, a two-part edge connector may look brand new on the inside even though the outside has been contaminated by dust and corrosion ([Ohadi and Qi, 2005](#)).

[Al-Damook et al. \(2016\)](#) demonstrate that one of the lowest cost means to prevent corrosion is the significant reduction of polluted airflow contact. However, [Da Silva Dias et al. \(2017\)](#) emphasize that the heat management strategy must change in most cases to conform to this simple rule of thumb. Reduction of airflow can be achieved by using a double-layered structure. In such a design strategy part of the PCBs and non-heat-producing components are protected against the cooling airstream.

A further level of protection could be achieved if components are cast in an inner material. Potting of electronics is a good example of this manufacturing strategy argue [Lall et al. \(2017\)](#). Potting does not absorb water, but it is expensive and needs special equipment and precautions to be effective. In an integrated approach, some parts could be potted, while others are simply protected by a baffle system. However, this design and manufacturing approach must be balanced against the fact that humidity and condensation will cause problems too.

10.7.4.3 *Moisture removal*

[Tencer \(1994\)](#) highlights that moisture removal from or desiccation of electronic enclosures is important. The internal part of enclosures must be maintained as dry as possible. Presence of moisture always increases corrosion risks. A relatively tight enclosure appears to be the best solution.

Enclosures usually allow external air ingress to facilitate heat management. The managed heat component could be utilized to keep contained electronics moisture free. The idea is to constantly keep various parts of the equipment warmer than its surroundings according to [Ge et al. \(2017\)](#), thereby preventing condensation effects.

The cooling airflow provides some assistance in the removal of moisture. However, [Tang and Joshi \(1999\)](#) explain that if the airflow is slow as in the case of natural convection, further precautions must be taken against long-term effects of trapped moisture and corrosion. Thus, all internal surfaces must be protected to a higher standard. It is also paramount to eliminate dripping water. Dripping water is often the result of collected condensation that invariably finds its way onto component boards and connectors ([Prisco, 2006](#)).

10.7.4.4 *Material interfaces*

[Staszak \(2017\)](#) highlights the fact that there are various material interfaces in electronics; connectors, microcircuits, PCBs, switches, and wiring patterns to name a few, according to [Fackler \(2015\)](#). Galvanic, also known as bimetallic corrosion, occurs

when two dissimilar metals are in contact. Higher temperature and increased humidity accelerate corrosion.

Uhlig (2011) proves that a contact between two surfaces of the same metal carries the smallest corrosion risk. The least amount of corrosion happens between dissimilar metal surfaces when the electric surface potentials are minimized. A galvanic series of metals chart can provide some guidance in the correct choice of mating materials. As a rule of thumb, the more the metals differ, the greater the probability of corrosion.

It is nearly impossible to avoid contacts between different materials in electronics. These include contacts made by the EMC seals with various other components within the enclosure such as PCBs (Lortz et al., 2013). EMC seals are naturally in contact with various other metals. The simple solution for a case like this is to design the seams of these seals in such a way as to stop moisture ingress.

The mechanical strength of tin-based intermetallic alloys is weak and they subsequently corrode quickly, especially in increased heat according to Mathew et al. (2005). Intermetallic alloys are formed, for instance, when using tin-based solder and the PCB or the component wires contain excessively thick layers of gold.

10.7.4.5 Protective coatings

There are times that it is necessary to protect the PCB against effects of contamination and moisture. Conformal coatings can be utilized for this purpose. Lowndes et al. (2015) explain that conformal coatings also protect boards from mechanical stress during assembly and service. PCBs designed for tough environmental conditions should be coated by immersion so that the gaps and area components, leads, and wiring are sealed.

10.7.5 Application similarities

The electronics enclosure label encompasses a huge variety of current and potential future applications. However, there are also so many commonalities that a unique program of training enclosure engineers is clearly warranted. Consider the following four *prima facie* greatly diverging applications: elevators, variable frequency drives, power supplies, and cell phones. These four applications were randomly selected from across the spectrum of enclosure possibilities. On the one end of the spectrum, a single unique enclosure is located. While on the other end of the spectrum, mass-produced fast-moving consumer goods (FMCG) applications are located. Yet, these examples share a lot of common general enclosure engineering features, especially with regard to corrosion protection methods according to Lyon et al. (2017). Similarities include product globality, environmental conditions, technology, supply chain, testing, and quality control practices.

10.7.5.1 Environment

Environmental conditions greatly vary across the globe. However, the environmental effect is very similar in each geographic location. Therefore, Oetjens et al. (2014) highlight that the environmental stresses are also similar. Similarity is further enhanced by

the fact that all four applications are global, that is, they are used everywhere on our planet. However, all examples use enclosures, which in fact create a very similar internal environment for the electronic components.

Usage methods and patterns differ for each of the examples. For instance, elevators are installed within the built environment, while drives and power supplies are spread around facilities, and cell phones are ubiquitous, but they are located close to people so the environment stresses are like what a human can sustain. Power supplies are usually installed within another equipment. A variable frequency drive could function as an individual installation or as a part of a larger unit.

10.7.5.2 Components

Materials and components are similar too. For instance, many parts of microcircuits are encased in plastic, and all examples utilize similar circuit boards. Most of the components are also very similar in these applications. Printed board multilayer technique is common, as is surface mounting technology (Liu et al., 2014). Plating with tin and gold are common both on contact points and wiring patterns. Liquid crystal displays and membrane or film input devices are most commonly utilized. Importantly, component level power densities are also very close to each other. The densest portion of the wiring patterns is also very similar in all examples. Ultimately, the biggest differences are found in product size, enclosure materials, and tightness. Staszak (2017) explains that applied heat management techniques diverge due to the great differences in total power levels.

10.7.5.3 Manufacture

Automatic assembly methods and surface mounting technology are employed in the manufacture of all the example products. Reflow or flow soldering is utilized according to Lau et al. (2016). Manufacturing facilities are similar, relatively well kept, clean, and HVAC is used to control both temperature and humidity during production. Most of the manufacturing differences originate from varied product sizes. The manual labor component is small in the mass-produced cell phones, while manual labor is significant during the manufacturing and assembly of elevators. Chudnovsky (2017) argues that conformal coating is rarely used despite the necessity of controlling humidity and minimizing contamination.

10.7.5.4 Transport

Most of the parts and components originate from subcontractors. Therefore, transportation-related corrosion issues are also similar (Hou et al., 2017; Zander et al., 2016). These include damage sustained during transport or storage of the soldering of PCBs, metal parts, devices, and components. Transport packaging specifications are varied across the supply chain and depend to a large extent on the subcontractor and buyer relationships. In general, there is a lot of room for improvement, both in transport quality and in the packaging techniques. For instance, Khanna (2017) states that moisture ingress still causes plenty of problems for the OEMs.

Maintaining sufficiently dry conditions by using absorbents is practiced as a trial and error predicament rather than an analytical practice argue [Achillas et al. \(2010\)](#). Lack of scientifically determined methods and practices becomes obvious in situations where the combined transport and storage time exceeds one week. The situation is exacerbated during maritime transport and in tropical environments ([Dean et al., 2000](#)).

Transport modalities also differ across the examples. Some of the products were transported by air, while some others utilized road transport or railroad, yet others were transported on ships. Storage times diverge as well. Therefore, [Ahmed et al. \(2015\)](#) clarify that all electronic components, parts, and subassemblies without an enclosure must offer protection against humidity and corrosion.

In addition, installation and usage trends are very different. For instance, elevator installation takes place during construction. This means that parts are exposed to the weather. A variable frequency drive or power source might be experiencing periodic overloads. Cell phone use is as varied as the user's lifestyles themselves around the globe.

10.7.6 Examples

Four applications are detailed here: elevators, drives, power supplies, and cell phones. These are discussed from a corrosion prevention stance.

10.7.6.1 Elevators

[Prasad et al. \(2017\)](#) explain that elevator electronics features are driven by the function of elevators. Generally, elevators have landings on each floor, which mandate dispersed electronics throughout the building. This means that electronics are in both protected and unprotected locations. The elevator motor and its associated controls are usually mounted as one unit. However, user panels are dispersed on each floor by the shaft and in the elevator. This results in complex wire routings around the shaft. Corrosive stress is caused by users and cleaners. The stress level varies with usage type such as apartments, hotels, hospitals, factories, and office complexes, each having its own unique corrosion regime.

[Jadhav \(2016\)](#) informs that installation of elevators poses special corrosion problems for the electronics. Construction is frequently started from the elevator shafts. Thus, elevators are installed and are operational prior to the completion of the building fabric. Therefore, elevators' electronics are often exposed to the weather, construction dirt, water, moisture, and dust. As a result, a great deal of enclosure engineering attention must be paid to the varying conditions that elevator electronics, its wiring, and connections are subjected to during the lifetime of the elevator.

Another important issue in elevator electronics' corrosion prevention is the heat management of high-power semiconductors according to [Avenas et al. \(2012\)](#). Not surprisingly, the aim is to maximize cooling of the insulated-gate bipolar transistors (IGBTs), while minimizing airflow over other electronic components to prevent widespread contamination. High-power connectors and connections are also important

design review targets in the conceptual stages of every NPD program. This aim is very similar to general drives, which are discussed next.

10.7.6.2 Drives

Wu and Narimani (2017) inform the variable frequency drives, often referred to as drives or motor drives. They can be very small devices with an enclosure volume of a few liters to as large as a city block for power station applications. Small drives are often cooled by free convection. The enclosure is relatively open. Emadi (2017) shows that due to great packaging and power density the power stages operate hot in between 85 and 150°C. An AC inverter can be in a variety of indoor spaces, including within other devices and equipment.

Large AC inverters require well-designed heat management systems and are exposed to large airflow regimes that make corrosion protection a top design review priority according to Rahman et al. (2018). Power changes cause repeated thermal cycling with associated thermal expansion and contraction. Emadi (2017) explains that this affects the entire structure, including the circuit boards, solder joints, and even mechanical bolted joints. High temperatures and large operating to shut down temperature ranges affect the aging characteristics of the isolation and various other materials in and within the enclosure. Funk et al. (2015) highlight that periodic maintenance and checking is paramount for this type of apparatus.

10.7.6.3 Power supplies

Power supplies are often designed as subassemblies of larger devices. Many power supplies are cooled by natural convection (Meng et al., 2018). The enclosure is usually fabricated from sheet metal or plastic. The enclosure could also have many openings. Power supplies can also be installed to form a separate dedicated power supply unit. This could be as large as a cabinet.

However, power supplies usually experience a relatively favorable corrosion environment according to Hahn et al. (2015). Power supplies are usually kept dry and warm. Unfortunately, some of the power supplies are directly exposed to external airflows as part of the heat management system. Such a situation can alter the power supply's environment drastically as the conditions become contaminating and thus much more corrosive.

High operational temperatures keep power supplies dry. However, this heat can damage the isolation and wiring materials. Emadi et al. (2017) demonstrate that the load of power varies, thus heat cycling becomes an issue. Large ΔT creates an environment that accelerates corrosion processes.

10.7.6.4 Cell phones

Black and Kohser (2017) inform that mass production, small size, constant operation, ever increasing packaging density, wear, and human behavior are the main corrosion factors. Many parts are relatively weak due to small size. Perera (1995) argues that this is one of the many reasons that connector reliability is difficult to ensure.

Cell phones are designed to be relatively closed. This is necessary due to exposure to various chemical and corrosive substances while being handled. ΔT are also common. Moisture penetration and the threat of wetting are great. Cell phones are also exposed to the elements during outdoor usage (Ichikawa et al., 2005). However, human secretions and the risk of water ingress are the greatest corrosion risks.

Mitigation of the corrosion risk is difficult due to the large number of exposed parts. For instance, keyboards and displays have many connections. In addition, the EMC seals and their contact areas are weak points from a corrosion perspective (Lee et al., 2014). Other exposed parts include the enclosure, the PCB, the battery, and of course the many connections for auxiliary devices. Optimization for corrosion is problematic. On the one hand, the enclosure should be air- and watertight. However, removal of moisture must also be possible. Hence, cell phones are a challenging proposition for enclosure engineers.

10.8 Hazardous areas

Hazardous areas are defined as sites, places, or locations where a potentially explosive atmosphere might exist in accordance with Cox et al. (1990). Potential means in this context, according to Morris et al. (1998), dangerous amounts of flammable substances which may coalesce in the form of dust, fiber, gas, haze, or vapor, and the oxygen content of air to create mixtures that can ignite or explode under certain circumstances.

Equipment used in hazardous areas is regulated due to its great potential to cause harm that result in loss of life, disability, injury, and property damage (Brauer, 2016; Rausand, 2013). Therefore, use of enclosures in hazardous areas is highly regulated. This means that equipment housed in enclosures require certification by third parties. Selection of enclosed equipment is country specific. Thus, selectors must consider current regulations and acceptability of relevant certifications. Importantly, Gas Grouping (McMillan, 1998; Bottrill et al., 2005), Zone Classification (Cox et al., 1990; Bozek, 2017), and Temperature Classification (Ebadat, 2010; Proctor, 2016) assessments must be performed and noted in the decision matrix.

10.8.1 Gas grouping

European hazard classification is displayed in Table 10.1 in accordance with McMillan (1998):

10.8.2 Zone classification

The likelihood of an explosion needs to be ascertained next. Both international and European standards use the zoning method for this purpose as displayed in Table 10.2 in accordance with Cox et al. (1990):

10.8.3 Temperature classification

McMillan (1998) explains that hot surfaces are a great concern in any hazardous areas as they could provide auto and spontaneous ignition sources. Therefore, every apparatus is awarded a temperature or T-rating. This rating corresponding to the apparatus' maximum surface temperature as specified by *EN 50,014:1998 Electrical apparatus for potentially explosive atmospheres. General requirements* and *IEC 60,079-0: 2017 Explosive atmospheres, Part 0: Equipment, General requirements*. Bozek (2017) informs that the primary purpose of the system is to allow the T-rating or T-classification system to be used as a cross-reference between the autoignition temperature and spontaneous ignition temperature, thus establishing uniformity and safety from hot surface—induced ignition.

For example, a T6 temperature class means that 85°C is the highest temperature the apparatus might reach under the most arduous operating conditions (Sutton, 2017). Note that for Group I, mining applications, the apparatus has a 150°C coal dust and 450°C methane limits rather than conforming to the general T-classification system (Ray et al., 2017).

10.8.4 Protection concept

Various concepts of hazardous area protection are available to suit an application. The enclosure specification section shows suitability of each concept and the type of enclosure that is applicable.

10.8.5 European regulations

The European Economic Area (EEA) provides relevant regulations under Directives (Jespen, 2016d). These are not, however, applied directly but rather implemented via national regulations in each member country. The most important Directives for electrical equipment in hazardous areas are as follows in accordance with Taylor et al. (2017a):

76/117/EEC Electrical Equipment for use in Potentially Explosive Atmospheres,
79/196/EEC Equipment Employing Certain Types of Protection, and
82/130/EEC Electrical Equipment for Use in Potentially Explosive Atmospheres in Mines Susceptible to Firedamp.

Leroux (2007) explains that the ATEX Directive 94/9/EEC covers both surface industries and mines. It adds requirements for mechanical hazards and potentially explosive dust-laden atmospheres. This Directive provides safety requirements that are essential in hazardous areas. These must be met by the equipment, such as the enclosure. Harmonized European standards (EN) can be utilized to demonstrate compliance with this Directive.

Bianco et al. (1994) highlight that the ATEX Directive classifies equipment according to its intended use. This is done by groupings and categorizations:

Apparatus group I (mines): category M1 and M2

Apparatus group II (surface industries): category 1, two and three

Apparatus must be marked as in the following example: CE ... Ex ...II...2...G and D.

CE means the CE marking, which must be in the format mandated by the Directive (Tricker, 2000). The letter Ex means that the equipment is for use in potentially explosive atmospheres. The lettering must conform to a specific format. The next characters could be either I or II. In this example II means that the equipment group is surface industry. The number two means equipment. “G” means gas and “D” means dust in the above example.

Rogers et al. (2003) inform that the United Kingdom implemented the ATEX Directive by the Statutory Instrument 1996 No. 192, The Equipment and Protective Systems Intended for Use in Potentially Explosive Atmospheres Regulations (1996). However, Northern Ireland has its own unique regulations. While the entire UK utilizes BS EN's to demonstrate mandatory compliance.

10.8.6 North American classifications

Korver (2012) explains that there are two systems used to classify hazardous areas in North America. These are the Class Division and the Zone systems. The United States and Canada predominately uses the Class Division System. The Zone system is generally utilized by the rest of the world. However, recent developments demonstrate a merging trend in between these two separate systems as displayed in Table 10.3 in accordance with Burns et al. (2015).

10.8.6.1 Class division system

Blair (2016) and Sutton (2017) describe that the Class Division system classifies hazardous locations according to Class, Division, and Group levels. Class defines the general nature and properties of the hazardous material in the surrounding atmosphere. The defined material may or may not be in sufficient quantities.

Class I means locations where flammable gases or vapors may or may not be in sufficient quantities to produce explosive or ignitable mixtures.

Class II means locations where combustible dusts either in suspension, intermittently, or periodically may or may not be in sufficient quantities to produce explosive or ignitable mixtures.

Class III means locations where ignitable fibers may or may not be in sufficient quantities to produce explosive or ignitable mixtures.

Division defines the probability of the hazardous material being able to produce an explosive or ignitable mixture based upon its presence.

Division one indicates that the hazardous material has a high probability of producing an explosive or ignitable mixture due to it being present continuously, intermittently, or periodically or from the equipment itself under normal operating conditions.

Division two indicates that the hazardous material has a low probability of producing an explosive or ignitable mixture and is present only during abnormal conditions for a short period of time.

Group defines the type of hazardous material in the surrounding atmosphere. The first four groups are gases classified under Class I. Groups E, F, and G are for dusts and particles contained within Class II or III.

Group A is a category for atmospheres containing acetylene.

Group B is a category for atmospheres containing a flammable gas and flammable or combustible liquid-produced vapor. Typical gases in this category include hydrogen, butadiene, ethylene oxide, propylene oxide, and acrolein.

Group C is a category for atmospheres containing a flammable gas, flammable or combustible liquid-produced vapor. Typical gases include either ethyl, ethylene, acetaldehyde, and cyclopropane.

Group D is a category for atmospheres containing a flammable gas and flammable or combustible liquid-produced vapor. Typical gases include acetone, ammonia, benzene, butane, ethanol, gasoline, methane, natural gas, naphtha, and propane.

Group E is a category for atmospheres containing combustible metal dusts. These are typically made of aluminum, magnesium, and their commercially available alloys.

Group F is a category for atmospheres containing combustible carbonaceous dusts with 8% or more trapped volatiles. These are typically made of carbon-based materials like carbon black, coal, or coke dust.

Group G is a “catchall” category for atmospheres containing combustible dusts that are not included in Group E or Group F. Typical dusts include chemicals, grain, flour, plastic, starch, and wood.

10.8.6.2 Zone system

[McMillan \(1998\)](#) explains that the Zone system classifies hazardous locations according to a gas or dust zone. Electrical equipment utilized in gas atmospheres is further subclassified into groups and even subgroups. The top-level classifier the “Zone” defines the probability of the hazardous material, gas or dust, being present in sufficient quantities to produce explosive or ignitable mixtures according to [Cole et al. \(2015\)](#).

Gas

Zone 0 is a category containing ignitable concentrations of flammable gases or vapors which are present continuously or for long periods of time.

Zone 1 is a category containing ignitable concentrations of flammable gases or vapors which are likely to occur under normal operating conditions.

Zone 2 is a category containing ignitable concentrations of flammable gases or vapors which are not likely to occur under normal operating conditions and do so only for a short period of time.

Dust

Zone 20 is an area where combustible dusts or ignitable fibers are present continuously or for long periods of time.

Zone 21 is an area where combustible dusts or ignitable fibers are likely to occur under normal operating conditions.

Zone 22 is an area where combustible dusts or ignitable fibers are not likely to occur under normal operating conditions and do so only for a short period of time.

Electrical

Electrical equipment is divided into three groups.

Group I is a subclassification of electrical equipment intended for use in mines susceptible to firedamp that is a flammable mixture of gases naturally occurring in a mine.

Group II is a subclassification of electrical equipment intended for use in places with an explosive gas atmosphere other than mines susceptible to firedamp. Group II equipment is further subdivided into three additional subgroups.

Group IIA is a category for atmospheres containing propane or gases and vapors of equivalent hazard.

Group IIB is a category for atmospheres containing ethylene or gases and vapors of equivalent hazard.

Group IIC is a category for atmospheres containing acetylene or hydrogen or gases and vapors of equivalent hazard.

Group III is a subclassification of electrical equipment intended for use in places with an explosive dust atmosphere. Group III equipment is subdivided into three subgroups.

Group IIIA is a category for atmospheres containing combustible particles.

Group IIIB is a category for atmospheres containing nonconductive dust.

Group IIIC is a category for atmospheres containing conductive dust.

10.8.7 Protection techniques and methods

[Bottrill et al. \(2005\)](#) highlight that various protection techniques and methods have been developed and employed around the world, consequently minimizing the potential risks of explosion and fire from use of an electrical equipment located in a hazardous location.

10.8.7.1 Class division system

Explosion proof is a categorization of a type of protection that utilizes an enclosure that can withstand an explosive gas or vapor within its envelope and or preventing the ignition of an explosive gas or vapor that may surround it and that operates at such an external temperature that a surrounding explosive gas or vapor will not be ignited thereby ([Abbasi and Abbasi, 2007](#)).

Intrinsically Safe is a categorization of a type of protection in which the electrical equipment under normal or abnormal conditions is incapable of releasing sufficient electrical or thermal energy to cause ignition of a specific hazardous atmospheric mixture in its most easily ignitable concentration ([Dubaniewicz and DuCarme, 2013](#)).

Dust Ignition proof is a categorization of a type of protection that excludes ignitable amounts of dust or amounts that might affect performance or rating and that, when installed and protected in accordance with the original design intent, will not allow arcs, sparks, or heat otherwise generated or liberated inside the enclosure to cause ignition of exterior accumulations or atmospheric suspensions of a specified dust ([Cross and Farrer, 2012](#)).

Nonincendive is a categorization of a type of protection in which the equipment is incapable, under normal conditions, of causing ignition of a specified flammable gas or vapor-in-air mixture due to arcing or thermal effect (Ahirwal et al., 2015).

10.8.7.2 Zone system

Jespen (2016b) explains that the following notions are high-level protection concepts. There are also sublevels of protection that may or not be applicable to each type. Also, some equipment may combine multiple types of protection.

Flameproof is a categorization of a type of protection in which an enclosure can withstand the pressure developed during an internal explosion of an explosive mixture and that prevents the transmission of the explosion to the explosive atmosphere surrounding the enclosure and that operates at such an external temperature that a surrounding explosive gas or vapor will not be ignited there (Schram et al., 2009). This type of protection is referred to as “Ex d.”

Intrinsically Safe is a categorization of a type of protection in which the electrical equipment under normal or abnormal conditions is incapable of releasing sufficient electrical or thermal energy to cause ignition of a specific hazardous atmospheric mixture in its most easily ignitable concentrations (Bottrill et al., 2005). This type of protection is referred to as “Ex I.”

Increased Safety is a categorization of a type of protection in which various measures are applied to reduce the probability of excessive temperatures and the occurrence of arcs or sparks in the interior and on the external parts of electrical apparatus that do not produce them in normal service. Increased safety may be used with flameproof type of protection (Sklet, 2006). This type of protection is referred to as “Ex e.”

Type n is a categorization of a type of protection applied to electrical equipment such that in normal operation it is not capable of igniting a surrounding explosive atmosphere (Hyatt, 2003). This type of protection is referred to as “Ex n.”

Type t is a categorization of a type of protection in which the electrical equipment is equipped with an enclosure providing dust IP and a means to limit surface temperatures (Jones et al., 1991). This type of protection is referred to as “Ex t.”

10.8.8 Equipment protection level markings

Wilson and Lawrence (2017) inform that the equipment protection level (EPL) marking indicates a level of protection that is based on the likelihood of the equipment becoming a source of ignition. Cole et al. (2015) explicate that the EPL marking also differentiate between explosive gas atmospheres, explosive dust atmospheres, and the explosive atmospheres in mines susceptible to firedamp.

10.8.9 Temperature code (T code)

Joseph and Team (2007) explain that a mixture of air and hazardous gases might be ignited by encountering a hot surface. Actual ignition will depend on the following: area of the hot surface, the surface temperature, and the concentration of the

surrounding gas mixture according to [Ebadat \(2010\)](#). The same is true for combustible dusts. Therefore, the “T code” of a product represents the maximum surface temperature that a product will not exceed while the ambient temperature is below a specified limit as displayed in [Table 10.4](#) in accordance with [Reason \(2017\)](#). For example, a product with a “T code” of “T3” means that its maximum surface temperature will not exceed 200°C provided it is operated in an ambient temperature below the OEM specification.

10.8.10 Terminology

10.8.10.1 Class/division system

The label “intrinsically safe” or alternatively the letters “IS” will precede the actual approval marking to indicate an equipment as intrinsically safe. Equipment is marked based on its approval according to which Class I, II, or III; Division one or two; Group A, B, C, D, E, F, or G; and temperature code T1 through T6 are rated for. Examples are listed below in accordance with [D’Souza et al. \(2017\)](#):

- Class I Division One Group B, C, D T5
- CL I Div. Two GP ABCD T5
- IS CL I, II, III Div. One GP ABCDEFG
- CL II, III Div. 1, Two GP EFG T4

10.8.10.2 Zone system

Equipment is marked according to the approved protection concepts like Ex i, Ex d, Ex n, and others, the group levels I, IIA, IIB, IIC, IIIA, IIIB, or IIIC, and the temperature codes from T1 through T6 that the apparatus is rated for. Equipment utilized in the United States will have a Zone system marking that will be preceded by which Class and Zone the apparatus is approved for. Examples are listed below in accordance with [Jespén \(2016b\)](#):

- Ex ia IIC T5
- Ex d IIB + H2 T6
- Ex nA IIC T6
- Class I Zone 2 AEx nC IIC T5

10.8.10.3 Additional terminology

[Rangel et al. \(2016\)](#) advise that the following nomenclature is not permitted for markings. However, they are commonly used to describe various types of approvals. Therefore, they are also included here.

- XP is a flameproof approval for Class I Division one
- EXP is a flameproof approval for Class I Division one
- NI is a nonincendive approval for Class I Division two
- DIP is a dust ignition proof approval for Class II Division one
- S means “Suitable For” for Class II Division two
- IS means Intrinsically Safe

10.8.11 Approval agencies

Schram et al. (2009) highlight that almost all countries require that products intended for installation in a hazardous location be certified by a recognized authority. This could be an approval agency, either governmental or independent. These bodies are often established by laws, regulations, or codes. See Table 10.5 for a list of the most common agencies in accordance with Bottrill et al. (2005).

10.8.11.1 North American approvals

There are 15 national testing laboratories in the United States according to Khalilieh (2016). However, Nolan (2016) informs that there are only two factory mutual (FM) and ULs qualified to approve apparatus for use in a hazardous location. In Canada, only the CSA can provide such an approval (Nolan, 2017).

10.8.11.2 European approvals

Each member country of the European Union has established one or more “notified bodies” for product approval (Williams, 2014). Notified bodies approve products for use within the entire European Union. Such an approval is known as CENELEC certifications. CENELEC is the acronym for European Committee for Electrotechnical Standardization. Therefore, an apparatus that has been CENELEC certified by any of the notified bodies is automatically accepted for use within all member states. All electrical equipment intended for use in an explosive atmosphere must comply with the EU ATEX Directive in order to be marketed in the European Union according to Nicols (2003).

10.8.11.3 International approvals

Pommé and Sijrier (2010) explain that countries participating in the International Electrotechnical Commission on explosion protected equipment, commonly known as IECEx or “Ex” Scheme can issue either an international certification or a national certification for the explosion protected equipment. Cole and McManama (2013) add that each country within the IECEx scheme establishes an Ex Certification Body (ExCB). Only these can approve an apparatus. ExCBs issue the national certification for their country based upon the IECEx standards, including any national deviations according to Kelly et al. (2018). They also issue any relevant international certification. However, Australia is the only country accepting international certifications for use in its territories (Jespen, 2016c).

10.9 Hose-down areas

Brown (2018) advises that product safety and contamination concerns have impacted food, beverage, and pharmaceutical producers. Producers must guarantee that machinery utilized in these areas is clean and free of contamination. Thus, wash-downs are essential. Maasberg (2012) informs that more intensive cleaning processes, high-

pressure wash-down sequences, and ever more concentrated chemical solutions are being utilized.

A successful wash-down removes all waste and leftover materials, residue, and other by-products from the processing systems and controls (Moerman and Lorenzen, 2017), thereby insuring continued product quality. However, development of a suitable wash-down sequence requires many steps.

For instance, Moerman and Wouters (2016) explain that it is important that all relevant employees are trained about proper wash-down techniques. Solution composition is paramount as a cleaning solution that is too weak or rich can reduce the level of sanitation or even damage system components (Schreier et al., 2016). Staff must also be instructed that solution particulates can linger in the air for many hours, thus, potentially and invisibly reducing product purity. Today's wash-down conditions are considered to be harsh from an electronics perspective according to Moerman and Fikiin (2016). Therefore, all equipment, systems, controls, and components utilized must be rated to match the actual application environment.

Buschart (2012) explains that electrical and electronic controls must be properly enclosed and thereby protected from harmful wash-down effects. Undesirable effects include product contamination, damage, or even corrosion. Food, beverage, pharmaceutical, and other producers might face devastating penalties according to (Moerman and Lorenzen, 2017). Other consequences include excessive production downtime in addition to expensive equipment replacements. Selecting an appropriate enclosure is paramount to ensuring that critical requirements are met.

Enclosures are rated by the National Sanitation Foundation (NSF). NSF was instrumental in developing the *NSF/ANSI 169—2012 Special Purpose Food Equipment and Devices* standard. This standard specifies the essential design criteria for enclosures in wash-downs. The NSF/ANSI 169 enclosure certification assures that hinges, mounting surfaces, latches, and doors will protect the equipment while resisting ingress of dirt and debris (Waide et al., 2014). Design and construction criteria in accordance with NSF/ANSI 169 include the following elements:

- Leg stands must provide a minimum stipulated unobstructed clearance beneath the enclosure.
- Lift-off hinges must incorporate removable pins and continuous hinges must not be used.
- No threads, screws, or studs must be exposed in a process or splash zone.
- Readily cleanable fasteners such as slot-head and quarter-turn latches must be available.
- Sloped surfaces must be incorporated to facilitate runoff, such as a sloped top, sloped door edges, and a sloped flange trough gutter above the enclosure openings.
- Welded seams and joints must be deburred.

An enclosure that is NSF/ANSI 169 certified will guarantee that important attributes such as construction, design, gasketing, hinging, latching, mounting, quality, and sealing help achieve acceptable sanitary conditions while also protecting the electronics and electrical components of the equipment in a wash-down environment according to Koban and MacDonald Gibson (2017).

10.9.1 Construction and quality

An enclosure must be constructed to withstand even the harshest chemical wash-downs. Enclosures used in wash-down applications must be made of a nonhygroscopic and noncorroding material. Typically, 304 and 316L stainless steels are deployed as they do not show surface corrosion or discoloration (Miller, 2006).

An enclosure's texture and finish is also important. Surface quality often determines whether contaminants can be easily removed from the enclosure's external surfaces during wash-down procedure according to Gibson et al. (2015). A number four or equivalent finish is typically recommended. Such a smooth surface will prevent contaminant accumulation on the surfaces. In addition, the enclosure must not have any ridges and burrs left on any of its welds. Kirmeyer and Martel (2001) explain that smooth weld surfaces minimize risk of contaminant infiltration and colonialization.

Automated manufacturing processes are preferred to produce high-quality wash-down capable enclosures. This ensures consistency of quality and repeatability. Carlson et al. (2014) argue that automation generally minimizes product variation. However, many wash-down-related applications require enclosure modifications and customization. Customized enclosures can save the on-site installation time and as such can have the lowest total cost of ownership.

10.9.2 Design

There are a few common wash-down-related enclosure problems. These can negatively affect both the protected components and wash-down effectiveness. The most frequent problems include the following in accordance with Schreier et al. (2016):

- contaminant entrapment between the adjacent wall and the wall-mounted backside of the enclosure,
- unreachable, sunken areas formed by freestanding floor stands of the enclosure, and
- wash-down solution pooling on the horizontal surfaces.

Wasson (2015) clarifies that these are challenges that can be easily overcome during the conceptual stages of the enclosure design process. For example, a wall-mounted enclosure standoff will provide access to the back of the enclosure, thus facilitating a more effective wash-down process by affording implementation of easy contaminant removal procedures. Difficult-to-clean areas underneath freestanding floor stands can be minimized by specialist hardware. Pooling can be avoided by properly sloping and adequately smooth surfaces. For an effective runoff solution, a minimum 10° sloped horizontal surfaces should be incorporated.

10.9.3 Standards for wash-down applications

Choi et al. (2013) advise that wash-down application standards are focused on high pressure and temperature. Some electronic enclosures can be sensitive to these dimensions. The NEMA, UL, and CSA are standards bodies in North America. Their standards are similar.

UL and CSA require enclosure testing. This must be performed by properly qualified evaluators. Both organizations monitor manufacturers' adherence to prescribed production methods and material selections. However, NEMA does not require independent testing. This means that compliance rests with the manufacturer. As a rule of thumb, an enclosure's certification cannot exceed its enclosed components. Thus, [Driscoll et al. \(2008\)](#) highlight that enclosure engineers must ensure that both the selected enclosure design and its enclosed electronic components are certified for the relevant wash-down procedure.

10.9.4 Hinging

The best performing enclosure door hinges for wash-down applications are the asymmetrical, bullet-style, and lift-off hinges according to [Moerman and Lorenzen \(2017\)](#). They all feature a properly rounded top. In addition, smooth finish is incorporated to allow easy and complete hinge area cleaning. Thus, these styles are minimizing entrapment while still providing simple enclosure access. Piano and any other continuous hinge designs should be avoided if the enclosure has even a limited a chance to be subjected to an occasional wash-down.

10.9.5 Mounting

[Dittrich \(2015\)](#) warns that inappropriate mounting practices are creating a challenge to clean areas beneath a freestanding floor stand. This could be minimized if the enclosure engineer chooses a smaller leg footprint or stand. Adjustable legs should be selected to increase convenience, minimize water retention, and reduce areas of contaminant entrapment.

10.9.6 Latching

Standardized industrial latches are not appropriate for wash-down applications according to [Moerman and Wouters \(2016\)](#). This is because standard latches are not created to facilitate cleaning solution runoff. General latches might not provide satisfactory seal performance either. A low-profile latch that is flush with the enclosure is the best choice for wash-down applications. These incorporate a smooth latch possessing minimal number of openings. It is also paramount to select a handle that latches securely enough to prevent wash-down solution and cleaning chemicals ingress.

10.9.7 Sealing and gasketing

Optimizing enclosure construction for wash-down environments is essential. Selecting a high-performance gasket or seal is a critical step in a successful enclosure's design process. [Tong \(2016\)](#) explains that seals and gaskets must be affixed by the proper adhesives and they must be compatible with their substrates. The substrate is usually stainless steel in wash-down applications. In addition, gaskets, seals, and their adhesives must survive high-pressure wash-downs. However, they must be checked periodically for loss of resiliency and rates of compression. It is important that all

cutouts and holes must be fully sealed with properly selected materials. Conduits entering an enclosure must be protected with a UL Type 4X-certified connector according to [Stafford and Wallnau \(2001\)](#).

10.10 Gasket selection

[Schwartz \(2016\)](#) clarifies that gaskets are a shaped sheet or ring made of rubber or other material for the explicit purpose to seal a junction between two mating surfaces in an equipment or a device. Gaskets are deployed to provide a seal between two adjacent surfaces, for instance, in between an opening and the enclosure main body according to [Cowan and Winer \(2015\)](#). Enclosure engineers know from practical experience that a correctly mounted, well-designed gasket is essential to the long-term protection of complex electronic devices located within an enclosure. Most gaskets are primarily utilized to eliminate harmful effects of the external environment. [Hochberg et al. \(2010\)](#) advise that a gasket's ability to exclude moisture, water, dust, dirt, other liquids, and particulate matter from the protected space are the primary engineering considerations. In addition, containment issues in many cases are also very important. Achieving electromagnetic compatibility (EMC) by minimizing or eliminating electromagnetic interference (EMI) and radio frequency Interference (RFI) are paramount aspects of gasket selection ([Gerke, 2018](#)). Gaskets can also be deployed to contain noise, vibration or other forms of harmful interference generated by the enclosed components according to [Fahy \(2000\)](#). Enclosure engineers need to ensure proper performance throughout the service life of the gasket. Therefore, [Middendorf \(2017\)](#) advises that engineers should specify a gasket that is designed and rated for the relevant application.

10.10.1 Ratings

There are many organizations that create industry standards for enclosures. Many of these standards also include provisions for the proper use of gaskets. [Manahan et al. \(2015\)](#) elucidate that the four most relevant enclosure standard creating organizations are the CSA, International Electrotechnical Commission (IEC), National Electrical Manufacturer's Association (NEMA), and UL. The *IEC 60,529 Degrees of protection provided by enclosures (IP Code)* identifies IP levels according to [Calder et al. \(2018\)](#). Therefore, this standard and its various national adoptions are often referred to as IP codes. [Madden \(2017\)](#) highlights that these ratings reflect an enclosure's ability to protect against access to the contained live that is electrified parts by dirt, dust, moisture, people, and tools. However, the IP codes are often not as stringent as other ratings issued in accordance with NEMA, CSA and UL standards. For instance, some IP ratings allow a small amount of water to enter an enclosure, so long as water ingress does not interfere with the performance of the contained equipment ([MacAngus-Gerrard, 2017](#)).

[Doh and Lee \(2016\)](#) explain that NEMA 250, UL 50, and 50E are different from IEC 60,529 ratings because of the specific exclusion of ingress into an enclosure.

They also address design attributes more than the IP codes. The NEMA and UL standards address similar points. However, NEMA simply specifies design intent. UL administers compliance by independent testing and randomized on-site inspection. UL ratings incorporate tests listed in [Table 10.6](#) to guarantee gasket protection levels ([Khalilieh, 2016](#)).

[Manahan et al. \(2015\)](#) advise that enclosure engineers usually select a gasket with a UL Type rating of 12 or 13 for an indoor application. Type 3, 4, 4X, 6 and 6P rated gaskets are most often utilized for outdoor applications. These enclosures can also be used indoor. However, they are generally much more expensive than Type 12 or 13 housings.

10.10.2 UL water tests

[Laughton and Say \(2013\)](#) inform that UL water tests incorporate drip, wash-down, and submersion. UL excludes ingress of water into the enclosure throughout the duration of the tests to acquire a rating. For example, [Murphy \(2017\)](#) describes that a Type 12 UL test ascertains resistance of the enclosure to dripping water and concrete dust, or atomized water. In the water drip test, the gasket must allow no water to enter the enclosure for a period of 30 min. The test specimen is exposed to 20 drops of water per minute. Atomized water, which is usually substituted for the concrete dust ingredient is sprayed at 207 kPa at potential leakage points during the concrete dust test explain [Mallick \(2015\)](#).

[Plog et al. \(2002\)](#) explain that the Type 13 UL test involves water sprayed at 7.6 L per minute for half an hour. [Hall \(2017\)](#) adds that the water includes a wetting agent to simulate oil. In the Type 4 and 4X tests, the water volume is increased to 246 L per minute and sprayed from 3 to 4.5 m straight onto the enclosure for a minimum of 5 min. The Type 6 and 6P UL tests completely submerge the enclosure in water for 30 min to attain a Type 6 certification and for complete day to gain Type 6P according to [Koshal \(2014\)](#).

10.10.3 Other UL requirements

[Senthilathiban et al. \(2016\)](#) inform that another UL examination is the oil swell test. This test attempts to determine how a particular gasket performs in case it is exposed to oil. [Farfan-Cabrera et al. \(2017\)](#) explain that the gasket is immersed in IRM 903 oil for 70 h. The gasket must not swell more than 25 percent swell or shrink more than 1 percent to pass this test. The test is administered for Type 12, 12K and Type 13 UL applications according to [Kusko and Thompson \(2007\)](#).

[Senthilathiban et al. \(2016\)](#) explain that yet another set of UL tests are the tensile and elongation examinations. These are required to attain Type 2, 3, 3S, 4, 4X, 5, 6, 12, 12K and 13 certifications. [Tailor et al. \(2017\)](#) add that the gasket specimens are aged at a temperature of 70°C for a time of 1 week. The performance of brand new and aged gaskets is compared by stretching all of them to the breaking point. The aged gaskets must extend to at least 60 percent of the new gaskets' stretch length.

The aged gaskets must exhibit a tensile strength no less than 75 percent of their new counter parts.

10.10.4 Additional tests

Nolan (2017) informs that some manufacturers perform a water absorption test. This examination is supposed to guarantee that water will not be drawn into the housing through the gasket. First, the gasket is placed in an environmental chamber. The specimen is submersed into 50.8 mm of distilled water for 3 min while a vacuum is applied. Hence, the need for the environmental chamber. Subsequently, atmospheric pressure is applied for 3 min. Finally, the gasket is dried and weighed. The mass is measured to determine water absorption amounts. Mass gain must be no more than 3 percent according to Fragassa (2016).

Horve (1996) advises that cold impact tests might also be performed. The specimen is frozen in a -51°C environment for 2 h. The gasket is then struck with a hammer weighing 0.45 kg and the area of the impact is measured to determine the compression rate, as well as note any permanent deformations.

Interestingly, Dunlap et al. (2007) note that compression testing is not a UL requirement. However, Bond and Shaw (2018) explicate that the American Society for Testing and Materials (ASTM) has created a standard for conducting this examination. The specimen is first heated in 70°C for 3 days. After this conditioning gaskets are compressed 20%, 30%, 40%, 50% and 60%. Then the specimen is cooled back to room temperature (22°C). The compression set is measured. Li et al. (2016) add that a participating gasket must be measured to within 10 percent of its original thickness dimension to pass this test.

10.10.5 Adhesion testing

Flitney (2011) informs that a foam-in-place (FIP) or strip gasket is placed onto a variety of substrates. Substrates include both mild and stainless steel, painted and other non-metallic surfaces. The specimens endure a series of tests. These include submersion in various chemicals and exposure in a range of environmental conditions. The adhesion level of the gasket is tested after conditioning. Wasay and Sameoto (2015) demonstrate that these tests supposed to guarantee that a gasket will not peel off a housing, rather the adherence will be so strong that the gasket is destroyed prior to losing adhesion.

Proper amount of adhesion is necessary for many gasket applications. However, Panek and Cook (1991) assert that blocking, which is unwanted adhesion must be avoided. For instance, Kim (2016) adds that blocking might weld two sealing surfaces together and as a result an operator will be unable to open an enclosure door. Therefore, a blocking test was also developed. Hilliard et al. (1977) describe that the specimen is clamped in between two substrates and compressed to 50% of its original thickness. The gasket assembly is kept at 70°C for a complete day. The test is passed if there is no adhesion to either of the clamped-on substrates according to Kim (2016).

10.10.6 Chemical resistance

Aibada et al. (2017) highlight that many manufacturers expose gaskets to a great variety of chemicals, including strong acids and bases to ascertain chemical resistance. Various cleaning solutions are also utilized to determine behavior of the gasket in a wash-down application. Exposures of 7 days 30 days are common. Srisang et al. (2014) explain that manufacturers check the specimen for any changes, swelling, permanent deformation, chemical absorption, structural changes and adhesion.

10.10.7 Designs

(Flitney, 2011) explains that there are three main types of gaskets: die-cut, FIP and strip. Hoag and Dondlinger (2016) opine that die-cut gaskets are superior in performance and usually available in two forms. Chouchaoui (2016) shows that regular-cut die-cut gaskets are created to conform to the exact perimeter of the joint surfaces. Chevron gaskets consist of two L-shaped matching pieces that conform to the surface perimeter according to Cocco (2014). Die-cut gaskets do not have seams and hence their superior performance. However, Hoag and Dondlinger (2016) warn that they are typically the most expensive gasket design.

A strip-gasket method is the oldest gasketing method. Lecklider (2016) explains that OEM adhere rolls, or strips, of the gasket material to the mating surfaces and cut them to suit in situ. Attoui and Bouzid (2016) add that many materials can be utilized for the purposes of creating a strip gasket. These include neoprene, nitrile, silicone and Viton®. A strip gasket is often the most cost-effective option according to Yates (2015). However, this method creates many seams, perhaps as many as one in each directional change. Prodan et al. (2015) highlight that seams make gaskets more vulnerable specially to wear and various damages during assembly and disassembly.

Hartmann and Corning (2016) assert that FIP gaskets are currently the most popular gasket type. This method utilizes a polyurethane material that is generally applied to a housing in its liquid form. The material is then allowed to cure into the desired shape as a cellular foam structure in situ. This method leaves no seams but can only be utilized if polyurethane's chemical resistance is acceptable in the application. Schubert (2015) highlight that the major advantage is that FIP gaskets have good compression set resistance and are usually less expensive than other gaskets.

10.12.8 EMC

Lecklider (2016) informs that electromagnetic compatibility (EMC) could be achieved by minimizing or eliminating EMI and radio frequency interference (RFI). Kerwien and Blair (2017) highlight that proper gasket selection is of paramount importance to implement proper EMC strategy.

Ozenbaugh and Pullen (2017) state that EMI and RFI ARE caused by stray voltages and currents from electrical and electronics apparatuses. Lack of EMC usually negatively affects the performance of the enclosed devices and other devices in the vicinity add Edis and Varrall (2016). A purposely designed gasket must be utilized to achieve

the necessary protection levels for the enclosed components according to [Kerwien and Blair \(2017\)](#).

[Kularatna \(2016\)](#) demonstrates that gaskets utilized for EMI and RFI shielding must feature a metal-to-metal contact. This is important as conductive gaskets create a low resistance path, which is essential to achieve acceptable EMC according to [Bingkun \(2017\)](#). [Kunkel \(2014\)](#) highlights that EMI and RFI housings must also incorporate conductive pathways at all other potential entry and exit points. [Tong \(2016\)](#) explains that this function might be achieved with the application of internal conductive plating or coating and various other shielding methods.

10.10.9 Increased performance

[Flitney \(2011\)](#) describes effective enclosure gaskets that can be designed to satisfy specialized applications. For instance, [Zhang et al. \(2017\)](#) describe that angled flange gaskets can channel water away from an enclosure. This excludes water ingress in wash-down applications. Therefore, many applications demanding angled flange gaskets can be found in the food and beverage and pharmaceutical industries. [Coomber and Latte \(2014\)](#) explain that designing hidden gaskets or tongue-and-groove seals avoid physical damage while minimizing the potential for UV damage and chemical exposure. However, [Patterson and Ferguson \(2015\)](#) warn that these methods increase associated costs.

10.10.10 Maintenance

[Stahley \(2001\)](#) confirms that all gaskets need occasional attention. Even gaskets that are correctly specified and certified for the environment and application must be maintained to ensure acceptable continued performance. [Yang et al. \(2017\)](#) advise that gaskets must be checked for physical damage. Gaskets can be impaired by cuts, tears, and gouges. In addition, aging gaskets can also become brittle ([Chang et al., 2016](#)). After prolonged service exposure to harmful environmental conditions gaskets might need to be replaced. However, [Manahan et al. \(2015\)](#) warn that replacing a damaged or aged gasket negates the enclosure's UL rating.

In many situations the enclosure's UL rating can only be maintained if the entire subassembly such as the enclosure door is replaced. [Flitney \(2011\)](#) informs that a frequently used option is to replace a damaged or aged gasket with a precut gasket that is custom-made for the enclosure. However, this method does not maintain UL certification and as a consequence should only be utilized as a last resort or if continued certification is no longer needed according to [Manahan et al. \(2015\)](#).

10.10.11 Materials

There are many potential gasket materials ([Arghavani et al., 2001](#); [Winter, 1990](#); [Czernik et al., 1965](#)). Each offer a specific use temperature range, compression set resistance, and other characteristics. Commonly used gasket materials include neoprene, nitrile, polyurethane, silicone, and Viton according to [Storgards et al. \(1999\)](#).

10.10.11.1 Neoprene

[Tailor et al. \(2017\)](#) believe that neoprene is by far the most common material used for gaskets. It is utilized to create both die-cut and strip gaskets. [Araujo et al. \(2016\)](#) add that it has a great service temperature range between -55 and 120°C . [Jahan et al. \(2016\)](#) highlight that this material affords excellent chemical, abrasion, and tear resistance. Neoprene is also waterproof ([Guler et al., 2016](#)).

10.10.11.2 Nitrile

[Araujo et al. \(2016\)](#) state that nitrile gaskets have a service temperature range of -40 to 121°C . This means that it cannot resist extreme cold as well as Neoprene, and its high temperature range is only minimally better than Neoprene's. However, [Xiu-meng et al. \(2014\)](#) emphasize that nitrile does compensate by offering excellent compression set resistance combined with good tear and abrasion resistance. However, resistance to ozone, UV, and other weather-related elements is poor, unless custom compounded to overcome these issues according to [Krishnan and Nair \(2018\)](#).

10.10.11.3 Polyurethane

[Flitney \(2011\)](#) believes that polyurethane owes its popularity to FIP gaskets. These are currently the most popular gasket type with a service temperature range of -40 to 70°C . [Jahan et al. \(2016\)](#) note that the top end of the service temperature range is too low to be useful for most applications where the gasket must be placed close to heat producing electronics. However, [Moriga et al. \(2015\)](#) polyurethane does offer a good compression set resistance. Also, FIP technology allows great ease in creating complex and irregular shapes according to [Flitney \(2011\)](#).

10.10.11.4 Silicone

Silicone gaskets are manufactured by molding or die-cutting sheet stock into the appropriate shape. [Schotzko and Lang \(2014\)](#) highlight that silicone has a service temperature range of -40 to 232°C . The high end of its range makes it suitable to even the hottest power electronics according to [Jahan et al. \(2016\)](#). In addition, it offers excellent compression set resistance. Furthermore, resistance to ozone, UV, and other weather-related elements is good. However, [Flitney \(2011\)](#) warns that silicone is more expensive than most other gasket materials with the notable exception of the fluoroelastomers.

10.10.11.5 Viton

[Worm and Grootaert \(2005\)](#) inform that Viton was trademarked by the DuPont company. However, [Mitchell and Lowrey \(2016\)](#) note that the fluoroelastomer material section of DuPont was spun off with the performance chemicals division and as such is currently the property of the Chemours Company. Fluoroelastomers have a good service temperature range of -28 to 204°C according to [Peacock \(1980\)](#). Yet, [Ogilvie et al. \(2011\)](#) highlight that excellent chemical resistance, especially to caustics

makes any fluoroelastomer a great gasket material. Fluoroelastomers, however, are very expensive. Their cost is the primary limiting factor in many otherwise suitable applications according to [Flitney \(2011\)](#).

10.11 Extreme weather

[Cressler and Mantooth \(2017\)](#) explain that extreme outdoor environments create many hazards that negatively affect reliability of equipment housed in enclosures. For instance, [Qazi \(2016\)](#) underlines that outdoor enclosures must resist UV radiation, heat, precipitation, wind and seismic loads, such as hurricanes, tornadoes, and earthquakes. [Wiesner et al. \(2015\)](#) explain that extreme weather-related elements ultimately influence the creation of rather unique FRS. For example, [Sarkar and Jain \(2017\)](#) list applications such as cell sites and mobile telecommunications, outdoor electrical junctions, outdoor industrial controls, railway signals, solar power stations, and traffic toll systems.

[Kareiva and Carranza \(2018\)](#) observe that extreme weather creates many environmental risks. However, [Kyritsis et al. \(2017\)](#) explain that other technical factors must also be considered in designing an appropriate enclosure for the application. A few of these are issues of ingress, chemical resistance requirements, EMC, and relevant standards according to [Tong \(2016\)](#). In addition, the enclosure engineer must ascertain whether the new enclosure needs a built-in cooling and heating system argue [Baracu et al. \(2016\)](#). Corrosion resistance issues are also important ([Cunningham et al., 1970](#)). Gasket and seal selection with respect to water, dust, and other environmental contaminants will also contribute toward creating the appropriate level of protection from the elements according to [Aparicio et al. \(2016\)](#).

[Cermak et al. \(2017\)](#) emphasize that the internal subassemblies, devices, and components of any enclosure must be designed for extreme conditions. Such conditions might include large range and temperature variations. This is still true despite the fact that the electronics are sealed off from extreme weather conditions. [Padilla \(2015\)](#) explains that other factors such as moisture ingress, condensation formation, chemical resistance, and exposure to corrosive gases among other issues can also affect component and material selection, layout, design, heat management, and manufacture.

10.11.1 Precipitation

[Saraf et al. \(2017\)](#) observe that water ingress is one of the more common problems that undermine electronics reliability. [Amir et al. \(2015\)](#) conclude that large differences in ambient air temperature can instigate condensation formation, thereby increasing the risk of electronic equipment malfunction and failure due to short circuits. Condensation can also manifest itself during nightly temperature reductions or after equipment shutdowns. Moisture-laden air can also enter when a door is opened either for maintenance or service purposes ([Moerman and Fikiin, 2016](#)). This is especially critical in wet or humid applications.

Moisture-related corrosion can adversely affect continuity and the life span of internal components, devices, and wiring connections within the enclosure ([Ahmed et al.,](#)

2015; Conseil et al., 2016; Ambat and Conseil-Gudla, 2016; Taylor et al., 2017b). It is therefore essential to choose corrosion-resistant materials in precipitation-driven applications according to Conseil-Gudla et al. (2017b). Williams and Sargent (2014) advise that it is also important to regularly inspect critical connections, such as power, grounding, and bonding for early signs of the onset of significant corrosion.

10.11.2 Dust

Chakrabarty et al. (2015) warn that accumulation of dust or other combustible particles within an enclosure considerably increases the chance of catastrophic failure due to equipment overheating or even fire. White and Delichatsios (2015) highlight that noncombustible particles also reduce the integrity and therefore reliability of the equipment. Solar radiation only accelerates these problems (Lubega and Stillwell, 2018). However, Mesa et al. (2017) elucidate that selecting a favorable location, excellent materials with the proper rating, the right heat management system, and even the color choice might minimize ignition-related issues.

Ingress-related failure can arise at the points where accessories or cable connections are penetrating through the enclosure (Madden, 2017; MacAngus-Gerrard, 2017; Gouda, 2016; Drury, 2016). These components must at the minimum match or better yet exceed the enclosure rating to correctly seal the enclosure from dirt, dust, and other particles according to Arora and Kapoor (2018). Therefore, the enclosure's and ingress rating will be successfully preserved.

10.11.3 Seismic activity

Ries et al. (2014) explain that seismic-rated enclosures are needed to be specified in application areas where earthquakes, regular shocks, or other vibrations occur. Sivakumar and Chandrasekaran (2016) inform that seismic applications include airports, power plants, railroads, and others. Seismic environments demand selection of an enclosure with oversized frame strength and rigidity to minimize seismic event-related stresses and resultant damages according to Bai et al. (2017).

10.12 Extreme cold

Keane et al. (2013) state that electronic products utilized in extreme cold are subjected to an environment that is not covered by most standard tests, certifications, and approvals. Safety and unimpaired functioning are the two key areas of concern. In addition, Rowe et al. (2001) highlight that the equipment's ability to successfully retain its explosion-protection capabilities at extreme low temperatures is of foremost importance for Class I applications. Schwartz (2016) clarifies that extreme cold fundamentally affects material properties, both the enclosure and the electronic components. Additionally, Keane et al. (2013) underline that the explosive atmospheres' properties are also altered. Functionality of most electronics is impaired by extreme cold temperatures according to Gupta and Gupta (2015).

Mugaas and Transeth (2010) show that extreme low temperatures affect the effectiveness of the enclosed electronics' ability to survive potential gas explosions.

Therefore, installation and utilization of electrical equipment are problematic (Horvath, 2010; Fowler and Gard, 2011). Studies have demonstrated that igniting explosive gases at extreme low temperatures produced increased pressure when compared to higher temperatures (Astbury and Hawksworth, 2007; Dryer et al., 2007). Therefore, Munro (2016) warns that increased pressure testing is required for flameproof enclosures (Ex d). Keane et al. (2013) explicate that the situation is further exacerbated, that while the pressure-related requirements are inversely proportional to ambient temperatures, the enclosures themselves appear to lose their strength due to brittleness at extreme low temperatures. Thus, low or normal temperature tests, certifications, or approvals are not satisfactory according to Munro et al. (2017). Potential problems arise because flameproof and explosion-proof enclosures' suitability to contain internal explosions are severely undermined by extreme cold temperatures states Munro (2017).

Elsheikh et al. (2014) advise that there are several important factors that have a negative effect on the proper functioning of electrical and electronic equipment. Jurgens (1982) stresses that for most electronics precautions may be required prior to deployment into an extremely low temperature environment. Fraden (2004) elucidates that one of the problems is that as the temperatures decrease below normal operating temperatures, changes usually occur both in the resistance and capacitance of the devices. This results in altered timing of integrated circuits, including waveform changes. Therefore, electrical properties of components are substantially altered. This change can have a detrimental effect on the behavior of sensitive components. Additionally, Jayne (2017) explains that materials utilized in the manufacture and mounting of the various components can be adversely affected by differential expansion and contraction during thermal cycling. Thus, Guyer (2017) concludes that all electrical components must be designed for extreme cold temperature environment and relevant certifications should be affirmed during design reviews.

10.12.1 *Metals*

Pineau et al. (2016) demonstrate that metals might lose ductility and develop brittleness in very low temperatures. Bhadeshia and Honeycombe (2017) warn that this behavior affects some metals' ability to provide protection during impact, shock, and explosion events. Rapid embrittlement is not a uniform behavior of all materials according to Hutchings and Shipway (2017). Krauss (2015) finds that a metal's crystal lattice structure strongly influences the ductility of the material at various temperatures.

Gunn (2014) explains that there are only three main crystal structures for metals. Söderlind et al. (1995) add that these are the body-centered cubic (BCC), face-centered cubic (FCC), and hexagonal close packed (HCP) structures. Liang and Khan (1999) show that most commonly utilized industrial metals possess BCC and FCC structures. Importantly, Wigley (2012) demonstrates that a BCC crystal lattice structure is more prone to ductility loss in extremely low temperature environments than other types. Liebowitz (2013) affirms that BCC metals experience a transition from ductile to brittle state. Ductile to a brittle state transition is caused by the marked reduction in the metal's dislocation movement ability as the ambient temperature decreases. This is significant as movement of dislocations permits plastic deformation. The BCC metal will lose its ductility below the ductile–brittle transition temperature

(DBTT) according to [Dudko et al. \(2017\)](#). [Laird et al. \(1986\)](#) point out that FCC metal crystal lattice structures possess more complex slip systems. This allows deformations to cascade, and thus temperature has much less effect.

[Krauss \(2015\)](#) asserts that carbon steels have a BCC lattice structure. This means that carbon steels are greatly affected by extreme low temperatures. In addition, [Sieradzki and Newman \(1985\)](#) warn that carbon steels have a quick transition from ductile to brittle, which make their use inappropriate in this environment.

[Tang et al. \(2013\)](#) show that most aluminum alloys have FCC lattice structures. Thus, they are minimally affected by extremely low ambient temperatures. Fasteners, mounting structures, doors, covers, terminal and equipment cases, and many other parts may be made of materials that are susceptible to embrittlement. Component materials installed inside enclosures may also be adversely affected by extremely low temperatures. Internal components are protected from impact by the enclosure. However, [Veprik \(2003\)](#) emphasizes that they could fracture due to vibration, differential expansion, and contraction or by other means if the extremely low temperature made them brittle.

[Puttlitz \(2004\)](#) highlights that solder poses yet another substantial problem. Nonleaded solders experience DBTT at high temperatures ([Prabhu and Deshapande, 2012](#)). Thus, the solder must be suitable for the extremely low operating temperature environments. The solder utilized in field installations must also be suitable for these conditions. [George and Pecht \(2014\)](#) argue that this is a challenge that most electronics companies are yet to master. Ignoring this problem manifests itself in unreliable products in a variety of extremely low temperature applications. [Tkaczyk \(2015\)](#) opines that spectacular failures cause strong customer complaints and ultimately drive redesign efforts. However, they are often unable to overcome the initial issue due to general misunderstandings and a failure to locate the root cause of the problem ([Wiklund et al., 2016](#)).

[Riley et al. \(2010\)](#) explain that differential expansion and contraction is a concern with all enclosure materials. This is because different materials have markedly different coefficients of expansion. Differential expansion and contraction of different metals is normally factored into all good enclosure designs. However, [Barbero \(2017\)](#) highlights that exotic alloys and many other materials can cause significant problems.

[Munro \(2017\)](#) states that explosion-proof and flameproof minimum flame path gap requirements must be complied with independent of the ambient temperature range. Differential expansion and contraction at extremely low temperatures could force a joint out of tolerance. Severe problems can also exist due to differential expansions in a nonhazardous environment. [Fischer et al. \(2015\)](#) assert that this is especially relevant for electronics where differential expansion and contraction often is the root cause of failure.

10.12.2 *Plastics*

[Arsenault \(2016\)](#) informs that plastics are also affected by extreme cold temperatures. Plastics also develop brittleness but usually at a higher temperature than metals according to [Koltzenburg et al. \(2017\)](#). [Agarwal et al. \(2017\)](#) add that for some plastics, the transition temperature can be as high as 0°C. The move through a DBTT is called the glass transition temperature for plastics. [Nicholson \(2017\)](#) clarifies that

this is a transition where a plastic material starts to behave like a glass, hence the name glass transition temperature. [Rodriguez et al. \(2014\)](#) advise that most plastics used in electronics could be very brittle at extremely low temperatures. However, [Arsenault \(2016\)](#) highlights that plastics generally exhibit a more gradual transition than metals.

Yet, another issue with plastics is the buildup of static charges on the enclosure surfaces in extreme cold temperatures ([Babrauskas, 2016](#)). This is due to low humidity. This increased possibility of static charge buildup increases explosion hazards. In addition, [Mardiguian \(2011\)](#) explains that the increased static charge buildup creates significant problems with the proper functioning of electronics. For instance, [Pecht et al. \(2001\)](#) inform that static charges cause incorrect or erratic readings in analog meters incorporating plastic faces.

10.12.3 *Elastomers*

[Brydson \(1999\)](#) shows that elastomers and many rubber components become progressively stiffer and much less flexible at extremely low temperatures. [Whelan \(2017\)](#) asserts that loss of flexibility is a major problem for elastomers. Stiffness causes inadequate sealing on the enclosure surfaces. Additionally, loss of tightness and grip on glands create major problems.

[Datta \(2016\)](#) warns that inadequate sealing instigated by loss of gasket flexibility can damage the explosion—protection properties of an enclosure in a hazardous location. A gasket is often utilized to provide protection against water ingress in combination with a flameproof joint providing a flame path for an explosion-proof enclosure. [Bahadori \(2014\)](#) explicates that stiff gaskets prevent complete closing of the cover and the flameproof joint gap becomes insufficient to act as a proper flame path.

In the design of enclosures, extremely low temperature is a limiting factor due to the elastomeric material selection for gaskets and bushings ([Mastro, 2016](#); [Fackler, 2015](#)). OEMs will often offer alternate construction materials for extremely lower temperature applications according to [Moore \(2015\)](#).

10.12.4 *Lubricants*

[Rudnick \(2017\)](#) demonstrates that another limiting factor in extremely low temperature applications are the lubricants. Lubricants can change phase and become solid ([Klein and Kumacheva, 1998](#)). Thus, [Bloch and Geitner \(2012\)](#) explain that lubricants can cause equipment to malfunction and to fail in a very low temperature environment. Therefore, [Pirro et al. \(2016\)](#) advise that lubricants must be specifically formulated for use in extremely low temperature applications.

10.13 Long-term exposure

[Drobny \(2014\)](#) informs that thermoplastics turn softer as the temperature increases. However, [Crawford \(1998\)](#) highlights that all plastics including thermosets will eventually degrade due to heat. Thermal degradation imposes an upper limit to the service

temperature range of plastics according to [Van Krevelen and Te Nijenhuis \(2009\)](#). [McKeen \(2014\)](#) clarifies that substantial thermal degradation can happen at temperatures much below ultimate mechanical failures. Thus, in many cases this could be a more restrictive limit than mechanical or electrical property loss.

[Vasile \(2000\)](#) explains that thermal degradation of polymers is a complex mechanism but could be characterized as a molecular conversion, a type of structural deterioration as a direct consequence of overheating. [Hamielec and Tobita \(1992\)](#) illustrate that at sufficiently high temperatures constituents of the long-chain backbone of any polymer begin to separate. This process is termed as molecular scission ([Louis et al., 2018](#)). The broken-up chain segments then start to react with one another. [Grassie and Scott \(1988\)](#) inform that new somewhat stable molecules may form that can have very different properties from the original polymer. Polymer degradation can be induced by the following environmental conditions in accordance with [Singh and Sharma \(2008\)](#):

- Heat—a thermal or thermal oxidative degradation.
- Light—photodegradation.
- Oxygen—oxidative degradation.
- Weathering—UV degradation.

[Olabisi and Adewale \(2016\)](#) enlighten that the ability of a polymer to resist the above degradation mechanism is referred by the plastic industry as stability. [Campbell et al. \(2014\)](#) observe that heat can cause thermal degradation both in service and during processing. Processing issues will be dealt with in a separate volume.

[Lewis \(2016\)](#) highlights that all polymers experience degradation during service. Degradation manifests itself in a gradual decline in properties. [Marturano et al. \(2017\)](#) add that degradation can be controlled by specialty polymer modifiers called stabilizers. They are relatively expensive and can only be detected by sophisticated control methods. As such stabilizers often fall victim to cost-cutting measures according to [Tolinski \(2015\)](#). However, [Kandel \(2018\)](#) explicates that customers will ultimately experience the devastating results of short-term savings in terms of failed products. Repercussions can be enormous according to [Lewis \(2016\)](#).

10.13.1 Property changes

[Cardarelli \(2008\)](#) explains that thermal degradation leads to physical, optical, electrical, and mechanical property changes relative to the initially specified enclosure material selection. Thermal degradation involves changes to the molecular weight and distribution of the polymer ([Hilado, 1998](#)). Characteristic property changes include the following observable signals in accordance with [Pielichowski and Njuguna \(2005\)](#):

- Reduced ductility and embrittlement
- Chalking
- Color changes
- Cracking
- General reduction in many other properties

[Lenk \(2012\)](#) informs that the main method of polymer degradation depends not only on the application's environment but also on heat history. [Dealy and Wissbrun \(2012\)](#) clarify that this means that the way the polymer was processed is also critical.

10.13.2 Polypropylene

Karian (2003) emphasizes that polypropylene is very susceptible to thermal degradation. Degradation happens even at normal temperatures. Therefore, Zweifel (2012) concludes that polypropylene must always be protected against thermal degradation with the addition of stabilizers. Heat-induced degradation causes chain scission. Therefore, the shortened chain length reduces molecular weight and distribution. This in turn reduces mechanical properties, often leading to greatly reduced ductility and associated embrittlement. Ultimately, Lewis (2016) believes that the enclosure or product fails in service.

10.13.3 Polyethylene

Shenoy (2013) adds that polyethylene is also highly susceptible to thermal degradation. Degradation results in chain branching and cross-linking. This in turn reduces melt flow, which is an important processing parameter. However, Lewis (2016) emphasizes that enclosure engineers are even more concerned about the associated embrittlement and color changes indicating the onset of catastrophic failure.

10.15.4 PVC

Wypych (2015) stresses that PVC is very susceptible to thermal degradation. Degradation, however, most often happens during processing. Degradation results in extensive property loss. Therefore, Ambrogi et al. (2017) conclude that heat stabilizers are vital ingredients in any PVC formulation.

10.13.5 Fluoropolymers

Liu et al. (2017a) assess that fluoropolymers processed such as PTFE, FEP, PFA, PVDF, THV, ETFE, and ECTFE all have excellent thermal degradation properties. This is primarily due to the carbon–fluorine (C-F) bonds in the backbone. Therefore, fluoropolymers do not require stabilizers. Fluoropolymers are one of the best polymers for long-term thermal degradation resistance (Ebnesajjad and Khaladkar, 2017). Cui et al. (2014) add that fluoropolymers also possess excellent high temperature mechanical performance. However, Gardiner (2015) opines that they are extremely expensive especially when their prices are compared to commodity resins such as polyethylene and polypropylene.

10.13.6 Engineering resins

Utracki et al. (2014) believe that other polymers such as PPS, LCP, PEEK, and many others have excellent resistance to thermal degradation. This is due to the strong bonds in their backbone that restrict heat-induced movement (Cogswell, 2013). Many of these polymers perform well in long-term thermal degradation testing and the relevant applications according to Strong (2008).

10.14 Review

Enclosure engineers need to specify electrical and electronics housings, casings, and shells correctly according to [Chapman \(2018\)](#). [McDonald \(2016\)](#) explains that one way to do this is to use the IP and IK codes. [Owens et al. \(2017\)](#) inform that the codes provide protection to the users and the enclosed devices from various intrusions such as water, dust, contaminations, and mechanical impacts. However, [Wasson \(2015\)](#) adds that there are other dimensions that also need to be carefully evaluated to create a successful enclosure for any electrical or electronic equipment.

[Merchant et al. \(2015\)](#) demonstrate that environmental considerations are paramount in enclosures that are exposed to the elements. [Yip et al. \(2017\)](#) conclude that many enclosures are effectively not only waterproof but airtight as well. [Sachdeva \(2015\)](#) elucidates that the perhaps surprising fact is that using watertight enclosures does not guarantee long-lasting protection and reliable performance. [Isermann \(2006\)](#) shows that this is because of the existence of ΔP . Thus, over time this delta P can cause difficult to detect leak paths ([Crowder, 2006](#)). [Lasnier \(2017\)](#) demonstrates that pressure equalization is not a simple task.

[Kreeley and Coulton \(2018\)](#) highlight that all enclosures are affected by the cooling effect or forming condensation if the environmental conditions deteriorate sufficiently. [Zhan et al. \(2008\)](#) explain that water droplets condense out of moist air if the air is cooled below its saturation point. [Amir et al. \(2015\)](#) explain that enclosures are opened for service and this activity provides an avenue for moisture entry. Many condensation prevention methods have been developed ([Vancauwenberghe et al., 1995](#)). None seems to be universally effective. Therefore, [Ge et al. \(2017\)](#) conclude that a combination of internal moisture removal and drainage system can provide an acceptable solution to many condensation problems.

[Xu et al. \(2018\)](#) observe that corrosion reactions are electrochemical and as such the process accelerates with an increase of the temperature. Therefore, [Rao and Wang \(2011\)](#) conclude that corrosion is more rapid as power density challenges existing heat management in new electronics. [Mathia \(2010\)](#) explains that corrosion resistance could be increased by improving robustness, minimizing air flow for cooling purposes, maximizing moisture removal, limiting dissimilar material interfaces, and by the application of protective coatings.

Equipment used in hazardous areas is regulated due to its great potential to cause harm that results in loss of life, disability, injury, and property damage ([Brauer, 2016](#); [Rausand, 2013](#)). Use of enclosures in hazardous areas are highly regulated and require certification by third parties. Selectors must consider Gas Grouping ([McMillan, 1998](#); [Bottrill et al., 2005](#)), Zone ([Cox et al., 1990](#); [Bozek, 2017](#)), and Temperature Classification ([Ebadat, 2010](#); [Proctor, 2016](#)) assessments.

Hose-down areas must guarantee that machinery utilized in these areas is clean and free of contamination according to [Brown \(2018\)](#). [Maasberg \(2012\)](#) informs that more intensive cleaning processes, high-pressure wash-down sequences, and ever more concentrated chemical solutions are being utilized. Enclosure engineers need to

understand appropriate design practices in terms of construction, quality, compliance with relevant standards, and a few critical components (Blanc, 2014). These are hinges, latches, seals, and gaskets.

Schwartz (2016) clarifies that gaskets are deployed to provide a seal between two adjacent surfaces in an enclosure. Hochberg et al. (2010) advise that a gasket's ability to exclude moisture, water, dust, dirt, other liquids, and particulate matter from the protected space are the primary engineering considerations. Achieving EMC by minimizing or eliminating EMI and RFI can also be important (Gerke, 2018). Gaskets can also be deployed to contain noise, vibration, or other forms of harmful interference generated by the enclosed components according to Fahy (2000). Therefore, Middendorf (2017) advises that engineers should specify a gasket that is designed and rated for the relevant application.

Qazi (2016) underlines that outdoor enclosures must resist UV radiation, heat, precipitation, wind and seismic loads such as hurricanes, tornadoes, and earthquakes. Extreme cold fundamentally affects material properties of the enclosure and the electronic components. Additionally, Keane et al. (2013) underline that the explosive atmospheres' properties are also subtly altered. Therefore, enclosure engineers need to consider these events very carefully.

Drobny (2014) informs that thermoplastics turn softer as the temperature increases. However, Crawford (1998) highlights that all plastics including thermosets will eventually degrade due to heat. Thermal degradation imposes an upper limit to the service temperature range of plastics according to Van Krevelen and Te Nijenhuis (2009). McKeen (2014) clarifies that substantial thermal degradation can happen at temperatures much below ultimate mechanical failures. Thus, in many cases this could be a more restrictive limit than mechanical or electrical property loss.

10.15 Hot tips

Meller and DeShazo (2001) assert that environmental considerations are paramount in enclosures that are exposed to the elements. However, Kreeley and Coulton (2018) highlight that all enclosures are affected by the cooling effect or forming condensation if the environmental conditions deteriorate sufficiently. Enclosures designed for hazardous and wash-down areas need special attention (Brauer, 2016; Brown, 2018). Enclosure engineers need to make sure that extreme conditions and long-term exposure are considered in all designs (Cressler and Mantooth, 2017; Keane et al., 2013; Van Krevelen and Te Nijenhuis, 2009). The following points summarize and highlight the most important aspects:

- FRS must include the proper assumptions for the operating environmental conditions according to Saxena et al. (2013).
- Pressure (ΔP) and temperature (ΔT) differentials facilitate ingress and must be investigated at the conceptual stage design review (Isermann, 2006).
- Internal moisture removal and drainage system can provide an acceptable solution to many condensation problems (Ge et al., 2017).

- Corrosion resistance could be increased by improving robustness, minimizing air flow for cooling purposes, maximizing moisture removal, limiting dissimilar material interfaces, and by the application of protective coatings, potting, or encapsulation (Mathia, 2010).
- It is important to note that care should be taken not to overspecify an IP rating for an application. This is because the cost of an enclosure increases rapidly with the rise in IP rating (Cole et al., 2015).

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11.1 Introduction to interference

The purpose of this chapter is to detail the fundamental considerations for system designers and other professionals working in the field of enclosures, housings, and packages without encountering massive problems with electromagnetic interference (EMI) and in accordance with [Perez \(2013\)](#) and [Violette \(2013\)](#). This chapter also provides information on electromagnetic compatibility (EMC) compliance with relevant laws and regulations ([Paul, 2006](#); [Dhia et al., 2006](#); [Ramdani et al., 2009](#); [Ott, 2011](#)). [Tong \(2016\)](#) explains that due to the extensive variability of practical electronic equipment installations only general guidance could be provided. The underlying fundamental principles are briefly explained to permit a qualified designer the quick delivery of a range of specific enclosure- and housing-related applications ([Noulis, 2016](#)).

[Paul \(2006\)](#) explains that electromagnetic compatibility is also called electromagnetic interference and radio frequency interference (RFI). [Chatterton and Houlden \(1992\)](#) assert that EMC can be achieved by preventing interference from penetrating or escaping from an enclosure or housing.

The simplest way to think about this challenge is to ensure that the enclosure acts as a Faraday cage according to [Dhia et al. \(2006\)](#). [Kumar et al. \(2015\)](#) explain that such a device is an earthed metal screen that surrounds an electrical equipment to exclude EMI. [Solín \(2017\)](#) adds that this means that a provision of an electrically conductive shield must be extended over all surfaces. [Mamiş et al. \(2016\)](#) point out that a Faraday cage works well if two separate conditions are met. Firstly, the conductor must be thick enough. Secondly, holes must be smaller than the electromagnetic radiation wavelength.

[Weston \(2017\)](#) highlights that it is important that all enclosure openings must be sealed from interference. [Xiao and Anlage \(2017\)](#) add that, in practice, the seal need not be continuous but it must be tailored to the shielded frequencies. [Tong \(2016\)](#) explains that there are dual function gaskets that incorporate ingress protection (IP) features as well as electromagnetic radiation shielding. However, [Kubík and Skála \(2016\)](#) warn that this combined sealing method's integrity is often compromised. Thus, two separate gaskets are often utilized, each dedicated to either IP or interference protection.

[Tajima et al. \(2017\)](#) elucidate that attenuation levels depend on design methodology, the type of gasket utilized, and envisioned maintenance practices. [Abbasova et al. \(2016\)](#) believe that maintenance is often crucial as with many current designs contaminants allowed to build up on the exposed surfaces. [Chung \(2001\)](#) finds that this in turn reduces surface conductivity, hence lowering the level of interference

attenuation. This negative effect is most common with a butt joint design according to [Weston \(2017\)](#). A better method is to incorporate a gasket interference seal with a wiping action that offers self-cleaning. This type of gasket retains its design shielding level longer. Maintenance, however, is unavoidable. [Geetha et al. \(2009\)](#) explicate that an opening in the shield can be incorporated by utilizing a conductive mesh. A provision must be made so that this mesh is continuously connected around the opening's edge.

[Ott \(2011\)](#) underlines that the European Directive on EMC became law in 1996. This law was revised and the current legislation is 2014/30/EU. This Directive sets the European interference standard. It states that all products susceptible to EMI must be designed and manufactured in a fashion that device functionality is not degraded due to EMI, according to [Williams \(2014\)](#). This Directive also states that devices capable of emitting EMI must be designed and manufactured in a fashion and that such a device does not emit EMI that would affect equipment in its environment.

[Williams \(2016\)](#) adds further that this Directive increased EMC protection and as a result also increased demand for various shielding products and associated filters. However, [Minteer et al. \(2017\)](#) assert that an enclosure neither produces nor is susceptible to EMI. Thus, an enclosure is not directly within the scope of the EU EMC Directive and as a consequence it does not have to carry the CE mark according to [Drury \(2001\)](#).

11.2 Electromagnetic compatibility

[Labussière-Dorgan et al. \(2008\)](#) explain that every electrical apparatus inherently generates electromagnetic emission due to its operation. Electronics can also be affected by electromagnetic energy. Electromagnetic waves are useful in certain situations. For instance, equipment containing radio-based communication systems utilizes emitters and receivers. Therefore, these devices are sensitive to EMC. Thus, their needs are usually incorporated as mandated thresholds according to [Weston \(2017\)](#).

An electromagnetic emission can be intentional or unintentional. Communication systems, for instance, utilize intentional emission while most other electronics fall into the latter category. [Lienig and Bruemmer \(2017\)](#) explain that the fundamental principle of EMC is that electromagnetic emission must not exceed the established immunity levels of associated apparatus. Therefore, both emission and immunity must be carefully controlled. There are many varieties and uncertainties associated with EMC effects, situations, and applications. Thus, [Hirsch et al. \(2015\)](#) add that an appropriate margin of safety must exist between the emission and immunity factors.

All electronics exhibit a certain degree of emission and susceptibility. However, the limiting EMC factors in most commonly occurring environments are related to radio equipment ([Redl, 1996](#)). This is due to the powerful transmitters and very sensitive receivers utilized in all radio apparatus. Therefore, [Holloway et al. \(1997\)](#) underline

that there is a strong correlation between EMC standards and requirements of the state-of-the-art radio communications systems.

The EMC phenomenon is relevant to an unlimited range of frequencies and wavelengths. However, most standards such as the EU EMC Directive limit their scope to a range of 0–400 GHz (Ponzelar et al., 2015). This range is still enormous. In fact, it is so wide that many diverse effects occur in this spectrum. Thus, there is a significant risk that all electrical phenomena are captured in the scope of EMC regulation. Rybak and Steffka (2004) believe that this is also the fundamental reason for the proliferation of EMC “rules of thumb.” Paul (2006) warns that these rules are at best guides and at worst contradictory to generally accepted design practices. Zhao et al. (2005) show that a method which is effective at a high frequency will not be effective at low frequency, and vice-versa. Thus, Weston (2017) emphasizes that it is important to understand the fundamentals of EMC and incorporate it into the electronic enclosure, housing, and package designs.

Yuan et al. (2015) state that it is currently improbable that an electronic equipment will create unintentional emission or exhibit sensitivity above 2 GHz. Therefore, the standard 0–400 GHz range for most applications could be restricted to a more manageable 0–2 GHz. A further assistance is to subdivide this spectrum into high- and low-frequency effects with the dividing line placed roughly at 100 kHz according to McCloskey and Dimov (2017).

Rathi and Panwar (2018) demonstrate that this categorization is useful because electrical conduction is the primary mode of low-frequency effects. However, induction is the primary mode of high-frequency effects according to Guibert et al. (2016). This means that EMC related to high frequency utilizes no physical connection. Importantly, there is no precise dividing line between these two effects. In principle, there is an inverse relationship between physical size and the importance of the induction effect. Thus, the larger a system becomes, the lower the frequency at which induction effect is the driving factor. However, this bimodal characterization clarifies some of the EMC-related principles.

11.3 Fundamental concepts

This section uses a digital motor drive to illustrate EMC concepts. Emission modes, filtration, ground leakage, suppressors, cables, and saturation theory are discussed from an application perspective to provide a fundamental at the same time practical understanding of relevant EMC theory as advocated by Christopoulos (2017).

11.3.1 Emission modes

Qian et al. (2016) explain that switch-mode power supplies, digital control, and other generally fast-switching circuits in a motor drive can contribute to radio frequency EMC emission. Suppression of these sources is a matter for the device designer, in this case for the motor drive engineers. Suitable design must keep such emission firmly

under control. However, incorrect installation of a digital motor drive provides with ample opportunities to create unintentional EMC emissions, warn [Gong and Ferreira \(2014\)](#).

The primary latent source of the emission is the main power stage especially the inverter of a pulse-width modulation (PWM) motor drive according to [Kazimierczuk \(2015\)](#). [Zhang and Chau \(2017\)](#) add that the inverter is an exceptionally great source of emission due to the fast-changing nature of the PWM output. Furthermore, this output is directly connected to the motor and motor cable, which in turn may act as an antenna to broadcast the EMC emission. Thus, [Yang et al. \(2015\)](#) argue that details of the installation are having a major influence on the drive's overall EMC behavior.

[Videt et al. \(2017\)](#) note that the output of a PWM waveform contains significant energy up to 30 MHz because its fast-changing pulse edges with a typical rise time in the range of 50–100 ns. This energy is present between output phases. It is also present between the output phases and the ground in the form of a common-mode voltage. It is this common-mode voltage component which is the major contributor of the EMC emission. [Rahimi et al. \(2016\)](#) emphasize that high-frequency current flow through stray capacitances of the motor windings and the motor frame via the motor cable to the ground is the source of this emission.

[Ayachit and Kazimierczuk \(2017\)](#) clarify that high-frequency current creates unexpected voltage drops in wiring due to self-inductance. A practical example can demonstrate significance of this effect. A 1 m length of wire has a typical inductance of about 0.8 μH . The actual measured value depends on the current return path. However, 0.8 μH could easily be considered as a typical value. The output current from a digital motor drive to the winding would typically be about 2 A peak with an associated rise-time of 100 ns in order to charge the stray capacitance. This 2 A peak current would create a voltage pulse of 16 V with the same temporal extension of 100 ns in the length of this short wire. This 16 V, 100 ns pulse is sufficient to create a significant error in a digital or a fast-acting analogue circuit.

[Hegde and Tallam \(2017\)](#) assert that the motor cable is the main potential source of EMC emission due to its high voltage. The motor cable will become an effective transmitting antenna under certain conditions, particularly if the motor cable length is an odd number of the quarter wavelengths. This means that, for example, a 20 m cable will be particularly effective transmitter at 3.75, 11.25, and 18.75 MHz. The emission will be altered slightly by the motor and other grounded objects. Thus, preventing this emission is paramount. Therefore, the cable must be shielded. High-frequency motor and cable voltage due to their capacitance causes current to flow into ground. The capacitance of a motor winding to its frame is typically in the range of 1–100 nF. The actual value depends on its design rating and insulation. Capacitance from the motor cable power cores to ground is about 100–500 pF per meter of cable length. Small values such as these are insignificant in a sinusoidal supply application. However, they cause substantial current pulses at the edges of the PWM voltage wave.

In addition, the current returns through various paths. These are usually very difficult to control according to [Vrankovic et al. \(2017\)](#). Current may flow from the motor frame back to the supply via almost any part of the machinery. This presents a major problem if the current passes through ground wires within a sensitive measuring

circuit. Such a current flow can cause major disturbance. Gebhardt et al. (2003) demonstrate that another common return route to the digital motor drive is through the supply wiring. Thus, electronics sharing the supply might be disturbed.

Ott (2011) asserts that electromagnetic emission from a properly installed motor cable is suppressed by its shield. However, it is essential that both ends of the shield are correctly grounded. This shielded cable due to its mutual inductance effect also minimizes ground current flowing from the motor frame into the machinery structure. This subject is well understood by EMC consultants according to Williams (2016).

11.3.2 Input filters

Pagani et al. (2017) explain that the input filter creates a low impedance path from the ground to the digital motor drive input lines. Thus, the high-frequency current returning from the motor cable shield is provided with an easy local return route, and therefore it does not flow into the power network, thereby insuring damage-free operation. Pahlevaninezhad et al. (2014) state that the most important role of the filter is the suppression of common-mode high-frequency emission. In addition, there are series-mode emissions due to the direct current smoothing capacitor's nonzero impedance value. The filter offers series-mode attenuation to control this problem.

Reyes (2016) explicate that capacitors between input lines provide a series-mode attenuation. This is done in conjunction with the leakage inductance of the inductive component. The capacitors to ground in addition to the inductance create a common-mode attenuation. The inductance is created as a common-mode component. Importantly, it is not magnetized by the main power current, therefore minimizing its physical dimensions. It often uses a high-permeability core. Thus, it can accept a very limited unbalance from a common-mode current.

Filters for voltage source digital motor drives are carefully optimized for the application according to Ji et al. (2015). These drives present an exceptionally low impedance source. Ala et al. (2016) believe that this means that conventional general purpose (GP) filters have little to no benefit. Insertion loss is the general method of filter specification (Weston, 2017). Such loss is measured in a test setup with 50 Ω source and load impedance. A more realistic test is using 0.1 Ω source and 100 Ω load. However, neither of these tests correctly represents a digital motor drive application. Thus, neither test can be considered completely satisfactory from a drive perspective.

11.3.3 Ground leakage

Suitable filters have extremely high capacitance values between lines and ground due to the low source impedance presented by a digital motor drive according to Karim et al. (2016). Low impedance results in a leakage current, also known as touch current, to ground. This is relevant at supply frequency exceeding the 3.5 mA current. This value is normally accepted as allowable for an apparatus, which derives its safety ground through a flexible connection or plug and socket set. Many filters require a

permanent fixed and large enough ground connection to minimize fracture risk. Alternatively, low leakage current filters are available at the expense of severe motor cable length restrictions (Barater et al., 2014).

11.3.4 Suppressors

Gurevich (2017) advocates the use of a ferrite ring surrounding a circuit that introduces impedance at radio frequencies, thereby reducing the current. Such a ring will not work if it surrounds a conductor carrying power current due to its high permeability to magnetic saturation. However, if the ring surrounds a three-phase set, then saturation is avoided since magnetic field is only caused by the common-mode current. Sai et al. (2017) explain that a typical manganese-zinc ferrite offers high loss in the 1–10 MHz frequency range. Sharma (2016) adds that this is the range where motor cable resonance occurs. Therefore, Miloudi et al. (2017) show that this ring provides very useful damping of the cable resonance and thus provides a substantial reduction in peak current. Importantly, Han et al. (2017b) observe that the loss in the ferrite does cause a substantial temperature rise. The temperature of the ferrite increases in long motor cables until equilibrium is reached. Equilibrium temperature is very close to the Curie temperature. Gurevich (2017) recommends to utilize three turns on the ring. This recommendation is based on practical EMC experience. The number of turns affects inserted impedance. This impedance is nominally a square law relationship. However, the interturn capacitance limits associated benefits. Therefore, it is not effective to exceed three.

11.3.5 Cables

Moon et al. (2015) elucidate that performance of a cable shield is generally characterized by the parameter Z . This represents the transfer impedance per unit of length. Any current flowing in the internal circuit produces no voltage between the ends of the cable shield in an idealized cable. In addition, current flowing in the shield from an external source produces no voltage in the inner circuit. These two idealized aspects would minimize the EMC emission from the cable. Therefore, immunity of inner signal circuits to external EMC sources would be maximized. There is shield resistance in a real-life application. The shield's coverage is also imperfect. Other details also cause a departure from the ideal nonzero value of Z .

However, this transfer impedance is not the only factor involved. Scully (2014) highlights that a real cable exhibits strong internal resonances. This effect causes high internal currents. This current in turn is damped by electrical cable losses. Therefore, Marlier et al. (2015) add that the shield's damping characterization is also important. Damping depends to a high degree on the material selected. For instance, steel shields have high resistance. Therefore, steel provides better damping than copper sheaths that have much lower associated resistance. Unfortunately, steel has an inferior transfer impedance when compared to copper. However, the two factors largely cancel out. Thus, a steel wire armored cable provides no greater EMC emission connected to a digital motor drive than a very good quality copper braided shielded cable.

11.3.6 Saturation

Xu et al. (2016) point out that saturation is a problem in long motor cables. Specifically, the common-mode current in the installed filter might rise to a high level according to Lewis-Rzeszutek et al. (2016). At this current level, Mallik et al. (2017) observe that the high-permeability filter inductor core becomes saturated (magnetically). In such case the filter is ineffective. Therefore, Velander et al. (2017) add that filters have cable length limits.

Ruffo and Guglielmi (2016) demonstrate that cable capacitance causes additional current loading both on the motor drive and the filter. Shielded cables with jacketed insulation located between the inner cores and the shield of the cable create a reasonable capacitance. He (2015) explains that many cables are shielded by a direct wrap around the inner cores. This method, however, Pienaar (2015) warns, causes unusually high capacitance, thus reducing permissible cable lengths, add Han et al. (2017b). Mineral insulated copper clad cables also suffer from the same malady (Williams, 2014).

11.4 Regulation

Giroto and Tonello (2017) observe that regulations exist worldwide to control EMC both in its intentional and unintentional forms. Lampe (2016) explains that the primary reason for this is to prevent interference with communication services. Local authorities normally have the legal power to shut down any apparatus, which interferes with radio-based services (Williams, 2016).

Most countries enforce regulations requiring consumer and other electronics to be tested and certified to meet relevant EMC emission levels (Valouch, 2015). For instance, Heirman (2017) highlights that the Federal Communications Commission (FCC) enforces the relevant rules in the United States of America. Similarly, Robinson (2016) notes that the C-tick system is utilized in Australia. The EMC Directive 2014/30/EU of the European Union (EU) is uncommon in that it is requiring immunity in addition to emission to be certified (Wainwright, 2015).

It is neither conceivable nor necessary to sufficiently describe all the various worldwide regulations in this handbook. Like all the other regulations, the EU EMC Directive has been the subject of much research, testing, and commentary (Maynard, 2015). Most emission regulations are based on the standards produced by Comité International Spécial des Perturbations Radioélectriques (CISPR). Mardiguian (2014b) explains that the three fundamental standards are the CISPR11, CISPR14, and CISPR22. These provide the platform for almost all significant EMC standards.

11.5 Standards

Williams (2016) highlights that the most significant principle of all important worldwide EMC regulations is that electrical and electronic apparatus must not interfere with

the proper operation of other equipment. Importantly, [Li et al. \(2015\)](#) assert that all regulations aim at protecting the integrity of communications systems from interference. Most standards incorporate a requirement that electronics must be certified to demonstrate compliance ([Smith, 2017](#)). Compliance is accepted to demonstrate that the electrical equipment is unlikely to cause significant and therefore problematic interference.

Equipment standards are focused on free-standing and self-contained products. For instance, many standards are written for consumer goods, office equipment, and similar. These are free-standing and self-contained equipment even though they do have the ability to form interconnections with peripherals and local or the wide area networks. The emission levels set in the relevant standards allow for several apparatuses to be colocated. However, [Williams \(2014\)](#) opines that industrial products such as variable speed drive modules have difficulty meeting these standards. This difficulty arises from three interrelated areas. Firstly, in some applications drive modules are utilized as self-contained units, whereas in other applications many drives might be colocated. Ascertaining the right clause of a standard for compliance is not a simple matter. Secondly, a drive module cannot be tested without its associated peripherals, such as a motor and joining cables. Thirdly, the effect of many colocated modules is not simple to forecast and creates enormous design challenges. Large industrial installations often contain numerous drives in addition to other electronic products. As a result, these installations cannot easily be tested against standards, which were mainly established for compact consumer-oriented products. Thus, most industrial electronics manufacturers have chosen a practical approach ([Hughes and Drury, 2013](#)). They are testing their products in arrangements, which are like their intended use. In addition, manufacturers provide installation guidelines.

[Dawson et al. \(2014\)](#) argue that the 2004 EU EMC Directive contained a few clarifications. A new definition of “apparatus” included subassemblies that generated or be affected by EMI. New requirements were also added. Apparatus captured by the scope of this standard was to be provided with information for installation and operation to meet all requirements of this Directive. Essentially, this means that approach practiced by industrial electronics manufacturers was legalized. In addition, a CE mark for EMC is also required.

Global EMC standards are produced by the International Electrotechnical Commission (IEC). Standards for application under the EU EMC Directive leverage European Harmonized Standards, which are commonly referred to as EN Standards. These are produced by Comité Européen de Normalisation Électrotechnique (CENELEC). [Arce et al. \(2017\)](#) point out that these two families of standards are harmonized and as a result most of them have identical technical requirements as well as classified under the same standards number.

[Gonzalez et al. \(2016\)](#) explain that emission standards specify an EMC emission limit curve as a function of frequency. The specified receiver simulates a conventional radio receiver and is a standardized and calibrated device. The receiver utilizes a coupling unit and antenna, which measures voltage typically up to 30 MHz and electric field above the 30 MHz threshold.

Many electromagnetic phenomena can cause interference. As a result, the most important phenomena tested for immunity standards compliance is listed here in accordance with [Väänänen et al. \(2016\)](#):

- Electrostatic discharge (human body discharge)
- Fast transient burst (electric spark effect)
- Radio frequency field (radio transmitter)
- Supply dips and short interruptions
- Surge (lightning induced)

Many tests are available. Several are required under the CENELEC standards. The most important standards for industrial applications are listed here in accordance with [Ewing et al. \(2016\)](#). These also have equivalent EN versions ([Kotsampopoulos et al., 2017](#)):

- IEC 61000-6-4 Generic emission standard for the industrial environment
- IEC 61000-6-2 Generic immunity standard for the industrial environment
- IEC 61800-3 Power Drive Systems contains emission and immunity requirements

IEC 61800-3 is a typical product standard in that it applies to variable speed drive modules only in cases where they are sold as end products ([Setiawan et al., 2016](#)). However, the scope of generic standards captures cases where the industrial drive will be a component of another product. Permitted levels are similar with the exception that IEC 61800-3 defines a nonresidential power user's environment with relaxed emission limits. As such IEC 61,800-3 permits development of useful economies in input filters, argue [Kosobudzki and Florek \(2017\)](#).

11.6 Behavior

[Williams \(2014\)](#) elucidates the immunity and emission together forms the essential elements of EMC behavior. Emission in turn is classified into low- and high-frequency segments ([Busatto et al., 2016](#)).

11.6.1 Immunity

[Pythoud and Tas \(2017\)](#) inform that most industrial electronics is expected to meet the specific immunity requirements of IEC 61000-6-2. For instance, industrial drives meet them without any unusual precautions ([Hughes and Drury, 2013](#)). Neither shielded signal wires nor filters are needed. An exception is for very fast-responding inputs. These might utilize data links or incremental encoder ports.

[Lucas et al. \(2015\)](#) opine that the IEC standard sets levels corresponding to a very severe industrial environment. However, on a few occasions actual levels might exceed the stipulated levels. As a result, the potential for interference cannot be eliminated completely according to [Weston \(2017\)](#).

11.6.2 Low-frequency emission

Stackler et al. (2016) show that industrial electronics generates supply frequency harmonics much the same way as any other equipment with a rectifier input stage. Harmonics generated by an individual component are unlikely to cause interference. However, Devore (2017) highlights that harmonics are cumulative. Thus, for instance, an installation encompassing a high quantity of drive loads might create difficulties.

Emission also occurs as a consequence of the switching of the power output stage (Kazimierczuk, 2015). This happens over a wide range of frequencies, which are harmonics of the basic switching frequency. This means that size times the supply frequency for a 6-pulse DC drive, and the PWM carrier frequency for a PWM drive. This phenomenon covers a range roughly from 300 Hz for DC drives and up to many MHz for AC drives.

Hackl and Deutschmann (2016) observe that electromagnetic coupling is unusual at frequencies below 100 kHz. Standards rarely set limits in that range because interference problems are unusual.

11.6.3 High-frequency emission

Industrial electronics for instance, the power stage of a variable speed drive is a powerful source of electromagnetic emission (Wunsch et al., 2017; Shakweh, 2018). This electromagnetic “noise” could be emitted due to rapid switching of high voltage and current. Sanders et al. (2016) explain that thyristors are relatively slow switches. Luszcz and Smolenski (2015) state that this characteristic limits the emission spectrum to roughly 1 MHz. Han et al. (2017a) inform that an IGBT is much faster, so the associated spectra might extend to 50 MHz. Interference is expected to arise in the frequency range of 100 kHz to 10 MHz due to the strongest emission if installation guidelines are not followed carefully. Williams (2016) explains that most of the conduction-related interference happens in the 150 kHz to 30 MHz range. Conversely, radiation-related emission is less frequent but it happens in the 30 – 100 MHz range.

Weston (2017) informs that the previous frequency range is lower than that of the personal computers and other IT equipment. These tend to cause direct radiated emission linked to the internal microprocessor clocks and fast digital logic circuits of IT equipment. Industrial electronics is seldom an important source of direct emission (Williams, 2014). This is so because its dimensions are much less than a half wavelength over the relevant frequency range. There might be strong electric and magnetic fields close to the housing. However, these diminish quickly, by an inverse cubic relationship, with increased distance from the device. Unfortunately, Ott (2011) points out that wiring connected to these devices are usually widespread and is therefore, likely to be lengthy enough to create an effective antenna.

Delhommais et al. (2016) explicate that the power output connections of an industrial device usually carry the highest level of high-frequency voltage. They can be the most important source of electromagnetic emission. Since the cable connecting, for instance, a drive to the electric motor is a dedicated part of the installation, its route can typically be

controlled to sidestep sensitive circuits, and it can also be shielded. Emission from this source is minimized if the shield is connected correctly at both ends.

Schanen et al. (2016) explain that output filters can also be utilized. These are offered by high-quality filter suppliers. Filter design is problematic because filters must offer high attenuation in both the common and series modes, at the same time as presenting an acceptable impedance to the drive output circuit and avoiding intolerable voltage drop at the working frequency. As a result, they tend to be expensive, state Masuzawa et al. (2015). In addition, they will typically work with simple open-loop control because of their complex impedance within the device closed-loop bandwidth. They may be justifiable in applications where it is not practical to utilize a shielded cable.

As an example, the power input connections of a drive can carry a high-frequency potential, which is chiefly created by the current flowing from the drive output terminals to ground through the capacitance of the motor cable and motor windings to the ground. Although the voltage level here is very much lower than at the output, control measures still may be needed simply because these terminals are connected to the extensive mains supply network, add Guacci et al. (2017). Usually, a type of radio frequency filter is installed in these locations. The control terminals of the drive carry high-frequency potential because of stray capacitance coupling within the industrial motor drive. This is usually of no consequence. However, control wires might be shielded to conform with relevant emission standards. Return currents in the common mode all flow in the ground wiring; therefore, grounding details are very important to achieve excellent EMC. Much of the installation detail is concerned with effectively controlling the ground return paths and minimizing common inductances in the associated ground system, which all can create unwanted coupling.

11.7 Reducing electromagnetic interference in plastics

Electronic components emit electromagnetic energy, which in turn creates unintentional interference. Interference in severe cases can disrupt the proper functioning of other electronic devices, and thus, electromagnetic emissions must be minimized (Weston, 2017).

Jagatheesan et al. (2015) highlight that contrary to current engineering wisdom, many plastics and composites can be excellent EMI attenuators. However, they must be formulated and their process designed with a strong EMC focus. For instance, Tong (2016) states that the National Aeronautics and Space Administration (NASA) uses EMI-shielded materials for its space exploration. The United States Air Force (USAF) uses EMI-shielded composites extensively (Gnecco, 2000). Cadirci (2009) asserts that this fact is evidenced by the stealth fighter and bomber programs. Furthermore, even law enforcement agencies use thermoplastic EMI-shielded enclosures in much of their own communications equipment, augment Krakówka and Stankiewicz (2017). This includes shielded consoles, which are effectively housing two-way radios and other electronics.

Lin and Dong (2015) note that materials used in the shielding of plastics vary enormously. Li (2014) suggests that only a qualified EMC-EMI plastics engineer can offer customized solutions to specific problems. However, Tong (2016) explains that typical materials include carbon, copper, nickel, steel, and others. Carbon features in carbon fibers, nickel-coated carbon fiber mat (Ni/Gr), and other exotic carbon composites. Nickel features primarily in nickel-steel alloy sheet, but also in many paints, coatings, and fillers. Copper is the essential ingredient of copper wire mesh. Various other varieties of coatings, conductive fillers, and paints are manufactured with these ingredients and a few other more exotic varieties.

Cabrera (2014) shows that most often integration of an EMI shielding material into a composite is accomplished by embedding the mat or film into the actual laminate. This method produces a relatively durable attenuating layer. However, maintaining designed-in conductivity in such a system becomes paramount, highlights Tong (2016). This is not a simple matter and limits composites usability to some extent. Joints need to be specifically created, as this is a “leak” point for any EMI shielding structure. Al-Thani et al. (2016) opine that custom-formulated thermoplastics overcome some but not all of these restrictions. Importantly, low-frequency, magnetic attenuation is perhaps the most challenging area for plastic shielding (Weston, 2017). This frequency range is best shielded by very conductive materials such as metals.

Micheli et al. (2014) observe that many military electronics shelters have been fabricated, tested, and delivered. Viswanadham and Rao (2015) add that shelters for military purposes almost always require EMI shielding. One way to accomplish this goal is to design a shelter with walls that are trusscore construction utilizing a copper mesh embedded in the center sections of the laminate (Islam, 2015). A variety of copper meshes have been tested against several other shielding alternatives. These included nickel foil and nickel-coated graphite veil. However, copper mesh showed the best all-around results for durable military grade shelter applications (Meyer et al., 2016).

11.8 Electronic shielding and thermal design considerations

Chen et al. (2015) highlight that use of magnesium alloys is growing in consumer and industrial electronics. Mechanical properties of magnesium are well known (Ashby and Johnson, 2013). Xia et al. (2015) advise that magnesium alloys have high specific strength and stiffness, which make magnesium a potential alternative to aluminum in applications where mass is an important optimization factor. Magnesium is also an alternative to other materials in enclosures where thermal and electromagnetic conditions present a new level of engineering complexity. Song et al. (2015a) believe that production costs have prevented a greater penetration of magnesium alloys in the consumer and industrial electronics industry. The combination of

its electrical, mechanical, and thermal properties indicates that magnesium will be used in enclosures in niche applications (Tong, 2016). In addition, Berman et al. (2016) opine that the development of processes, which lower the cost of producing very complex, thin-walled, net-shaped parts without any secondary operations, will only consolidate magnesium use in its current niches. Hino et al. (2017) note that one such niche is in complex enclosures where thermal and EMC challenges are combined.

11.8.1 *Magnesium shields*

EMI need to be controlled in many applications (Weston, 2017). Williams (2014) explains that the frequency range of the greatest concern is in the radio and audio frequency bands that stretch from 1 kHz up to 10 GHz as was allude to in the Section 11.6.3. Elbert (2016) adds that interference in this spectrum is called RFI. Tseng et al. (2015) note that a well-working strategy to minimize or eliminate RFI is to provide a conductive barrier between the emitter and the receiver. Thus, enclosures must provide this service, concludes Tong (2016). The purpose of this conductive barrier is to ground the emission, rendering it harmless from the EMC perspective. Zakaria et al. (2008) elucidate that this concept was first discovered in 1821 by Michael Faraday. That is the reason for the well-earned label: Faraday's cage. In this frequency range conductivity is paramount according to Weston (2017). Therefore, Soueid et al. (2015) point out that metals are often utilized in EMI/RFI shielding. For instance, Hu et al. (2012) advise that a thin-walled magnesium enclosure is a simple but very effective Faraday's cage in operation.

Huang (1995) explains that plastics are inherently insulative, so they must rely on careful design of formulation or surface modification or both. Surface modifications utilized include conductive paints, bonded layers, and ion plating (Mittal and Susko, 1991). Chung (2001) adds that a variety of conducting fillers are also utilized to facilitate dissipation of static charge buildup. Such additives include aluminum, carbon, nickel, and some other exotic materials. Formulation and surface modification can be expensive and often lead to decreased tool life according to Das et al. (2000). Ashby (2000) explains that these issues, however, can be designed around but do require practical experience integrated across several engineering domains. As such the global expertise base is thin on the ground at present according to Coleman (2017).

Aghion and Bronfin (2000) highlight that magnesium alloys compare favorably with aluminum as well as plastics with respect to EMI properties. Geetha et al. (2009) explain that many shielding applications utilize electromagnetic reflection. In such cases the mass minimization benefit of using magnesium cages extends over the entire frequency spectrum (Kojima, 2000). In other cases, Weston (2017) asserts that absorption is the primary shielding mechanism. In such cases while aluminum is better, magnesium is fairly close, but only on a per mass basis comparison according to Ashby and Cebon (1993). However, Tong (2016) informs that increasing frequency decreases the necessary wall thickness for a predefined shielding level. Bahadorzadeh and Moghaddasi (2006) explain that the range affecting most commercial applications is above 1 MHz. In this area, the required thicknesses are very small (Tong, 2016).

Thus, processing limits and structural integrity become the dominant optimization parameters (Ashby and Johnson, 2013). This range allows magnesium to compete effectively with alternatives. Specifically, the capability of producing net-shaped thin-walled structures, affords the lower density magnesium an advantage over aluminum for a few enclosure-related applications according to Fu et al. (2017). Therefore, Kumar and Wu (2017) conclude that magnesium alloys are particularly well suited for shielding applications in the consumer and industrial electronics market. Wall thicknesses could be decreased to 1 mm or even as low as 0.65 mm. Despite such thin walls, a well-designed enclosure still provides the necessary stiffness and strength. This is in addition to the inherent EMI shielding. Ashby (2000) adds that the low density of magnesium provides further advantages for mass optimization that is paramount in portable, space, or airborne electronic products.

11.8.2 Thermal properties of magnesium

Bar-Cohen et al. (2003) opine that an interesting application of magnesium is in heat sinks. Heat sinks are extensively utilized in electronic applications to cool heat-producing components (Schelling et al., 2005). This is especially true in industrial and traction devices using power semiconductors according to Drury (2001). However, Yin et al. (2013) note that even the key component of any computer system, the venerable central processing unit (CPU) often generates more than 50 watts. This amount might not sound too much but given the ever-increasing power density of CPUs and other electronics, heat management is becoming the most difficult engineering aspect of any complex electronic system according to Laloya et al. (2016). Andresen et al. (2018) explicate that this is because the reliability of semiconductor-based devices is critically affected by any increase in the maximum junction temperatures. Therefore, Arshad et al. (2017) inform that enclosure engineers must attempt to maximize heat dissipation via the appropriate selection of a properly sized and configured heat sink. Aluminum has traditionally been the number one choice (Bayomy et al., 2016; Shih et al., 2016). Bilen et al. (2017) point out that it is utilized in most electronic applications due to of its high thermal conductivity. In addition, Oddone et al. (2017) explain that aluminum also possess high thermal diffusivity and low density. Ashby and Johnson (2013) highlight that in mass-critical applications magnesium's even lower density is an advantage. Thus, Costa and Lopes (2014) note that the use of magnesium in heat sinks is increasing.

The Aluminum Association (1984) finds that thermal conductivity is the most important factor that determines the ability of a heat sink material to dissipate heat during steady-state conditions. However, thermal diffusivity becomes the supreme factor in transient conditions. Table 11.1 displays the comparative values for aluminum and magnesium. Under transient conditions heat transfer will be similar in geometrically identical fins manufactured from aluminum or magnesium due to the thermal diffusivity values, which are nearly equal. However, it must be noted that thermal conductivity of aluminum is much greater than magnesium's. This means that aluminum heat sinks are much more efficient under steady-state conditions.

Table 11.1 Comparison of aluminum and magnesium

Material	Thermal conductivity (W/m °K)	Density (g/cc)	Thermal diffusivity (cm ² /s)
Aluminum 6063-T5	210	2.70	0.68
Magnesium M1A	138	1.76	0.70

[Brown et al. \(1993\)](#) tested two geometrically matching heat sinks. One was made from 6063-T5 extruded aluminum. The other was created from M1A grade magnesium. The air velocity over the fins was increased from none, that is, 0 to 7 m/s. At air speeds, less than 1 m/s the fins were operating under transient conditions, therefore thermal diffusivity dominated. Thus, the thermal transmission ratio, which is defined as a ratio of the amount of heat dissipated from the heat sink to its surroundings, was about 5%–10% less for the magnesium heat sink versus the aluminum one. Importantly, in such a transient condition, the nearly 40% difference in thermal conductivities does not result in a meaningful difference in thermal transmission ratios. However, when air velocities were increased beyond 1 m/s, conditions become nearly steady state and as such thermal conductivity dominated. In this region magnesium heat sinks performed 15%–25% less efficiently. However, [Ashby and Johnson \(2013\)](#) add that magnesium is easier to fabricate in thin shapes, which can be a great advantage despite a somewhat compromised efficiency in high-velocity air streams. A careful heat management design can exploit this advantage and thereby minimize overall expenditures according to [David et al. \(2014\)](#).

With the exception when a heat sink is operating with a temperature very near to ambient conditions with an associated very high air velocity, the actual amount of heat transferred by magnesium could be significantly more according to [Brown et al. \(1993\)](#). Achieving better heat transfer means that the designs are not geometrically identical, but the heat sink is a genuine magnesium design. This is extremely important in the many consumer and industrial electronic products, which need to be portable. Over 35% reduction in mass could be accomplished by utilizing proper design practices. In addition, designing with magnesium eliminates fans thereby creating increased reliability on the device. These designs operate under transient thermal conditions. However, this presents some engineers with unexpected analysis challenges. Therefore, [Ravikumar et al. \(2017\)](#) observe that many engineers engage in this design paradigm only reluctantly, thereby, [Weston \(2017\)](#) adds, limiting their new products' performance especially with regard to EMI/RFI shielding combined with heat sinking into a single integrated packaging configuration.

11.8.3 Dimensional stability

[Hassan and Gupta \(2002\)](#) inform that dimensional stability of magnesium is another great advantage for the electronics industry. [Butler et al. \(2013\)](#) explain that many new nanotechnologies and classical optical devices, such as digital cameras require

dimensional stability unachievable by aluminum die casting. [Berkmortel et al. \(2000\)](#) enlighten that an automobile original equipment manufacturer (OEM) compared parts with two cored holes with respect to repeatability and dimensional stability. Magnesium parts had significantly greater repeatability and less associated shrinkage. These parts demonstrated the following results:

- solidification shrinkage, 56% of die casting;
- standard deviation of shrinkage, 14% of die casting; and
- standard deviation between the two cored holes, 28% of die casting.

The dimensional stability inherent in magnesium allows creation of much more complex tools ([Luo et al., 2016](#)). For instance, locating pins and holes could be created with improved precision and repeatability. Such complex features require additional and often very expensive machining when using parts produced by aluminum die casting. As a result, enclosures as structural components are manufactured with magnesium replacing aluminum especially in areas where additional EMC is sought by the new product development team according to [Hughes and Drury \(2013\)](#).

11.8.4 Case study 1—digital camera

A digital camera was intended for portable, outdoor use, meaning that the parts had to be mass optimized as well as functional. The presence of numerous electronic components within this device also demanded an excellent method of shielding. The original material selection was a predictable choice in the electronics industry: ABS. However, an external consultant suggested magnesium during a conceptual stage design review. Subsequently, the company compared housing components made from magnesium and ABS. Mechanical, thermal and electromagnetic shielding properties were compared.

Magnesium parts were compared directly with unshielded ABS components with regard to electromagnetic performance. The results were checked against compliance with the FCC Class B specification. The ABS results show that 25 points exceeded the FCC Class B standard over the measured frequency range of 30–1000 MHz. In comparison, the magnesium results show only 7 points in excess. In addition, ABS parts allowed as much as a 25 dB excess, while the maximum allowed by magnesium components was less than 5.3 dB. The large OEM deemed the magnesium protection level satisfactory, while the ABS components needed additional and very expensive processing.

Furthermore, magnesium also proved to be an effective control method for electrostatic discharge abatement at the critical joints for user control input. ABS parts necessitated coatings in the vicinity of these input devices. Therefore, the coatings would also have added significant cost to the final assembly. In all cases, magnesium was adequately conductive to avert electrostatic problems without additional processing or added expense.

Temperature was measured at several points in the enclosure. A 3–5°C temperature drop resulted at all points from the simple substitution of magnesium for ABS. It is expected that this figure will improve significantly once design method changes are

incorporated into the new product development program. Designing with magnesium will distribute heat more effectively and at the same time less expensively.

The mechanical properties of the components were also analyzed with an emphasis on improved impact strength. The camera was subjected to various methods of inducing mechanical shock. These included a standard impact and a drop test. Magnesium components had a higher stiffness and were superior to the ABS samples. The OEM's analysis showed that magnesium parts would have survived these tests with a 50% thickness reduction, thereby further increasing the advantage of magnesium over its ABS counterparts.

11.8.5 Case study II—computer enclosure

Many components for mobile computing devices have been die cast from magnesium due to a combination of lightweight, heat dissipation, EMC characteristics, and corrosion resistance. A large mobile computing OEM's engineers analyzed the associated benefits and potential drawbacks of using magnesium components as enclosures for their laptop-, notebook-, and subnotebook-sized devices. This OEM found that mechanical, thermal, and EMI shielding properties in thin-walled components supports selecting magnesium in the mobile computing industry.

It was found that a typical 2.2-mm-thick ABS enclosure could be substituted with a 0.8-mm-thick magnesium case without any loss in stiffness. In such case tensile strength in the magnesium component would be 2.4 times that of the ABS equivalent while at the same time still achieving a mass reduction of 46%.

The OEM also analyzed heat dissipation and EMI shielding performance. A significant temperature drop inside the computer was found when substituting notebook-sized enclosures of die cast magnesium in place of geometrically identical ABS parts. The heat source was 118°C and the temperature inside the computer was lowered from 62.5 to 56.5°C through a simple substitution by magnesium. This OEM concluded that magnesium's advantage is most pronounced in enclosed electronic systems with no or very little ventilation.

The OEM also measured magnesium's effectiveness in EMI shielding application using the Advantest method on 100× 100 mm plate specimens. These tests covered the frequency range of 30–200 MHz. The OEM compared a 1.4-mm-thick magnesium specimen with single-sided Cu 2 mm + Ni 0.25 mm and double-sided Cu 1 mm + Ni 0.25 mm Cu–Ni plating. Magnesium outperformed both samples. Other studies showed negligible difference in EMI shielding characteristics in magnesium samples with thicknesses varying from 1.0 to 2.0 mm. A 1.0-mm-thick magnesium sample was compared with a 0.8-mm-thick samples of AISI 304 stainless steel, galvanized steel, and A5052 aluminum. These tests show only insignificant differences in the shielding characteristics.

11.8.6 Performance of magnesium

Both case studies have demonstrated that the use of magnesium in enclosures is advantageous. [Polmear et al. \(2017\)](#) explain that magnesium allows for better management

Table 11.2 Postcasting operations

Process	Digital camera	Computer Enclosure
Raw materials	3.7	11.0
Melting/casting	16.8	10.4
Trim/deburr/finish	13.5	16.7
Machining	23.2	13.0
Surface treatment	5.2	8.2
Paint/putty	37.6	40.7

of thermal and electrical problems in electronic devices while also offering improved mechanical properties. [Xu et al. \(2015\)](#) highlight that magnesium’s high strength to weight ratio is ideal for portable products. The thermal, electric, and mechanical properties along with the production of complex net shape parts are making magnesium an attractive choice to designers of electronic enclosures. The high stiffness and corrosion resistance was also found to be important characteristics. However, [Cho and Goodson \(2015\)](#) believe that the higher initial part costs prevented greater penetration of magnesium into the enclosure markets. Both studies have found that postcasting processing operations made up more than 50% of the total part cost. As displayed in [Table 11.2](#), these additional operations ultimately determine profitability of the enclosure.

[Campbell \(2015\)](#) demonstrates that magnesium die casting process eliminates many of these postcasting operations. Thereby, [Patzer \(2016\)](#) implies that magnesium significantly decreases the cost of electronic enclosures. [Buzolin et al. \(2017\)](#) explicate that importantly, thinner-walled sections, and even fins, can be made without additional machining. This improves the thermal dissipation in the enclosed product. [Luo et al. \(2016\)](#) explain that the ability to design more complex shapes creates the possibility of building more effective heat sinks and integrating these into the structural components of the products.

11.9 Review

Every electrical apparatus inherently generates electromagnetic emission due to its operation ([Tong, 2016](#)). [Kerker \(2016\)](#) demonstrates that electronics can also be affected by electromagnetic energy. Therefore, [Williams \(2014\)](#) argues that enclosures need to be designed and manufactured to meet or exceed relevant interference regulations. [Soueid et al. \(2015\)](#) explain that EMC is also called EMI and RFI. EMC can be achieved by preventing interference from penetrating or escaping from an enclosure or housing.

Emission modes, filtration, ground leakage, suppressors, cables, and saturation theory were discussed from an application perspective to provide a fundamental at the

same time practical understanding of relevant EMC theory (Mardiguian, 2014a; Ozenbaugh and Pullen, 2017). Regulations exist worldwide to control EMC both in its intentional and unintentional forms. Williams (2016) explains that the primary reason for this is to prevent interference with communications services. The most important standards for industrial applications are the IEC 61000-6-4 Generic emission standard for the industrial environment and the IEC 61000-6-2 Generic immunity standard for the industrial environment according to Sakthivel et al. (2003). Immunity and emission together forms the essential elements of EMC behavior (Ott, 2011). Finkenzerler (2010) explains that emission in turn is classified into low- and high-frequency segments.

Gnecco (2000) and Jagatheesan et al. (2015) highlight that contrary to current engineering wisdom, many plastics and composites can be excellent EMI attenuators. However, they must be formulated and their process designed with a strong EMC focus. Most often integration of an EMI shielding material into a composite is accomplished by embedding the mat or film into the actual laminate according to Cabrera (2014). Magnesium alloy use is growing in consumer and industrial electronics (Chen et al., 2015). Mechanical properties of magnesium are well known. Ashby (2000) explains that magnesium alloys have high specific strength and stiffness, which make magnesium a potential alternative to aluminum in applications where mass is an important optimization factor. Magnesium is also an alternative to other materials in enclosures where thermal and electromagnetic conditions present a new level of engineering complexity (Song et al., 2015b).

11.10 Hot tips

EMC can be achieved by preventing interference from penetrating or escaping from an enclosure or housing. Here are a few tips to help consistently achieve this important design goal:

- Enclosures need to be designed and manufactured to meet or exceed relevant interference regulations such as IEC 61000.
- The simplest way to think about this challenge is to ensure that the enclosure acts as a Faraday cage.
- Many plastics, composites, and magnesium can be excellent EMI attenuators in addition to aluminum.

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12.1 Introduction

This first book of the handbook series entitled: *Electronic Enclosures, Housings and Packages* focused on the contextualization of the parts forming an envelope around the enclosed electronic parts and assemblies. Hubka (2015) explains that reading, understanding, and customizing the contents of this book allow the practicing enclosure engineer to create a firm foundation from which to design many useful applications harnessing these important concepts.

However, it must be said that this book, while firmly embedded in the chip—package—board—main and subboards—enclosure—cabinet—shelter paradigm, can in fact provide a basic map for many other new product development (NPD) efforts, because its topic list parallels similar contexts.

These days, most novice engineers entering commercial NPD efforts do not have the luxury of a proper introduction into the contextual setting of their NPD project. As such they are often perplexed about unforeseen complexities resulting in delays, budget overruns, and adjoining lackluster career developments. This first book of the series offers an in-depth analysis of the foundation that is the contextual environment.

12.2 Ubiquitous

The contextual setting was explicated in two parts. The first part entitled: ubiquitous. This part emphasized the omnipresent nature of enclosures. It is possible to ignore this part and still can design a relatively sensible enclosure, but it is unlikely that a well-rounded enclosure engineer could practice without these elements.

12.2.1 Induction

Most companies realize the importance of a thorough introduction. Yet, often the companies are either mechanical or electrical focused. This state-of-affairs leaves the enclosure engineering community in an unenviable position. Important elements such as industrial design, integration across several engineering domains, and complete fulfillment of user requirement specifications (URSs) are at stake.

Enclosures are a vast business opportunity. Some enclosures are designed and made very well, while others could be improved. Enclosure-related labels were discussed to provide information about the language of the enclosure engineer and the supply chain. A definition of enclosure was provided to offer a fundamental building block of understanding. It was proposed that a new discipline Enclosure Engineering be instituted.

Enclosures are a significant business opportunity and as such need to be systematically studied to understand its dynamics. Fastener and connector—based issues were identified as significant improvement possibilities, as was heat management. These areas form the technology triangle. These are the induction set of tips for the enclosure specialist:

- Learn the language of electronic enclosures for better understanding.
- Periodically check the state of potentially disruptive technologies.
- When in doubt seek expert help.
- Study the technology triangle to master solving the most urgent problems in electronic enclosures.

12.2.2 Innovation

Understanding the fundamental innovation waves and how subsequent waves reshape the innovation landscape is fundamental to implement a successful NPD program. The current global trend is to get ever-more power into an ever smaller space in electronics. [Cho and Goodson \(2015\)](#) posit that this fact will have extremely serious consequences and as such deserves to be discussed in its very own chapter under heat management.

There is also a remarkable long-term trend to integrate. In this context it meant along electrical elements, but now it also means to integrate between the active circuitry and its substrates. [Siengchin et al. \(2016\)](#) underline that this is the driving factor behind molded interconnect devices (MIDs), which will be discussed in detail in the last book of this handbook series. Electronics innovation waves were investigated and their effect on the electronic enclosure industry was explicated. Six emerging technologies and their potential disruptive influences were analyzed. It was found that nonlinear optics, spintronics, and memristors while being interesting concepts present no short- to medium-term disruptive power in electronic enclosures. However, 2-D, organic, and molecular electronics present exciting potentials for the short and medium term. In addition, MEMS (microelectromechanical systems) technology was reviewed as it represents one of the first nanotechnologies that have already progressed to the rapid innovation adoption phase. It is proposed that all technologies be monitored to prevent future surprises. Electronics innovation waves were investigated, so market-based activities could be accounted for.

A few tips could make all the difference between success and the lack of in the field of electronic enclosures:

- Innovation waves display trends that are important for the success of the electronic enclosures industry.
- Emerging technologies need to be monitored periodically.
- Technology review must be based on real information rather than hype.

12.2.3 Markets

Development of a balanced portfolio of enclosure customers is an imperative that not many suppliers can afford to ignore. It is therefore helpful to review various enclosure

markets. Segments such as the chemicals, explosive environments, energy offshore, food, beverage, tobacco, material handling, off-road, and pharmaceuticals require very specialized expertise. These segments can of course be learned from this handbook, but supplementary materials will be needed to successfully address their industry specific challenges. Other industries such as aerospace and defense, automotive, built environment, consumer electronics, electrical, instruments, medical device, and robotics will find this handbook very helpful. It was found that automotive, the built environment, consumer electronics, electrical, instruments, medical device, and robotics offer the highest growth market segments at present.

Every industrial segment has its own rules and regulations. There are, however, similarities across all markets. The following tips could make any electronic enclosure projects more successful:

- Check for the specific industry standards prior to starting a new electronic enclosure project.
- If possible focus on a more rapidly growing market segment.
- Check periodically to make sure that the segment is not in relative decline compared to other opportunities.

12.2.4 Requirements

Enclosure requirements are important to understand to design proper NPD programs. Elements of the functional requirement specification (FRS) creation were reviewed. Practical examples were furnished to supplement core concepts. Based on the work of [Cooper et al. \(2002\)](#) procedural and administrative functions were inserted into the introductory section of the FRS to contribute to a smooth NPD.

A product overview was furnished to supplement understanding and to communicate overall design intent to the NPD team ([Camba et al., 2014](#)). Operating conditions were displayed to orient the design team and to provide the initial seed for the development of valid design concepts in accordance with [Homburg et al. \(2015\)](#). Modularity instructions were added due to recognition that customization is critical in almost all aspects of housings and enclosure manufacture and even more importantly for achieving sustainable profitability ([Wang et al., 2014b](#)).

Aesthetics were addressed and industrial design criteria were added to facilitate positive purchase decisions prior to addressing product safety issues ([Tjalve, 2015](#)). Product safety was positioned as a critical aspect of any NPD effort ([Stark, 2015](#)). Many important areas were addressed such as conformance to various and relevant standards, desired ingress protection rating, pollution degree requirements, protection from live parts, creepage and clearance calculation guidance, flammability requirements if the enclosure contains polymers, safety labels and markings, and earthing requirements.

Construction-related topics were highlighted including design-related issues, welding, bolted joints, casting, vacuum forming, extruding and molding issues in accordance with [Hubka \(2015\)](#). A finely detailed example was added to anchor understanding of the related material. Many enclosure only topics were discussed in the form of internal fittings, locks and hinges, and lifting arrangements.

It was recognized that thermal management of electronics is of paramount importance (Kordyban, 2005). A practical FRS example displayed information on thermal analysis, system integration, fan requirements, considerations for heat sinks, and PCB cooling.

Structural robustness issues were detailed to avoid duplication of known NPD failures (Dieter and Schmidt, 2013). The importance of appropriate engineering calculations and analysis was emphasized. A structural robustness example was provided to supply vital information about requirements for polymeric enclosures, impact resistance, shock and vibration testing, calculations and analysis, and packaging.

Important aspects of material selection were reviewed based on the work of Ashby and Johnson (2013). A substantial example was provided that contained information on material selection, polymeric material requirements, polymeric enclosures and external parts, polymeric internal parts, other parts, UV requirements, gasket material requirements, molding methods, metallic material requirements, copper conductors, and sheet steel requirements. The criticality of proper fastener selection was also discussed along with corrosion information.

Design for manufacturing and maintenance issues were highlighted in accordance with Boothroyd (1994). The importance of compliance with all applicable environmental and sustainability requirements was emphasized. In continuing to develop an in-depth understanding, the following chapter will discuss the types of enclosure, housing, and packages that are currently dominating the electronics industry.

There are many requirements that drive development of any new products. Some are unique, but there are many general criteria that most development projects will encounter. However, the most important three aspects are emphasized here:

- URS to FRS conversion must be done efficiently and in a way as to motivate the NPD team according to Dick et al. (2017).
- Every strategic design criterion must be incorporated into the FRS (Kiss and Barr, 2017).
- Design compliance must be achieved if the product is to be successful (Burgelman et al., 1996).

12.2.5 Types

There are many types of enclosures each needing a slightly different balance of engineering skill sets. Thus, an introduction to the standard types of packages, housings, and enclosures was furnished. First the seven levels were defined to provide clarity (Newton et al., 2016). Some of these levels were grouped together to form the three final levels providing an easy-to-remember classification exactly coinciding with the title of this handbook series: enclosures, housings, and packages in accordance with Töpper (2017).

This handbook ordered the level classification according to size (Amo et al., 2004) and therefore packages were discussed first. A historical perspective in the form of a timeline was provided as per Hopkins et al. (1998). Development drivers were identified to provide understanding and facilitate NPD planning (Verona, 1999). Design

considerations identified by Wallmark (1960) such as cost, electrical functionality, mechanical, and thermal characteristics were investigated.

Through-hole (Fillion et al., 1995) and surface-mount technologies (Prasad, 2013) were explicated including pin grid arrays and ball grid arrays. Issues such as packaging, handling, testing with respect to bare die implementations were discussed. Chip-scale packages (Ghaffarian, 2001) and module assemblies (Albrecht et al., 2014) were reviewed to provide a platform for the discussion on advanced package substrates (Bagen et al., 2013). System-in-packages (Nair et al., 2017) and through-silicon-vias (Marro et al., 2014) were analyzed to further their applications in the field.

The next level: housings were discussed first by focusing on circuit board mounting issues (Andersson et al., 2014) and then by reviewing backplane connections (Gumaste et al., 2016). Selection ideas for the next level: enclosures were also incorporated. Basic layout and a quick cooling guide closed this assessment in accordance with Mallik et al. (2011).

A variety of standard enclosures were reviewed based on McClung et al. (2005), such as small, portable, and wall-mount cabinets. Chassis, card racks, rack-mount chassis, open, cabinet, server, colocation, and seismic racks were described in detail to assist the professional enclosure engineer as well as academia in accordance with Islam (2016).

It is important to keep in mind that the most unreliable components in any electronic system utilizing a housing or an enclosure will be the following according to Wang et al. (2014a):

1. Connectors and cables
2. Bolted joints, basically anything that uses screws
3. Cooled components

Always use an electronics cooling specialist (ECS) when these components are installed (Song and Wang, 2013; Smith, 2017).

12.2.6 *New product development*

NPD closes the first part of this handbook. Understanding the process of new product development, commonly referred to by its acronym NPD, is critical.

Following a well-described NPD and new product introduction (NPI) process is a critical factor to create a long-term competitive advantage for the host organization. This process is a conceptual model for creating a viable idea and developing it into an enclosure, housing, or packaging product in the minimum amount of time. This general mental model subdivides the overall NPD effort into eight distinct phases.

Each phase is subdivided into manageable steps that are assigned to a function within the NPD cross-functional team (CFT). All 161 steps displayed in Fig. 12.1 are described to present a complete map of the electronic enclosure product development (EEPD) process.

Most NPD processes use management decision gates. This has been found to create extreme difficulties for NPD teams. A better approach is to integrate management functions into the day-to-day operation of the cross-functional NPD team. Preparation

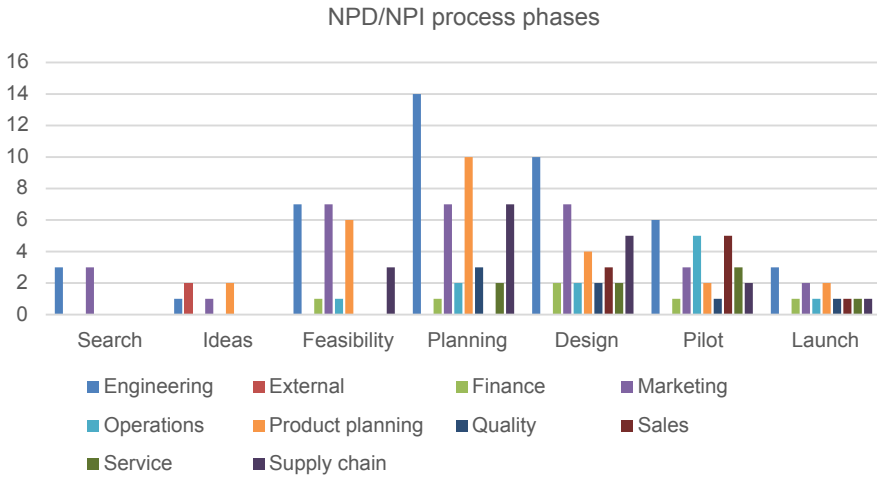


Figure 12.1 Functional involvement in the electronic enclosure product development process. *NPD*, new product development; *NPI*, new product introduction.

time and effort for gate reviews are eliminated in this model. In addition, senior executives are persuaded to have an in-depth understanding of the most important process drivers.

Locating opportunities is the very first phase in the EEPD process. Other processes name this step Market Research. It is instead a continuous search process for new market-driven ideas that are emerging by harnessing enterprise-wide customer relationship and engineering management data. A secret ingredient of the NPD success formula is in the way these very different two worlds are merged into a useful database.

A well-developed plan and organization-wide implementation of idea generation are prerequisites for successful innovation in the electronic enclosures field. The overall goal of this phase is to create an innovative environment that fosters creation of actionable ideas. Concepts need to focus on opportunities that could be feasible within the organizational context. Therefore, ideas must be sorted based on customer and corporate fit.

The Concept Feasibility phase aims to quickly define the product in sufficient detail to determine its feasibility both from technical and commercial perspectives. Another secret ingredient of the NPD success formula is that the Concept Feasibility phase development is quick but very thorough at the same time. Up-front engineering investment within a framework of a well-functioning CFT pays huge dividends downstream in the EEPD process.

The CFT collaborates to substantiate discovered market needs and product value drivers based on the proposed functional requirements in the Project Planning phase. The primary goal of the NPD CFT is to complete the conceptual design and thus demonstrate a proof-of-concept early in the EEPD process.

Detailed design, development, and system integration are completed using best cost components and processes in the Design Development phase. A preproduction run is

completed that proves manufacturing and the supply chain are ready to execute and provides testing with a small number of prototypes to ensure product requirements and specifications have been met.

In the Ramp-Up otherwise known as Pilot phase, the product design is validated, customer beta testing is completed, and manufacturing processes are verified to assure operational readiness. While in the NPI phase, the enclosure encapsulated product is available to customers within the prime target markets. Once the manufacturing phase is reached, the enclosure, housing, or package is universally available to customers.

The solution to any enclosure engineering problem should conform to a simple tiered priority. Assessment of a new enclosure development problem is most efficiently performed by following the Regulatory-Function-Cost-Schedule-Budget system. This is the last secret ingredient of the EEPD success formula.

First, innovation waves must be understood, especially their interactions. Then the global drivers must be incorporated into the right innovation strategy. Market needs must be discovered, for instance, by traveling on top of lifts, visiting mine sites, ports, and other important applications. The right process must be followed and parallelism opportunities must be harnessed. Only then is the executive management team being able to drive NPD and NPI to its ultimate success.

12.2.7 Summarizing part 1: ubiquitous products

Fastener and connector—based issues as well as heat management were identified as an applied problem facing the enclosure industry. In addition, five important aspects were reviewed.

Technology waves are important as they represent the fundamental understanding on which to build a robust and long-term enclosure strategy. Review of the relevant market segments justified the use of the word ubiquitous, as enclosures, housings, and packages are truly everywhere.

Enclosure types and requirements were reviewed in Chapters 4 and 5, respectively. They serve as an orientation for the novice and review for those with substantial experience in the industry. This last chapter offers an insight into the secretive world of NPD and NPIs by providing a map of the process and a few additional helpful hints for the practitioner.

Therefore, this first part provides a strong foundation on which to build an understanding of the social and environmental framework to complete a review of the Contextual Drivers affecting successful enclosure development.

12.3 Societal and environmental framework

The second part entitled: societal and environmental framework included all the elements that a practicing enclosure engineer would encounter other than design and manufacturing. The common denominator in this part of the book is that these elements form the societal and environmental framework, hence the title of this part.

Engineering today is so specialized that many practicing engineers do not realize the full extent and all the ramifications that the societal framework imposes on their everyday activities. These elements were included to emphasize all the societal building blocks of enclosure engineering.

12.3.1 *Standardization*

Successful technical standardization is a cornerstone of successful NPD and NPI in the electronic enclosures, housings, and packages industrial segments according to [Kang and Motohashi \(2015\)](#). A short review of the origins and development of standards and the process that produce them was provided.

First the use of the word standard was defined in this context and was pointed out that standards are instruments of consistent measurement ([De Vries, 2013](#)). These measurements could take place in many economic transfer dimension, but this chapter focused on technical aspects exclusively. The interaction of standards and the law was discussed in the conceptual framework of Net Benefit and Stakeholder Support.

Four standards development pathways were described in accordance with [Weiss and Cargill \(1992\)](#). These are the national accredited standards body (NASB), externally funded, association managed, and internationalized versions. Prioritization and selection activities as well as participation in a technical committee (TC) were explicated.

Importantly, stages of a general technical standards development were explained as per [De Vries \(2013\)](#). The process starts with a proposal, which may or may not warrant an approval from the NASB. Assignment of the project to an existing TC or constitution of a new TC was described next. Drafting of any technical standard is an enormous undertaking; however, it must not produce a finished standard because public comment must be solicited, received, and appropriately dealt with prior to balloting the TC and the ultimate publication of the standard.

This process must always be followed at the various levels that standards are created, including corporate standardization practices ([Jakobs, 2017](#)). Four examples were incorporated to highlight a few of the many possibilities for corporate level technical standardization. A material, mechanical, heat sink, and a tool example were furnished to complete the review of standardization activities.

Standardization establishes a “level playing field” for the competition. Therefore, it behooves participants to understand its rules.

- Standards development process is based on three internationally recognized principles: openness and transparency, consensus building, and balanced representation.
- The most important is to exert appropriately indirect influence by mastering the concepts of net benefit and stakeholder support.
- The four development pathways need to be understood to select, recommend, and propose the most fitting approach to solve a standardization issue.
- Understanding and implementing the eight standardization steps are critical at every level including corporate standardization activities.

12.3.2 Intellectual properties

Development of a sound intellectual property (IP) rights portfolio is paramount from the electronic enclosures, housings, and packages perspective (Idris, 2003). There are many seemingly isolated types of IPs. As a result, Drahos (2016) demonstrates that the use of the IP label and its philosophical foundation is vigorously debated. Therefore, the enclosures industry needs to monitor future of this debate carefully.

Patents are by far the most frequently utilized IP instrument (Baker and Mezzetti, 2005). It has the longest history; therefore the most familiarity enables utilization of patents for IP protection purposes. However, there are other methods of protection available. For instance, copyrights applied to embedded software offer a much longer protection period than patents (Joyce et al., 2016).

Beckerman-Rodau (2015) asserts that industrial design rights and trademarks are also important. The former can protect some aspects of the enclosure or housing, while the latter provide overall brand image protection services. Trade dress is an emerging form of protection that could be incorporated into the IP defense shield (O'Connor, 2014).

Finally, Menell (2017) informs that the longest protection is offered by trade secrets. This form of protection, however, needs extremely careful planning and implementation to be effective. Once such a system is embedded, the protection can continue forever, thereby this form of protection offers the longest and quite possibly the most effective electronic enclosure, housing, and package protection (Pres and Wende, 2017).

Infringement and misappropriation is big business, and over 5% of the global trade engages in counterfeiting according to David and Halbert (2017). Enforcement most frequently is entrusted to the rights holders. Therefore, monitoring and vigorous litigation is necessary even if it is meant that pejorative labels such as “patent troll” might be earned in the process (Risch, 2014). IP rights are important for the survival of any electronic enclosures, housings, and packages—related business.

A well-designed IP rights portfolio establishes differentiation from the competition (Fang et al., 2017). In addition, Reitzig (2004) an excellent IP rights portfolio provides long-term and in a few cases unassailable competitive advantage. Therefore, it benefits electronic industry participants to understand its complex rules (Drury, 2001).

- Develop a well-designed and balanced IP rights portfolio.
- Incorporate your trademarks into your portfolio and monitor for similar new trademark registrations.
- Create a patent “wall” to protect your visible and reengineering-prone IPs.
- Understand your copyrights and do not infringe on other, especially be careful of your competitors’ rights.
- Exploit industrial design rights along with trade dress to create brilliant IP improvements.
- Create and implement a trade secret protection regime to substantially increase IP portfolio valuation.
- Monitor the IP debate and implement changes fast.
- Fight infringements and misappropriations vigorously.

12.3.3 Sustainability

There are a few sustainability-related legislations that demand awareness, monitoring for changes such as new or expired exemptions, understanding of their myriad of complexities, and ultimately full and proven compliance (Kiron et al., 2013). No electronic enclosures, housings, and packages developer or manufacturer can afford to be found negligent in these areas (Griffin et al., 2014; Hines, 2013; Hughes, 2016). Park and Roome (2017) warn that every one of these laws' jurisdiction is limited, but in a globally interconnected economy their true influence is indeed worldwide. Therefore, the most important initiatives have been reviewed.

Conflict minerals legislation and compliance is important from an electronics perspective (Zhang et al., 2017; Dalla Via and Perego, 2017; Jameson et al., 2016). Bonevich (2013) explains that lead-free solders rely on tin, which is regulated by this law. Other elements are also important materials in electronics. 3TG is the label, which generally indicates conflict minerals according to Barume et al. (2016). These are tin, tungsten, tantalum, and gold.

The concept of end-of-life (EoL) is important from a supply chain point of view (Govindan et al., 2015). Stark (2015) explains that significant hardware and software issues could manifest themselves if the NPD team does not prepare a workable strategy on how to overcome the disparity in various industries' EoL time frames. Kühn et al. (2016) emphasize that the heavy metals category is another area of concern that legislators have been regulating. Therefore, Chen et al. (2016) assert that knowledge of this area is a prerequisite in the electronics industry.

REACH is the overhauled EU chemicals policy according to Biedenkopf (2018). Rudén and Hansson (2010) explicate that understanding of the registration, evaluation, authorization paradigm of REACH is important. Avoidance of substances of very high concern (SVHC) is paramount (Giubilato et al., 2016). Biedenkopf (2015) advises that knowing the rules of "only representative" services is a must for non-European OEMs and their supply chains.

Ganesan and Pecht (2006) inform that RoHS is not only the "lead-free" initiative. For instance, Cusack and Perrett (2006) add that the banned flame retardants were extremely important from an electronics housing perspective. Rakotomalala et al. (2010) believe that their replacement is neither simple nor cheap. Hua et al. (2009) highlight that hexavalent chromium is important with respect to fasteners and other metal surface treatments. Kanapathy et al. (2016) warn that compliance of a product cannot be assured by assembling compliant components due to the inherent complexities of RoHS legislation. Therefore, Iannuzzi (2017) emphasizes that high-quality expertise must be applied to assure compliance. WEEE adds another important criterion into the product development mix and it is intended to work in conjunction with RoHS according to Koh et al. (2012).

The electronic enclosures, housings, and packages developer and manufacturer must create a robust process to deal with sustainability issues (Hallstedt et al., 2010). Importantly, Kanapathy et al. (2016) warn that the sustainability label camouflages a substantial compliance undertaking. Therefore, Rakotomalala et al. (2010) advise that this function must be resourced adequately. Pinsky et al. (2016) add that

some of these initiatives also affect electronics reliability and require additional high-quality engineering effort to mitigate its consequences. The most important issues are as follows in accordance with [Luzzini et al. \(2015\)](#):

- Conflict resources, REACH, RoHS, and WEEE, have global reach despite their limited jurisdiction.
- 3TG conflict minerals equals tin, tungsten, tantalum, and gold.
- Synchronize EoL time frames to avoid unexpected future difficulties.
- Understand the registration, evaluation, authorization paradigm of REACH.
- Avoid SVHCs.
- Compliance of a product cannot be assured by assembling compliant components.
- WEEE recycling targets and labeling compliance need to be planned for at the NPD stage.

12.3.4 Environmental considerations

Enclosure engineers need to specify electrical and electronics housings, casings, and shells correctly according to [Chapman \(2018\)](#). [McDonald \(2016\)](#) explains that one way to do this is to use the IP and IK codes. [Owens et al. \(2017\)](#) inform that the codes provide protection to the users and the enclosed devices from various intrusions such as water, dust, contaminations, and mechanical impacts. However, [Wasson \(2015\)](#) adds that there are other dimensions that also need to be carefully evaluated to create a successful enclosure for any electrical or electronic equipment.

[Merchant et al. \(2015\)](#) demonstrate that environmental considerations are paramount in enclosures that are exposed to the elements. [Yip et al. \(2017\)](#) conclude that many enclosures are effectively not only waterproof but air-tight as well. [Sachdeva \(2015\)](#) elucidates that the perhaps surprising fact is that using watertight enclosures does not guarantee long-lasting protection and reliable performance. [Isermann \(2006\)](#) shows that this is because of the existence of pressure differentials (ΔP). Thus, over time this delta P can cause difficult-to-detect leak paths ([Crowder, 2006](#)). [Lasnier \(2017\)](#) demonstrates that pressure equalization is not a simple task.

[Kreeley and Coulton \(2018\)](#) highlight that all enclosures are affected by the cooling effect or forming condensation if the environmental conditions deteriorate sufficiently. [Zhan et al. \(2008\)](#) explain that water droplets condense out of moist air if the air is cooled below its saturation point. [Amir et al. \(2015\)](#) explain that enclosures are opened for service and this activity provides an avenue for moisture entry. Many condensation prevention methods have been developed ([Vancauwenberghe et al., 1995](#)). None seems to be universally effective. Therefore, [Ge et al. \(2017\)](#) conclude that a combination of internal moisture-removal and drainage system can provide an acceptable solution to many condensation problems.

[Xu et al. \(2018\)](#) observe that corrosion reactions are electrochemical and as such the process accelerates with an increase in the temperature. Therefore, [Rao and Wang \(2011\)](#) conclude that corrosion is more rapid as power density challenges existing heat management in new electronics. [Mathia \(2010\)](#) explains that corrosion resistance could be increased by improving robustness, minimizing air flow for cooling purposes,

maximizing moisture removal, limiting dissimilar material interfaces, and by the application of protective coatings.

Equipment used in hazardous areas is regulated due to its great potential to cause harm that results in loss of life, disability, injury, and property damage (Brauer, 2016; Rausand, 2013). Use of enclosures in hazardous areas is highly regulated and requires certification by third parties. Selectors must consider gas grouping (McMillan, 1998; Bottrill et al., 2005), Zone (Cox et al., 1990; Bozek, 2017) and temperature classification (Ebadat, 2010; Proctor, 2016) assessments.

Hose-down areas must guarantee that machinery utilized in these areas is clean and free of contamination according to Brown (2018). Maasberg (2012) informs that more intensive cleaning processes, high-pressure washdown sequences, and ever more concentrated chemical solutions are being utilized. Enclosure engineers need to understand appropriate design practices in terms of construction, quality, and compliance with relevant standards and a few critical components (Blanc, 2014). These are hinges, latches, seals, and gaskets.

Schwartz (2016) clarifies that gaskets are deployed to provide a seal between two adjacent surfaces in an enclosure. Hochberg et al. (2010) advise that a gasket's ability to exclude moisture, water, dust, dirt, other liquids, and particulate matter from the protected space is the primary engineering consideration. Achieving electromagnetic compatibility (EMC) by minimizing or eliminating electromagnetic interference (EMI) and radio frequency interference (RFI) can also be important (Gerke, 2018). Gaskets can also be deployed to contain noise, vibration, or other forms of harmful interference generated by the enclosed components according to Fahy (2000). Therefore, Middendorf (2017) advises that engineers should specify a gasket that is designed and rated for the relevant application.

Qazi (2016) underlines that outdoor enclosures must resist ultraviolet (UV) radiation, heat, precipitation, wind, and seismic loads, such as hurricanes, tornadoes, and earthquakes. Extreme cold fundamentally affects material properties of the enclosure and the electronic components. Additionally, Keane et al. (2013) underline that the explosive atmospheres' properties are also subtly altered. Therefore, enclosure engineers need to consider these events very carefully.

Drobny (2014) informs that thermoplastics turn softer as the temperature increases. However, Crawford (1998) highlights that all plastics including thermosets will eventually degrade due to heat. Thermal degradation imposes an upper limit to the service temperature range of plastics according to Van Krevelen and Te Nijenhuis (2009). McKeen (2014) clarifies that substantial thermal degradation can happen at temperatures much below ultimate mechanical failures. Thus, in many cases this could be a more restrictive limit than mechanical or electrical property loss.

Meller and DeShazo (2001) assert that environmental considerations are paramount in enclosures that are exposed to the elements. However, Kreeley and Coulton (2018) highlight that all enclosures are affected by the cooling effect or forming condensation if the environmental conditions deteriorate sufficiently. Enclosures designed for hazardous and washdown areas need special attention (Brauer, 2016; Brown, 2018). Enclosure engineers need to make sure that extreme conditions and long-term exposure is considered in all designs (Cressler and Mantooth, 2017, Keane et al., 2013,

Van Krevelen and Te Nijenhuis, 2009). The following points summarize and highlight the most important aspects:

- FRSs must include the proper assumptions for the operating environmental conditions according to Saxena et al. (2013).
- Pressure (ΔP) and temperature (ΔT) differentials facilitate ingress and must be investigated at the conceptual stage design review (Isermann, 2006).
- Internal moisture-removal and drainage system can provide an acceptable solution to many condensation problems (Ge et al., 2017).
- Corrosion resistance could be increased by improving robustness, minimizing air flow for cooling purposes, maximizing moisture removal, limiting dissimilar material interfaces, and by the application of protective coatings, potting or encapsulation (Mathia, 2010).
- It is important to note that care should be taken not to overspecify an IP rating for an application. This is because the cost of an enclosure increases rapidly with the rise in IP rating (Cole et al., 2015).

12.3.5 Interference and shielding

Every electrical apparatus inherently generates electromagnetic emission due to its operation (Tong, 2016). Kerker (2016) demonstrates that electronics can also be affected by electromagnetic energy. Therefore, Williams (2014) argues that enclosures need to be designed and manufactured to meet or exceed relevant interference regulations. Soueid et al. (2015) explain that electromagnetic compatibility (EMC) is also called electromagnetic interference (EMI), and radio frequency interference. EMC can be achieved by preventing interference from penetrating or escaping from an enclosure or housing.

Emission modes, filtration, ground leakage, suppressors, cables, and saturation theory was discussed from an application perspective to provide a fundamental at the same time practical understanding of relevant EMC theory (Mardiguian, 2014; Ozenbaugh and Pullen, 2017). Regulations exist worldwide to control EMC both in its intentional and unintentional forms. Williams (2016) explains that the primary reason for this is to prevent interference with communications services. The most important standards for industrial applications are the IEC 61000-6-4 Generic emission standard for the industrial environment and the IEC 61000-6-2 Generic immunity standard for the industrial environment according to Sakthivel et al. (2003). Immunity and emission together form the essential elements of EMC behavior (Ott, 2011). Finkenzeller (2010) explains that emission in turn is classified into low- and high-frequency segments.

Gnecco (2000) and Jagatheesan et al. (2015) highlight that contrary to current engineering wisdom, many plastics and composites can be excellent EMI attenuators. However, they must be formulated and their process designed with a strong EMC focus. Most often integration of an EMI shielding material into a composite is accomplished by embedding the mat or film into the actual laminate according to Cabrera (2014). Magnesium alloy use is growing in consumer and industrial electronics (Chen et al., 2015). Mechanical properties of magnesium are well known. Ashby (2000) explains that magnesium alloys have high specific strength and stiffness, which

make magnesium a potential alternative to aluminum in applications where mass is an important optimization factor. Magnesium is also an alternative to other materials in enclosures where thermal and electromagnetic conditions present a new level of engineering complexity (Song et al., 2017).

EMC can be achieved by preventing interference from penetrating or escaping from an enclosure or housing. Here are a few tips to help consistently achieve this important design goal:

- Enclosures need to be designed and manufactured to meet or exceed relevant interference regulations such as IEC 61000.
- The simplest way to think about this challenge is to ensure that the enclosure acts as a Faraday cage.
- Many plastics, composites, and magnesium can be excellent EMI attenuators in addition to aluminum.

12.3.6 Contextual pillars

This first handbook provided the essential foundations for an appreciation of the various contextual factors affecting enclosure engineering. These were summarized in this last chapter to serve as a reminder or as a quick reference guide to an engineer, manager, or any other stakeholder who wishes to refresh his or her memory in a quest for up-to-date knowledge on this exciting subject.

12.4 Design

The second book in this series of handbooks discusses design aspects of enclosure engineering. This handbook contains three parts: thermal, materials, and mechanicals. Thermal issues drive many engineering decisions within the enclosure engineering discipline. Therefore, this topic is introduced first. It is only possible to select the proper enclosure materials once the maximum, minimum, and the temperature range and its transient and steady-state behaviors are well understood. Material selection often drives the overall economics of any NPD efforts. Therefore, this aspect is described in detail forming a prerequisite to a complete understanding of the enclosure mechanical part. However, these three aspects together form the fundamental elements of successful enclosure engineering.

12.4.1 Thermal

This part is dedicated to thermal management of electronics and the interplay between the heat-producing devices and the enclosure. Specifically, principles of heat transfer are discussed to provide a fundamental understanding of the major issues involved. Current measurement and testing practices are described to create the fundamental tool box for the novice enclosure engineer. Thermal simulation is discussed next primarily from the vantage point of the two main analysis programs utilized by the

industry. Many of the most commonly used thermal management devices, such as thermostats, heaters, louvers, fans, heat exchanges, heat sinks, coolers, and numerous others, are discussed.

12.4.2 Materials

Material selection and behavior are the fundamental topics covered in this part. First, an introduction into the principles of material selection is made. One of the most important aspects in today's and quite possibly in the short- and medium-term's electronics industry is thermal management due to miniaturization and its associated power density increases. Therefore, this part uses the temperature analysis developed in the first part to enable the practicing enclosure engineer to select the right materials first time. A variety of metals are discussed. Sheet metals utilized in so many enclosure applications are described. The various types include mild steel, stainless steel, aluminum, and a few others. Cast metals often utilized in heat sink applications are discussed next. These include iron, aluminum, and magnesium. However, plastics form majority of discussion in this part. They are subdivided into their usual categories such as thermosets and thermoplastics. The former category includes phenols, vinyl esters, epoxies, polyurethanes, and polyesters. The latter category includes ABS, polycarbonates, PC/ABS, GRP, PVC, PA, and a few more exotic materials. This part spends a considerable effort on initiating enclosure engineers into the economics of material selection. Therefore, massive benefits could be secured for any NPD efforts that incorporate enclosures for its electronic devices.

12.4.3 Mechanicals

The mechanicals part contains enclosure design aspects. It can further be subdivided into three fundamental aspects: component design, tool design, and the often forgotten but nevertheless crucially important process design.

Component design provides an introduction into the various aspects of this activity such as description of the design process, detailed structural considerations, prototyping, and experimental stress analysis. The design process starts with stress-strain behavior, which itself consists of short-term effects, creep, and stress relaxation. Impact resistance is discussed next. Fatigue concepts are introduced to warn the novice enclosure engineers of the nonlinear nature of many materials utilized in enclosure engineering. Rheological issues are discussed next to highlight that even the same material can behave differently depending on its process history. Material data reliability is discussed after the rheological fundamentals are discussed to show the effect on any design. Structural considerations introduce industrial design methodology and the three paradigms: experience based, experimental, and analytical. Successful framing of the design problem is critical from the NPD process perspective. Therefore, this section details this process leveraging simplification and validation of virtual models as well as looking at the problem of stress concentrations as prerequisites to applying boundary conditions such as loads and supports into any finite element analysis or computational fluid dynamics calculations. This section also discusses relevant

material properties and associated safety factors to be used by the practicing enclosure engineers. Fundamental mechanical elements such as wall, projections, holes, beams, plates, and shells are discussed to form a fundamental understanding and to prepare for the next section discussing various mechanical engineering issues. These include torsion, buckling, and dynamic loads. Prototyping reviews current technologies, surfaces, tooling, and measurement aspects, while experimental stress analysis includes coatings, strain gauges, photoelastics, and optical measurements.

Tool design primarily focuses on injection molds. However, many of these elements could easily be transferred to diecasting. This section starts with a description of the art of mold making and how it has developed. This topic provides the necessary bridge to detail the fundamentals of mold constructions. Ejection methods, feed systems, and parting surfaces are discussed next. Thermal management from a tool design perspective is reviewed. The use of standardized mold systems can shorten tool projects enormously; therefore they are discussed in detail. Advanced mold features such as splits, core and cavity slides, undercuts, threads, and hot runners are reviewed to complete the tool design fundamentals. Managing tooling projects for enclosures is incorporating a business perspective on tool design.

Once again process design fundamentally focuses on injection molding although the principals apply equally to diecasting of heat sinks and enclosures. Therefore, both plastic and metal flow analyses are included.

12.5 Supply chain dynamics

The third book in this series of handbooks discusses supply chain aspects of enclosure engineering. This last handbook in the series contains three parts: manufacturing, positioning, and forecasting.

12.5.1 Manufacturing

Plastics shaping, molding, potting, injection molding, assembly methods, and technological developments are reviewed in this section. Plastics shaping technologies reviews blow molding, extrusion, films, machining, injection and rotational, SMC/BMC, other GRP, thermoforming and vacuum forming technologies. The section on molding technology highlights various aspects of compression, SMC and BMC aspects. Potting is discussed next. A detailed review of injection molding is warranted as this is by far the most popular of plastics shaping method today. Therefore, machine basics, tooling fundamentals, and control systems are discussed. Mold filling, weld line formation, shrinkage, warpage, cooling, and solidification as well as part ejection is reviewed. Solutions to the most common injection molding problems are also included. The assembly methods section focuses on mechanical fastening, ultrasonic assembly, metal inserts, snap and press fits, living hinges, heat welding, sealing, solvent, and adhesive bonding practices. The technological development section describes multicomponent, assisted, multishot, and overmolding aspects.

12.5.2 Positioning

This part adds perspectives on how to become the only solution in electronics enclosures. Specifically, this part discusses four important elements: product development, links in the supply chain, specialized knowledge development, and seizing the opportunities presented. Product development provides a review of the new products and minor and major revision processes from a supply chain perspective. The section on the links in the electronics supply chain reviews commoditization versus customization, materials suppliers, compounders, processors, and tool makers. The specialized knowledge creation section is devoted to product as well as service creation. The last section details on the right timing of involvement in these activities, how to control the all-important specifications, the quotation and tendering process, negotiations, and closing the deal by forming partnerships.

12.5.3 Forecasting

This part adds a new dimension to the supply chain member of any enclosure engineering project. This part focuses on the 5D innovations, increased intensity, improved heat management, plastic electronics, and forging a competitive advantage. Specifically, 5D innovations review relevant product, technology, business, sales and marketing, and human resources—related progress and potential trajectories. The section on increased intensity examines power density and miniaturization developments and potential future pathways especially in light of the current nanotechnology wave. The improved heat management section details natural and forced convection and liquid cooling aspects along with a few novel ideas. MIDs and plastic electronics are reviewed by examining electrical elements, mechanical features, and integration of interconnect technologies. The last section on forging a competitive advantage focuses on potential new materials, compounding opportunities, the future of the tool making landscape, and injection molding fortunes.

12.6 Handbook series

It is impossible to adequately address all the issues of enclosure engineering in a single volume. Therefore, editorial oversight is necessary to establish the proper boundaries in between the various books and parts of these books. It was decided that without a thorough understanding of the fundamentals, it is nearly impossible to successfully navigate the treacherous waters of enclosure engineering. Therefore, the contextual pillars were reviewed in the first handbook.

12.7 Review

Enclosures are a vast business opportunity. This means that enclosure engineering will be important for a long period of time. Therefore, acquiring the necessary knowledge

to gain understanding first and proficiency second is important. The first book in this handbook series addressed the contextual pillars. This handbook first proved that enclosures are everywhere by reviewing the relevant concepts of innovation, markets, requirements, types, and the NPD process. The second part of the handbook is devoted to the societal framework. Specifically, it reviewed standardization, IPs, sustainability, and interference technologies. In addition, this last chapter provides a flavor of the next two handbooks in this series, which provides design and supply chain development assistance.

12.8 Hot tips

It is paramount to understand the contextual pillars of enclosure engineering. All the important topics have been reviewed: innovation, markets, requirements, types, the NPD process, standardization, IPs, sustainability, and interference technologies. Knowing these, however, only provide the essentials.

- Design and supply chain dynamics completes the enclosure picture.

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Electronic Enclosures, Housings and Packages considers the problem of heat management for electronics from the encasement perspective. It addresses enclosures and their applications for industrial electronics as well as LED lighting solutions for stationary as well as mobile markets.

Electronic Enclosures, Housings and Packages first introduces its readers to fundamental concepts and establishes its focus by defining dimensions of success in electrical enclosures. This is followed by environmental considerations, shielding, standardization, materials selection, thermal management, product design principles, manufacturing techniques, and sustainability. In its closing chapters, the book is focused on the business fundamentals by outlining successful technical propositions and potential future directions that would lead to actionable insights benefitting materials scientists and engineers, product developers, additive suppliers, and molders.

Key features:

- Introduces the concepts of materials recycling and sustainability to electronic enclosures
- Provides thorough coverage of all technical aspects related to the design and manufacturing of electronic packaging
- Includes practical information on environmental considerations, shielding, standardization, materials selection, and more

Dr Frank Suli was the former interim VP of Technology at Emerson (and previously Chief Engineer, Chairman of the CAE Committee, R&D Manager, and Principal Mechanical Engineer). Frank has introduced a new product development methodology for creating Emerson's Electrical Enclosures, enabling decreased manufacturing costs by 35% while increased value to customers resulting in doubling this business within 18 months.



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