TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

RIKU LAGER

TOOLS FOR IMPROVING RELIABILITY DURING PRODUCT DEVELOPMENT PROCESS

Master of Science Thesis

Examiner: University Teacher Erja Sipilä
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ABSTRACT

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One of the most influential factors when talking about industrial products are quality and reliability of the products. As company grows, grows also need for reliability plan. Purpose of this thesis was to present a variety of different reliability tools, and give examples of utilizing these tools.

First tools revolved around Design for Reliability methodology. Its fundamental idea is to implement the reliability in the design process. Methods from the Design for Reliability consists of many different tools, while concentrating on preventive design with different analysis and simulations, and by using iterative design methods for testing, and redesign. Second set of tools was presented as a computer aided design. These tools takes advantage on developing computers, and digitalization, which can be utilized throughout the design process. Simulation for mechanical, electrical, and thermal phenomena can increase the reliability during the design process and in the meantime decrease time to market.Third part consists the important part for every design process, an analysis and selection of the components used. Errors on choosing the right component can have effects seen at long after the production process is over. It is important to know how to control the components reliability parameters, and also be aware the different ways of giving the reliability information. Also tolerances, parameter degradation and rating of components are discussed over the third part of this thesis.

At each tool sets, the possible use is discussed during the presentation of the tools with the proper and right timed use. Also the possible impact the proper use of these tools might have to the new product development process is discussed.

TIIVISTELMÄ

RIKU LAGER: Työkalut luotettavuuden kehittämiseen tuotesuunnitteluprosessin aikana
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Eräs suurimmista elementeissä nykyaikaisissa teollisuuden tuotteissa on laatu ja luotettavuus. Yhtiön kasvaessa, myös luotettavuussuunnitelman on kehityttävä ja kasvettava tuotteille asetettujen vaatimusten tasalle. Tämän diplomityön tarkoitus on esittää erilaisia luotettavuustyökaluja, ja esittää mahdollisia käyttökohteita näille työkaluille.

Ensimmäinen työkalusarja liittyy Design for Reliability metodologiaan. Perusidea tässä työkalussa on sisäistää luotettavuus jo tuotesuunnitteluprosessin aikana laitteeseen. Työkalusarja koostuu useista erilaisista työkaluista jotka usein keskittyvät ennaltaehkäisevään ja ennakoivaan tuotesuunnitteluun. Näitä on erilaiset analyysit ja simulaatiot, sekä iteratiivinen projektin kulku useissa tuotesuunnitteluprosessin kohdissa. Toinen työkalusarja liittyi läheisesti digitalisaatioon ja tietokoneiden jatkuvaan kehitykseen. Näitä työkaluja voidaan hyödyntää koko tuotesuunnittelun ajan, jo erittäin varhaisesta vaiheesta lähtien. Mekaanisten ja sähköisten ilmiöiden ennustaminen lisää luotettavuutta, samalla vähentäen testaukseen kuluvaa aikaa. Viimeinen työkalusarja keskittyy komponenttien luotettavuuteen. Komponenttien parametrit voidaan ilmoittaa luotettavuuden osalta monella tapaa, ja näiden tasapuolinen vertailu ei aina ole yksinkertaista. Tämä työkalusarja käy läpi myös komponenttien toleransseja, sekä uusien komponenttien parametreja.

Jokaisen työkalun kohdalla on keskusteltu mahdollisesta oikeasta käytöstä. Usein työkaluja käytettäessä oikea-aikaisuus jo tarkoituksenmukaisuus ovat kriittisiä työkalun lopputuleman kannalta. Työssä myös keskustellaan mahdollisista hyödyistä työkalujen käyttöön liittyen.

PREFACE

This work about reliability tools has been done to Danfoss, Vaasa site. My supervisor at Danfoss was Ph.D. Kati Kokko. I would like wholeheartedly thank Ph.D. Kokko for support and guidance throughout the long process. This thesis was examined by University Teacher Erja Sipilä who I would also like to acknowledge for the support and understanding of the process. Support from the colleagues was vital for this thesis' completion, and special thanks for M.Sc Tommi Manninen for valuable conversations regarding reliability.

This trip would have not been the same without my family. My gratitude to all my friends who made me the person I'm today. Gratitudes also to a certain team of athletes, for balancing studying with other activities. Lastly, for everlasting support, thank you Maija.

Vaasa, 21.3.2017

Riku Lager

"Vaasa is a beautiful city at the summer"
-Unknown

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LIST OF ABBREVIATIONS AND SYMBOLS

ALT	Accelerated life testing
CAD	Computer aided design
DC-link	Direct current link
DFMEA	Design failure mode and effects analysis
DfR	Design for reliability
DFSS	Design for six sigma
DOE	Design of experiment
EMI	Electromagnetic interference
ESD	Electrostatic discharge
FEA	Finite element analysis
FEM	Finite element model
FMEA	Failure mode and effects analysis
FIT	Failures in time
HALT	Highly accelerated life test
IC	Integrated circuit
IEC	International electrotechnical commission
IGBT	Insulated gate bipolar transistor
ISO	International organization for standardization
LS-Analysis	Load strength analysis
MIL-HDBK	Military handbook
MTBF	Mean time between failures
MTTF	Mean time to failure
PRISM	One standard for reliability predictions
PCB	Printed circuit board
RIAC	Reliability information analysis center
RPN	Risk priority number
SFMEA	System failure mode and effects analysis
SN92500	Siemens' standard for reliability predictions
SN-Curve	Stress-cycles to failure curve
SR-332	Telcordia's standard for reliability predictions
TAAF	Test, Analyze and fix product development methodology
TR-332	Bellcore's standard for reliability predictions
TRS	Technical requirements specification

C_1	Complexity
D	Detection value
D	Total damage to achieve failure
D_i	Damage from ith source
m	Number of test runs
N_i	Cycle count
N_i	Quantity of part
O	Occurrence value
S	Severity value
T	Temperature
t	Time
β	Shape parameter
Δ	Tolerance limit
η	Scale parameter
η	Sensitivity
γ	Location parameter
λ	Failure rate
λ_{bi}	Base failure rate
μ	Average value of distribution
pi_E	Environmental factor
pi_L	Learning factor
pi_Q	Quality factor
pi_t	Time factor
pi_T	Temperature factor
σ	Stress
σ	Standard deviation of distribution
${\sigma_{total}}^2$	Variance

1. INTRODUCTION

Objective of this work is to present possible methods and tools that the reliability engineer can utilize, while working on a new product development project. This thesis aims to find and present methods that are most useful for increasing, or estimating the lifetime of a system.

This thesis bases much on earlier experiences of reliability development. Reliability is studied a lot by companies, but findings are usually not published. This makes the thesis' topic interesting, as the data is quite theoretical. Practical implementation of the tools and methods vary greatly depending on industry and company structure, and clear lines how to execute some methods are not available. The tools presented are found with relatively ease, but examples and case studies tend to be quite specific, especially when concentrating on more unknown tools.

At chapter two, the basics of reliability is presented; failures, lifetime, failure mechanisms at quite common level, to make foundation for further method analysis. Theory is in chapter two, but much of the rest of the thesis relies also on theory. Chapters three to five introduces possible tools to implement in product development process to increase reliability of the product. At chapter three, a design for reliability method is presented, including few analysis methods as well as Failure Mode, and Effects Analysis (FMEA). Chapter four concentrates on few possibilities on simulation, while chapter five is about engineer's guidelines for choosing and rating the component properly considering the reliability.

2. RELIABILITY IN GENERAL

This chapter introduces concepts in reliability. First we introduce basics of reliability by defining reliability, failure and failure rate. Then we focus on analyzing and gathering the data for reliability and with these themes the mathematical models for life expectancy are also introduced. Lastly testing as a part of reliability design is introduced.

2.1 Basic Concepts

Reliability is often defined as a probability of the item's ability to perform its required function properly for specific time in a specified operating conditions. It is generally designated by R. In reliability's sense the item could be as complex or as simple as possible. Item could be a hardware or software based, or a hybrid of these two. It might include redundant parts but the human interaction is often thought as ideal. Usually item without human is referred as technical system. As the theory says, reliability is often changed with the operating environment and time. Because of this, definition of operating conditions, required function and time is needed to acquire valid information about system. [1, p. 2]

Firstly defining operating conditions of system is vital part of a reliability, as different materials and systems have different characteristics depending on environmental conditions. In electronics especially temperature is a critical characteristic affecting the reliability. Next, the time-parameter is needed for a good and accurate estimate of the reliability. Also operating conditions and required functions might be time-dependent. In reliability's point of view, time doesn't have to be calculated in hours, but it can also be other quantitative value, such as revolutions, kilometers or clicks. Because of the fact that reliability is time dependent value, the reliability function is defined by $R(t)$. Reliability function, sometimes called as a survivor function, means that there is no failures at highest level of system between $(0, t]$. Finally, a system's required function is important to clearly define as is the task that device should be able to perform, if the device is considered operational. Usually these functions are defined as follows: for given inputs there are specific outputs within some tolerance and these outputs are predictable. If device isn't able to perform its required function, it has a failure. For an end user, this black and white definition is usually enough, but for a reliability's point of view it is not. Failure has multiple different properties that define the failure. It is noted that generally it is assumed that the system is operational at $t = 0$. Parameters for failure are at least frequency, cause, effect, mode and mechanism: [1, p. 3]

Frequency: Frequency of failure is the time between $t = 0$ and time of failure. Generally frequency is relatively low, but the failure can happen almost instantly, for example because of transients caused by turn-on. Non-repairable systems can endure only one failure, as in the event of failure the system ceases to operate. Repairable systems can endure either downtime or decommission on the failure event.

Cause: Cause of failure is a reason for system to stop its required function on a system level. There are two types of causes: intrinsic failures, which are caused by internal weaknesses and wear out, or extrinsic failures, which are caused by environment, misuse or mishandling the system.

Mode: Failure mode is a local effect on a system that causes the failures. These can be of shorts, opens, cracks or parameter drifts. Technically, mode is anything that causes failure. It is worth noting that even though cause and mode are quite similar, they answer to two different questions. For example in Integrated Circuit (IC) overcurrent situation, cause of failure is overcurrent, and failure mode is e.g. short circuit in regulator circuitry.

Effect: The effect tells what consequences of failure to the current system are. For complex system it is important to think also what are effects to the upper level system. Effects can be of many levels: non-relevant, partial, complete and critical failures. These classifications serve as a good example for possible levels of effect.

Mechanism: Mechanisms is a process that leads to the failure. Chemical and physical processes are most common failure mechanisms. Example for chemical process is oxidation, where as physical example could be shock caused by dropping the system.

Not all systems break same way, even if they are made similar way. System failures can occur either suddenly or systems can degrade to the state of failure. Time in this sense is relative: some systems are designed for yearly use, whereas some are designed to work only once. In electronics, sudden failures often have more energy than degradation failures. Examples of sudden failures are breakdown of insulator, whereas example of degradation failure is stuck bearing. [1, p. 3]

Defining a system, and its use, the rate for failures is critical for both reliability and quality. Failure rate is the rate on which failures occur on defined conditions while working it's required function between time interval t and $t + dt$. Even though the time to failure is not always continuous variable, it often can be approximated by continuous variable. For example the amount of mechanical switch operations is discrete, but continuous approximation is enough in our application and because the time to failure is a subject to variation, failure rate can be described in two ways: [2, p. 15]

$$\lambda(t)dt \tag{2.1}$$

where $\lambda(t)$ is the failure rate. Failure rate can be also be presented as a probability density function in equation 2.2.

$$f(t)dt \tag{2.2}$$

where $f(t)$ is called failure probability density function. This connects to the failure distribution function in equation 2.3.

$$F(t) = \int_0^t f(u)du \qquad \text{when } t > 0. \tag{2.3}$$

Both probability distribution function $f(t)$ and failure distribution function $F(t)$ are represented in the figure 2.1.

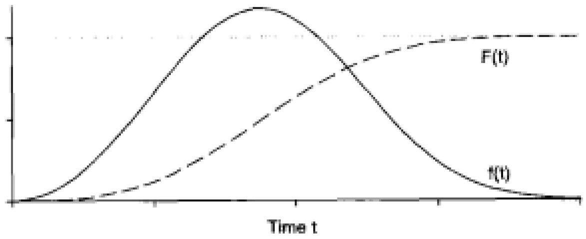


Figure 2.1 *Failure probability density function $f(t)$ and failure distribution function $F(t)$. [3]*

Distribution function tells the probability that the system has failure in a certain time. To connect this information to the survival function $R(t)$ we can write the equation in following way:

$$R(t) = 1 - F(t) \qquad \text{when } t > 0. \tag{2.4}$$

By connecting 2.3 and 2.4 an equation linking reliability and failure probability distribution function can be build. This equation can be rewritten as:

$$R(t) = 1 - \int_0^t f(u)du = \int_t^\infty f(u)du \tag{2.5}$$

This can be presented also in a figure 2.2.

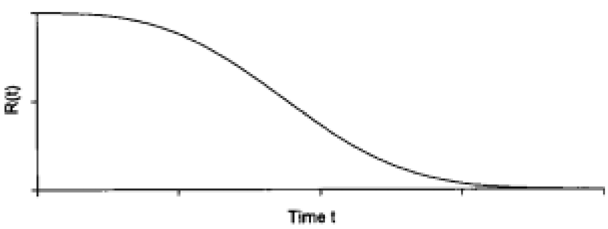


Figure 2.2 *Survival function as a function of time. [3]*

As seen from 2.2 the probability of survival decreases in function of time. The function is strictly decreasing only when the parameters are not changed during the use. If operating conditions, or required function changes, the survival function should change too. Same happens if a preventive maintenance is done to the system. Strictly decreasing survival function is presented in equation 2.6.

$$\lim_{t \to \infty} R(t) = 0 \tag{2.6}$$

Equation 2.6 states that with time is running infinitely, the survival function of system is closing to zero. This is obvious consequence of non-zero failure rate of single components as a function of time, it is also assumed that the system would not be repaired during the use. [2, p. 16]

2.2 Failures in Electronics

As previously introduced, failure is a discontinuity in a period, where system ceases to function. In electronics causes of failure can be either hardware or software based as more and more integrated circuits and programs are implemented in the PCBs. Even if the failure mode is clearly either software or hardware based, the effects of failure might still be seen on both. All faults can be also divided in two depending how critical they are. The division is done regarding if fault can be recovered from. Software based faults that cause no hardware breakdowns can usually be recovered from. Hardware failures on the other hand are somewhat non-recoverable and require often at least some kind of maintenance. [3, p. 3] Exception is those hardware failures that are caused by environmental conditions. For example many ICs have a thermal shutdown, which turns the IC off, when a certain temperature is reached. [4]

Because of the great and clear difference in fault mechanisms and testing possibilities between software and hardware this thesis concentrates on the latter. Also the human reliability is a valid field of study, but the challenges with humans are always unique depending on incident and the human reliability is not considered in this thesis. Common to all hardware based failures are that they can be presented in a strength stress diagram. [3, p. 3] Example of such is in figure 2.3.

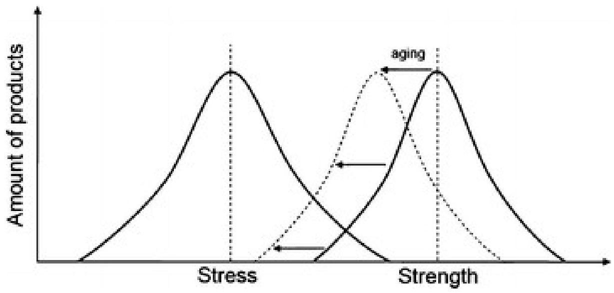


Figure 2.3 *Example distributions for system stress and strength. [5]*

At figure 2.3 there are two independent distributions, which are not always normal distributions. Stress distribution is for how much strain certain system experiences at current time. This stress level is then compared to the systems strength level. If the stress is higher than the strength of the system, then a failure happens. Both of the distributions may move depending on multiple parameters. Stress distribution might move with external environment and usage. Strength distribution moves towards stress when it ages, and away from stress with maintenance due the new components and updates. At functioning state rate that failures are introduced to the system is not constant, but can be divided into a three clear entities: decreasing, constant and increasing failure rate. These three parts can be seen in 2.4. [6]

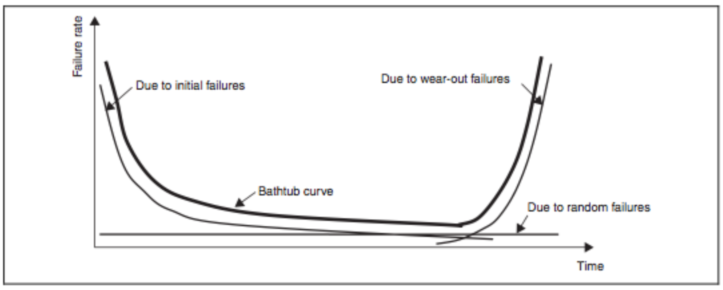


Figure 2.4 *Fault rate depicted as bathtub curve. [7]*

The figure 2.4 is not a failure rate for a certain system, but a distribution of a population failures in a population. As can be seen from the figure, all failure rates are presented in a whole system runtime.

Decreasing failure rate is the first of these that is introduced with new systems. Decreasing failure rate is a result for hazardous environment before final assembly of the system. These failures are usually related to manufacturing and quality of subsystems: Faulty components at subsystems, electrostatic discharge at assembly or open connection at printed circuit Board(PCB) to name a few. Decreasing failure rate or early life failures are expected to decrease with time, as the faulty components are broken due the stress levels compared to their relatively low strength. There are few tools to reduce the amount of failures in early life, mainly these consist of quality control, on both final assembly, and with subcontractors to decrease the amount of low strength products in final system. Other major possibility is so called burn-in testing where the device is artificially aged before customer receives the system. This method uses the knowledge of rapid decreasing of failure rate to generate improved reliability. [6]

A constant failure rate is observed in whole lifetime of the system. It represents the stress related factors caused by the fluctuations in stresses that affects the system. These changes usually are externally induced to the process. For example overstress situations because of faulty use, failures induced to system during maintenance and unforeseen harsh environmental effects like current surge on power supply. Common for all these failures is that they are relatively random. The failure rate might not be high, but it can be statistically seen as a constant rate for the when population of systems is large. [8]

Increasing failure rate, or wear out failures are generally a parameter for a good item. This means that the item starts to fail after its useful life period has past. Common failure mechanisms at wear out stage are corrosion, atomic migration and fatigue. Wear out happens due the aging of the system. More precisely, when the strength of the system degrades towards the stress. This drift is seen at figure 2.3. [8] [9]

These three entities are not related to certain time-frame such as 90 days infant mortality, but to a period of time where failure rate is decreasing because of certain issues. Same is with wear out stage, the failure rate might start to grow just after few months of use. [6] [8]

Even though faults are easy to recognize from system, the real challenge in terms of reliability is finding the root cause and determining what and especially when the failure occurred. When calculating estimation of a lifetime, it is important to acknowledge the accelerating environmental and physical phenomenon. The environment needs to be accounted for to accurately calculate and evaluate the possible lifetime. In electronics one prominent accelerator is temperature, which effects on ICs and components. Especially the component efficiency, which in turn increases losses, and generates heat. Other major aging environmental issues is caused by humidity, and vibration. [1, s. 139-144]

2.3 Failure Mechanisms

This section will cover most probable failure mechanisms in electrical devices: temperature, humidity and mechanical failure modes. These modes usually affect clearly on the whole system. Because high temperature is the main breakdown mechanism of electrical devices, the failure modes are not introduced more in depth. Failure modes are important for reliability analysis, but the sheer amount of modes in electrical system is so overwhelming that it is not expedient to process them all.

Temperature is one of the major challenge with electronics. As modern electronics, and electrical devices operate all the way to the +125 degrees Celsius the temperature can hasten the chemical reactions, gaseous and liquid diffusion. [10] Faster chemical reactions affects the parameters of the integrated circuitry, and might cause worse efficiency and higher heat output. Other method temperature affects the devices is by thermal coefficient. Thermal coefficient is a parameter of a every material which dictates how much change of temperature affects the size of the material. When two parts that has different thermal coefficients are connected, the thermal retraction or expansion causes strain in interface. Especially challenging this is when temperature changes cyclically, and interface is on constant strain from expansion or retraction. [9, p. 219]

Mechanical stress is caused by thermal expansion, but also by vibrations, and shocks often caused by some external effect. Shock does not always cause a visible failure, but it can dislodge joints in casing, PCBs, or connectors. Mostly shocks effect on relatively high-mass components, and components that have high height to width ratio, which in turn means that the top of component is having a greater impact than base of the component. This in turn increases the stress in connections at contact surface, which in electronics' case is usually the PCB. When the frequency of shocks is constant, they can be classified as vibration. Usually vibration affects the system with lower force, because the high force in shocks that break components would break the system immediately. Vibration has a parameter frequency, which tells how many times in a second the system vibrates. Frequency tends to be inverse proportional. At higher frequencies the effects are mostly stresses on connections, when component vibrates differently than the system it is connected to. Other effect worth mention is the mechanical nuts and bolts. Vibration can loosen the connections made by nuts and bolts, if frequency is right and the amplitude of vibration is high enough. [9, s. 216-217]

Humidity of the air is an amount of vaporized water in the air. To electronics and hardware based systems, it is one of the most critical failure mechanism. It is critical to systems on all levels, high and low. Dry air, where the relative humidity is low, is often better structurally to electronics, but some polymers suffers from absence of water molecules. Dry air makes polymers to dry out, which seems to wear out as the dry air is making the components more brittle. For electronics, the dry air is more susceptible for electrostatic discharge, or ESD for short. ESD is a local voltage difference caused by material in contact with other material. When relative humidity is low, the air is more uniform, and the voltage needed for ESD is lower thus making the discharge more probable. Moisture can be permeated inside frames, effecting metals and plastics yield or ultimate strength. In plastics, water can break covalent bonds in polymers. This changes the structural integrity of plastics, and making it more vulnerable for changes in shape and strength. Electronics point of view humidity and moisture makes the oxidation process possible. Oxidation can happen in any two surfaces, where there is moisture and electricity. To counter the effects of high humidity is encapsulation. Usage of component, and the monetary reasons usually determine, if the encapsulation is non-hermetic or hermetic. Meaning if the moisture is able to penetrate the encapsulation. The ceramic encapsulation does not allow any moisture inside, even with time. The metallic encapsulation holds the moisture away, but is very susceptible for corrosion and the plastic encapsulation is not hermetic, as with time the moisture is able to penetrate the frame. For ESD, damp air does not stop the charge for forming, but the moisture gathers at the surface of the material, forming a way for the charges to move and dissipate.

Electronics are susceptible to many environmental effects. Depending on use environment, the effects may vary. Because of different use environments it is vital to address external and internal environmental effects, and design the product in a such way that the effects does not impede with usage of the device.

3. DESIGN FOR RELIABILITY

Design for reliability(DfR) is quite new way for thinking how the new product development process is supposed to be done in the terms of reliability. Design for reliability is effectively a toolbox for design and reliability engineers, not a single tool. Much of the tools featured in DfR are also featured in DFSS(Design For Six Sigma). DFSS is emerged from Six Sigma methodology and is also, as is DfR, a proactive tool pack. Even though the DFSS and DfR shares a common tools, the scopes are different. DFSS aims to decrease variation and nonconformities, where DfR aims to improve reliability of the product from design all the way to the wear out phase. [11]

As modern product development process increases the pressure to decrease the time to market, new ways to implement reliability is needed to overtake the old concept of test, analyze and fix (TAAF). TAAF is effective on some parts of the design process, but it increases the design time when applied alongside with the normal design process, and the testing is done as an extra work to the process, not as part of it. To implement better the testing and reliability design a DfR process can be used. DfR is a concept of introducing the reliability into the process, and using preventative methods to decrease time to market, reduce waste in reliability and give more precise information about the design in earlier phase of design process. Because of the cost of design change varies during the product life somewhat like in figure 3.1, it is easily justified that changes should be avoided in later design. [9, p. 177]

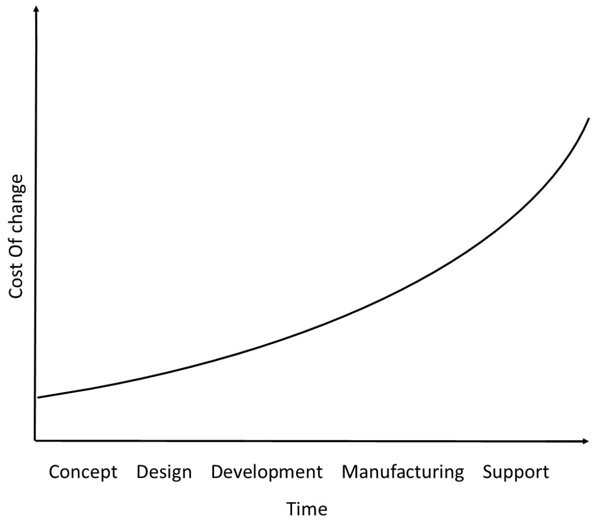


Figure 3.1 *Cost of change as a function of time. [9, p. 178]*

To many designers DfR means a bunch of new tools in analysis, design and in new corrective actions. This means that to utilize DfR to its full extent, product designers and project managers needs to be supported by reliability engineers, as they have most knowledge of reliability tools. Because the reliability is "built in" the system, the role of reliability engineer is more like a mentor, or facilitator, than that of a design engineer. Reliability engineers role consist of finding the best processes for the company, depending on multiple different parameters, and all tools are not compatible with all the companies and projects. Reliability engineer also trains the engineers for right usage of these tools and processes. This causes idea of the ownership of the design reliability to move from the reliability engineer to the design engineer, which in turn causes more effort in reliability in design. This means that the responsibility and possibility to make changes lies in same place, increasing reliability. Of course in the whole project must have good communication between designers and reliability engineers as guidance is needed throughout the whole process. [9, p. 177]

To improve the product, few different strategies can be applied. These basic strategies are presented in a figure 3.2.

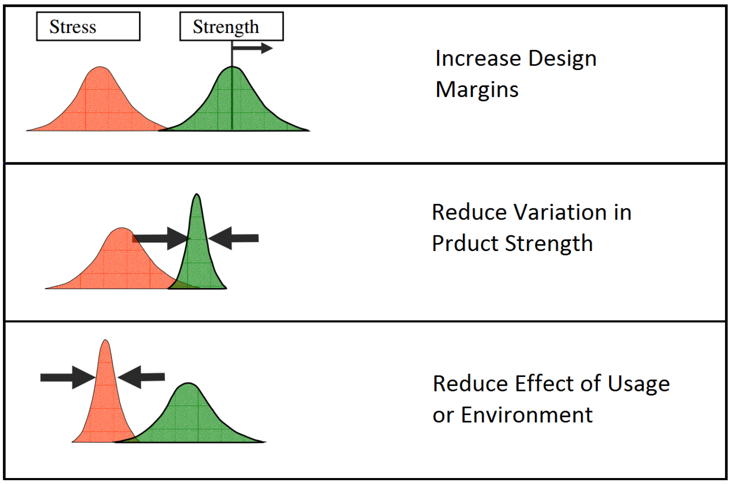


Figure *3.2 Strategies for reliability improvement. [11]*

In figure 3.2 the topmost strategy means that by increasing the strength, or reliability, of a product, the useful lifetime can be increased while decreasing then probability of failure. Figure in the middle of 3.2 depicts the idea of decreasing the amount of variation in product strength. Effectively this means that the tolerances, and variation of the components consisting in a product are minimized or at least decreased. This again affects most to the lowest strength components. Lowest picture in figure 3.2 means that by observing and controlling the environmental effects like temperature and humidity, the system can be more efficiently optimized. Other meaning is that by controlling the usage the use patterns are more predictable and mentioned optimization can be made to the product.

Design for reliability uses big variety of tools and practices that are actually familiar with quality and reliability oriented personnel. The process is studied by multiple different companies and research communities, and whilst the tool implementation and time of implementation is widely discussed, Mettas(2010) has made a framework for structured outlines of the process and key design activities, alongside with the appropriate reliability analysis tools. [11] With the different use environments, like consumer goods and aeronautics, the needs for design for reliability also varies. However the activities flow can be said somewhat every time presented like in figure 3.3.

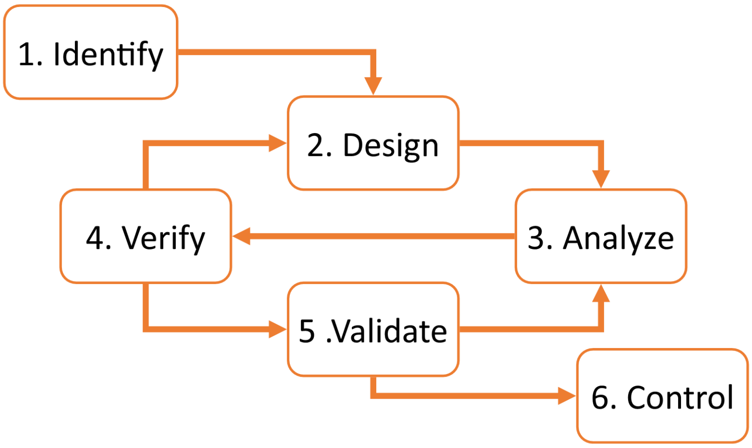


Figure 3.3 *DfR activities flowchart, adapted from [9, p. 179]*

As can be seen in figure 3.3, the DfR goes well with the common concept-design-development-manufacturing-support -process flow, with the critical difference that the design and development process is highly iterative in DfR. Implementation of the DfR can be, at least first few projects when the whole process is finding its place, extremely tedious, time consuming and frustrating. Usually this is the case in every new process, before the ways of working are properly understood and implemented. Even though the DfR process and its implementation increases the costs of the system, the decrease in product redesign costs, warranty claims, and after sales challenges will cost more to handle. [9] Next we are going through the phases of DfR one by one and show few tools in every phase, some might have been explained in their own chapters in this thesis due the importance in reliability design as a whole.

Process step of identify is a critical piece, but easily overtaken, when time is of the essence, and any real data is not yet validated, or finalized. What does the specifications means in a reliability terms. How the operation hours turn into specifications, and design. At identifying phase the usage of the system needs to be understood, so that the rest of the process supports the right things. Lessons learned from previous systems of similar usage and user base can be used to assess the usage of the oncoming product. The main point on the identify step is that the reliability engineers are in close communication with the design engineers, and are highly involved on the system design, as the system costs follows somewhat figure 3.1. If the system has new technologies, that are not addressed before in the reliability terms, the identify step is good time to include reliability and risk assessments to gather information about the technology in close interaction with the design engineers. Some tools that can be used in this steps include risk assessment, quality function deployment and usage and environmental assessments. System failure mode and effects analysis (SFMEA) is also advantageous to start in this phase, when the system does not have clear structure, and points of interaction are being designed. In the identify step, the groundwork for later DfR activities are laid, and actions and analyses made in this step are valuable information to the later steps easing off the load of analysis and specification based expectations. [9, s. 179-183]

At design step, the real system design begins. Circuit layout, mechanical drawings supplier selections to name a few. This means that also the level of detail in design rises, and this again makes further calculations of reliability possible. Also some criticality assessment, and hazardous operations are used. Because the whole point in DfR is to implement the reliability in design, the reliability engineer's job in this part of the cycle is quite important, as there are many things regarding the reliability in design phase, and many processes that can be started. One of the most used processes is FMEA on either system (SFMEA) or design (DFMEA) where SFMEA is an analysis for concept level of system, whereas DFMEA is concentrating on a risks on a design. Usually at the same time as design starts to develop, the DFMEA is launched to support the design process. Even though the reliability engineer's role in DfR is quite strictly observer, or steerer, in early time implementing this process, the close communications, and interaction with the reliability engineer is needed to increase the involvement of reliability on familiar design process. If the process does not have enough time and resources, and the motivation is lost, the advantages of the DfR is lost due the poor implementation of the process. The reliability is artificially implemented, usually on top of the design, and the positive effects of DfR is lost. Main point in design phase is to take into account the risks and reliability of the design and make an effort to decrease risks, with the close interactions with analyze and verify steps. [9, s. 183-196]

At analyze step the design that has been made in design phase is thoroughly analyzed and the amount of different analysis methods are endless. For mechanical structures, a finite element analysis (FEA) is one of the most revealing in terms of physical damage, as FEA can be used to analyze the nominal use, but also the forces the design endures during the drop, vibration from the transportation, and physical strain from temperature cycling. To address design with different options for components, design of experiments (DOE) can be used, also derating analysis and reliability predictions can be used in this phase of DfR. To identify the possible challenges in design, also some development from previous revisions or product families can be analyzed with the help of data from active products developers, to decrease the possibilities to make same mistakes twice. [9, p. 198]

Verify step starts when physical product is done, usually this means first prototype. Verification in DfR can be seen as problem finder, where physical product is tested and analyzed with the life analysis and reliability growth tools. The found problems are taken into structured problem solving methods, like root cause analysis or failure tree analysis. After structuring the root cause, or multiple possible causes, the important information can be communicated back to the design phase, and cycle of product's reliability improvement is complete. Also in verify step the few different reliability tests can be done, to develop the product, and gather data for analysis. Highly accelerated life test (HALT) and accelerated life test (ALT), degradation testing, design of experiments are all possible test types, for the verify phase, and gives good information feedback to develop the design further. [9, s. 197-198]

Validation comes after a few iterations with the design-analyze-verify cycles, and the design starts to close the maturity. In DfR validation means usually the environmental and functional testing against specifications made in earlier stages. Because of the nature of validation these tests are done to the success, on the contrary in verify step, where the design is challenged by HALT and ALT testing which are usually to the failure tests. This step can also be divided into two different parts: design validation and process validation. In design validation, the tests are done to the prototype. Idea behind these tests are that the testing is done against the specifications, and that the design is in fact capable for the environment and functionalities that first drafted in earlier phases. In production validation, the design is run through the manufacturing that has produced in intended facility with intended devices. Idea in production validation is to validate also the ease to manufacture so that device could be manufactured repeatable way and that the manufactured device can achieve same specs than the prototype one can. [9, p. 199]

At the control phase there has been device roll out and it is actively marketed and sold. Aim for control is to handle the process as much as possible, while maintaining low as possible process variability. Tools that can be associated in this stage includes Process FMEA to find and repair process pitfalls, stress screenings, both environmental and accelerated and burn-in phase in production. Goal of the control phase is to keep small variance in manufacturing process. [9, s. 199-200]

In this appendix a presentation of DfR process with alongside traditional product development process is presented in figure 3.4.

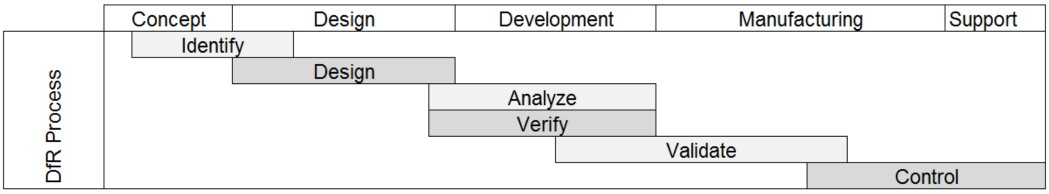


***Figure* 3.4** *Design for Reliability process alongside traditional product development process. Adapted from [11]*

As can be seen at the figure 3.4, DfR process follows quite well the traditional design process. Greatest differences are found at development phase, where analyze and verify phases is drawn to happen at the same time. This is derived from the iterative nature of development in DfR. Other point to be noted in this figure is that phases tend to start little earlier with DfR. This is caused by the proactive nature of the tool. It is easier to change something for the better if the challenges are handled before the design. At the figure 3.5 the tools presented earlier in this thesis are gathered under the DfR phases.

Identify	Design	Analyze	Verify	Validate	Control
•Benchmark •Environmental distribution •Mission Profile •Quality Function Deployment •Risk assessment •Critical to reliability •Voice of customer	•Computer Aided Design •Failure Mode, Effects and Criticality Analysis •Load Strength analysis •HAZOPS •Parts Materials Processes Review •Non Material failure modes •Critical items list •Load protection •Strength degradion •Design Review (based on failure modes) •Human reliability	•Physics of failure •FEA •Warranty data •Design Review continued. •Prediction of Reliability •Design of Experiments •Lessons learned •Derating analysis •Life Data analysis •Reliability block diagram •Reliability growth	•ALT •HALT •Life data analysis •Degradation analysis •Configuration control •Sub system level testing •Reliability growth modelling •Structured tools •Root cause analysis •Fault tree analysis •Ishigawa	•Design validation •Tests excecuted on prototype •Environmental •Durability •Capability •Functional •Process validation •Piloting	•Automated inspections •Control Charts •Audits •Human factor •Burn-in •Known issues analysis •Ess •Hass •PFMEA •Started earlier, continued. •Poka yoke •Testability analysis, •Test yield analysis, •Maintainability analysis

***Figure* 3.5** *Tools for each Design for Reliability process phase.*

As can be seen at 3.5, the amount of tools connected with DfR is huge and all of these are not presented in this thesis. As a whole, DfR is a collection of vast amount of tools and methods. The use of DfR aims to implement the reliability to the design, and decrease the excessive time used for reliability testing, and reliability development as a whole. This is done by doing right things at the right time, moving responsibility of the reliability to the design engineers and increasing the focus to communication and proper reliability support. This usually results at higher ownership of the reliability, increased motivation for reliability design and shorter design cycles. By reducing the design cycle time by using right tools and tests, the time to market of the design, be shorter, and more design flaws are noticed in earlier phase, making the product development process cheaper. [9, p. 201]

3.1 Failure Mode and Effects Analysis

Failure modes, effects and analysis is a big part of design for reliability, and one of the most used process in reliability design. FMEA is a reliability analysis tool that is used to assess the possible failure modes in a complex processes. The FMEA process was originally intentioned to production management, this process is known as PFMEA, but it has been adopted to product development. In a part of product development the FMEA is used for multiple purposes: system level FMEA, known as SFMEA and design level FMEA, known as DFMEA. SFMEA is used as a main document of the system level design, meaning that it concentrates on customer point of view. Furthermore this means, that the main focus is connectivity in surrounding world, and possible failures the connections and external influences can cause to the system. [12]

DFMEA can be seen as a supportive document for SFMEA. Process of FMEA does not change regarding of which FMEA is used (S/D/P) but the scope is changed. FMEA is a preventive process, which gives a corrective actions not only to already known failure modes, but also the unknown modes not yet experienced with earlier revisions of the devices. Some known of failure modes can be acquired from warranty data, known printed wiring board failure rates, inspection and repair data and customer service records. FMEA is takes into account two quite different views regarding the design: failure mode and failure effect. Failure mode in this sense is understood as a fault where design is not fulfilling a customer requirement whereas failure effect is concentrating to the designs failures and the causality to the designs fitness. To calculate the possible ranking of failure modes, a number to point the risk needs to be calculated. This number is called risk priority number (RPN) and it is made from 3 different parameters of the failure mode. These parameters are severity, occurrence and detection. There is multiple ranking methods for these three parameters but no doubt the most common is from 1 to 10. There is also one 5 stepped system from "low" to "high". Of course all different methods have pros and cons. [9]

In ideal case the FMEA process has a multi-discipline process group, with a wide knowledge of a designs properties. In electrical industry, some participants could be mechanical-, electronics-, power electronics- software- and reliability engineers, as well as sales personnel. Together this multi-functional team assess the functions, features and requirements of the design. These functions are the backbone for the FMEA process and it is a critical to recognize all functions, also those that are not officially said, but are expected nevertheless. Normal functions are quite easy to recognize, but the unexpected failures are the challenge. After what is known to be wanted from design the potential failure modes are thought through: how can the items from the first step not meet the desired function. There might be a multiple ways to item for the fail and the obvious ones are the one that the designers probably would notice by themselves. After successful analysis of failure modes the risk probability is analyzed. RPN is calculated to every single one of the items failure modes. Severity for simple means how challenging are the situations if the failure mode is realized. Highest number is usually reserved for fatal accidents. Also the potential effects of failure is written down in the documentation. In occurrence part the analysis is concentrated what are the possible causes of the failure modes, and how can a design allow this failure to happen in a first place. From this some kind of likelihood of occurrence can be valued numerically. Lastly the detection is analyzed. How are the failure modes and functions validated and tested? And in a broader scope, what are the process controls regarding this particular item and failure mode. This comes to numeric value for detection. Detection usually is understood as a probability of detecting either the cause for failure or the failure mode. This is a quite challenging to evaluate as the most hazardous failures detection is quite clear as there might be visible cues to failure, but the preventive detection would be much more important. At detection, also the ability to detect the failure before it even happens from degradation or similar observable effect. After numeric values are calculated, the RPN is easily calculated from them by using the formula 3.1. [3, s. 90-96]

$$RPN = f(S, O, D) = S * O * D \tag{3.1}$$

In formula 3.1 function inputs are Severity (S), Occurrence (O) and Detection (D). If FMEA process uses 1-10 ranking system, the maximum value for RPN is 1000, but for complex systems and designs there could be two or more modes with a same points. To further rank these the achieved RPNs, the severity score is most significant number, and the more severe mode should be addressed before the mode with lover severity. If also severities are the same, then occurrence is deciding value. [12, s. 1-14]

Motivation to use of FMEA is clear: early stage design risk assessment to improve device reliability and quality with a minimal rework. From time to time, this motivation is not clear to the designer, and FMEA process is not done properly, which leads to faulty and inaccurate data. With inaccurate or invalid data, the actions made from this document is not as accurate and vital as they should be thus making FMEA process less and less lucrative to use. Besides designer's motivation, the reluctance from upper management to use FMEA will cause the used resources for the process to be inadequate in terms of personnel or time. Even if both management and designer are doing their part of the process, there is still some danger for process to be unsuccessful. The failure modes mentioned before needs to be adequately analyzed, reasons and relations are important. Without an extensive and full list of functions and items on a design the analysis is not thorough enough. This again means that it does not answer to our needs why the FMEA is even used. RPN value and the analysis of the distribution of values in it is also critical. There is an easy 1-10 numerical ranking system is usually used because there is no good alternative. This is challenging as there is a part guessing without a literal explanation of the numerical value. Also the ten point system is quite broad, and for the sake of FMEA the amount of values could be decreased to somewhere from 4 to 6. Less is challenging as it does probably not depict well enough the severity, but more is challenging to detection and occurrence. The decrease of numerical values decreases the guesswork, as the alphabetical is easier to humans to comprehend and this leads to faster and more unanimous decisions. For FMEA point of view, the ranking still works, as the biggest RPN is analyzed first, whereas lowest can be done last, and the overlapping of these values is not a severe risk for FMEA process. [9, s. 180-191]

FMEA is a quite powerful tool for whole new product development organization, if applied properly. It is important, that especially the reliability engineer is at the level of the job. This method can easily turn the project from total failure to victory, by detecting the possible failure modes, and ranking them by effects. This is quite heavy tool, as the DFMEA needs to be done to every subsystem, and on top of that the SFMEA to handle the concept of the system. FMEA as presented has been implemented in new product development process, both DFMEA, and SFMEA. Because the FMEA was previously faultily used, the new way of working the FMEA causes some uncertainty and challenges. These challenges faced were quite popular pitfalls for FMEA. To increase the effectiveness of the FMEA, the core teams at the sessions needs to be more multidisciplinary. Also the changes on RPN values should be on special observation, as there have been few mistakes, that the severity of the design was changed due the design change. Of course if the failure mechanism stays the same, the severity of the failure stays same. Every problem with the FMEA can be handled by reliability engineer, if the engineer has enough resources to guide the participants.

By using the FMEA to control the risks either system has, or the design risks, more controlled approach can be achieved. When handling challenges logically from most critical to least critical, resources are allocated more efficiently, and design does concentrates on right things from the beginning. If the design risks are not considered, the failures on the systems can effect on warranty and even the reputation of the company. When ensuring the right risk control for the design, a proper methods for fixing the risks can be used saving resources and decreasing cost. Of course the more effective resource usage can be also seen at improved reliability and quality as well.

3.2 Mission Profile

When device is sold to a customer, the customer's use of the system is often unknown. This uncertainty of system requirements is somewhat challenging in a terms of reliability. Depending on a use and environmental stresses, the lifetime of product can vary. Higher stress environment and harsh use within the specified limits, wears the device more than nominal usage on temperate environment. The representation that has all the relevant conditions the device undergoes during the whole lifetime is called mission profile. If the designers understand the mission profile of a device they are designing, the reliability and quality can be more accurately assessed. [13]

At the beginning of a design process, the mission profile is vague. As the design process develops, also the mission profile can be updated to be more precise. As with other reliability measurements also the mission profile is more of a good guess than definite value of the use of the product. To more accurately estimate this mission profile, an information of use is needed from the actual users. This makes the challenge as the real usage and data gathering is challenging at least. Different users and use locations affect greatly on the mission profile. By understanding the use and environment of the product, design can be guided to increase the robustness of a handle the critical components that is seen to perform poorly on certain mission profiles. Mission profiles can also change depending on level of depth and the size of the system. Some parts, for example IGBT (Insulated Gate Bipolar Transistors) are quite temperature dependent due the high current throughput, whereas whole system is more affected by corrosion or high humidity. [14]

To implement the mission profile on reliability engineering, while not overextending the amount of different profile documents, a criticality of the components needs to be assessed. In example document, an IGBT is chosen to be a critical component, which it is in many power electronics system. A one parameter to affect greatly on lifetime of IGBT is a temperature, especially the junction temperature and the amplitude of a temperature. [15] Because real life applications either the amplitude of the temperature cycle or the junction temperature are not constant a Palmgren-Miner rule can be used. Palmgren-Miner rule states that the system can tolerate certain amount of damage before it breaks. [16] This damage can come from one source or from multiple sources, as long as the mechanism is similar. Mathematical representation is in equation 3.2:

$$\sum_{i=1}^{N} D_i = D \tag{3.2}$$

where D_i is the damage received from ith source. To develop the idea further to support the mission profile, this linear concept with fatigue can be presented with cycles with alternating stress. This means that the components are subjected to n_1 cycles for stress σ_1, n_2 cycles for stress σ_2,...,n_N cycles for stress σ_N. When the information is plotted to so called S-N curve, or stress-cycles of failure curve, the single time for failure can be calculated to all single stresses. This plotting is pictured in figure 3.6.

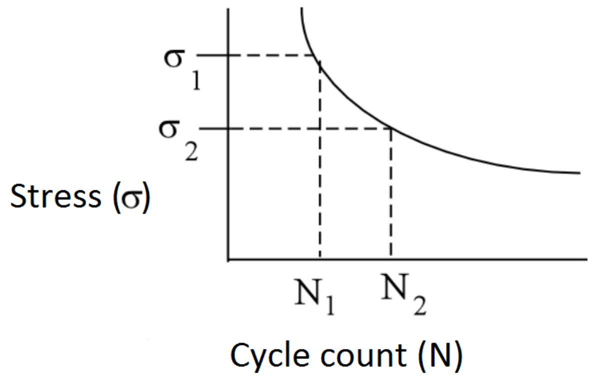


Figure 3.6 *S-N curve connects stress to number of cycles until failure. [16]*

To calculate when fatigue failure occurs, equation 3.2 can be rewritten as:

$$\sum_{i=1}^{N} \frac{n_i}{N} = 1 \tag{3.3}$$

This again means that by summing up the different stresses and weight their relative occurrence, the fatigue stress can be calculated. [16]

By understanding the mission profile, a lifetime calculations can be more accurate, all while the design of the product can be effectively take more interest in the use patterns and optimize the product better. By knowing the use profiles for products, the reliability testing and design can also concentrate better on the challenges the system faces in the field. Challenges are clear: the data gathered is not extensive enough and while company sells products all around the world, the nominal use can be challenging to acquire as it might change greatly depending on industry and location. This leaves a room for improvement. There has not been analyzing sensors at the system, or the data couldn't have been extracted. [13]

One great application for mission profile and Palmgren-Miner rule could be the counter for failure. By basing the information about failure in few key components, and their failure methods, the computers can estimate the time of failure in current usage. This increases customer satisfaction, as long as the algorithm is correct, when customers can see the status of the systems real time, when using the product.

Power electronics are sold worldwide, and into many different environmental uses, making the construction of mission profile a challenge. When developing the mission profile, an understanding of systems environment and use is vital, and because of that the profile that fits into every users needs is impossible to make. When constructing the profiles it is important to know the main areas that systems are sold to. This means that the system should aim to fulfill the environmental challenges on its main business areas. When the main business areas are known, the testing based on this profile is easier, and the focus is on right phenomena. In aeronautics, the focus should be at temperature changes, and cold temperatures, whereas on marine applications, the focus should be at high temperatures, humidity and saline. By knowing the focus of sales, the mission profile can be used to more precisely pinpoint the probable challenges, and when the challenges are known they can be controlled and fixed.

All and all, the understanding of a system's use and environmental challenges is a great way to improve effectiveness of the design process, and at the same time increasing the customer satisfaction. This can be either done with design phase by building the system to endure certain stresses, or at maintenance, to give proactive data to control the system's life.

3.3 Data Gathering

To analyze and develop the system, a data from different sources needs to be gathered and analyzed. In this chapter, some of the used data gathering and analyzing methods are presented. At DfR the data gathering starts right at the beginning, FMEA gathers possible failures from multidisciplinary team. And the data gathering continue throughout the process, all the way to the warranty claims and field data gathering, continuously increasing the understanding in the developed product and its reliability. All of the mentioned analysis and gathering techniques are not valid to every field and device, but the analysis on analyzing methods is needed when deciding the best practices for certain manufacturers and companies.

3.3.1 Warranty Data

Warranty data is the first source of the actual data during the new product development process. Because of that, warranty data, or field data can be used in reliability calculations because it uses all the environmental stresses simultaneously. Warranty claim data can be used to find failure causes and forecast the future failures. Of course there is limitations of the usage of data and confidence in this kind of data. These limitations needs to be understood before acting from the data analysis.

To further discuss about the warranty data, engineer needs to understand that the data is usually quite unstructured. The failure modes in warranty data varies greatly depending from industry and devices. Some of the failures might never been able to reproduce. It is important to be able to remove this noise, as it is basically faulty data, and can lead the analysis to the wrong direction. Relevancy of the data is up for the user to decide, but depending on industry, manufacturer or even types of products, the data might change greatly. When going through the warranty data, it is important to remember that every failure reported, customer has been unsatisfied, in one way or the other. At figure 3.7 is presented root causes of the warranty claims, in a general way, not binding the data in any specific industry.

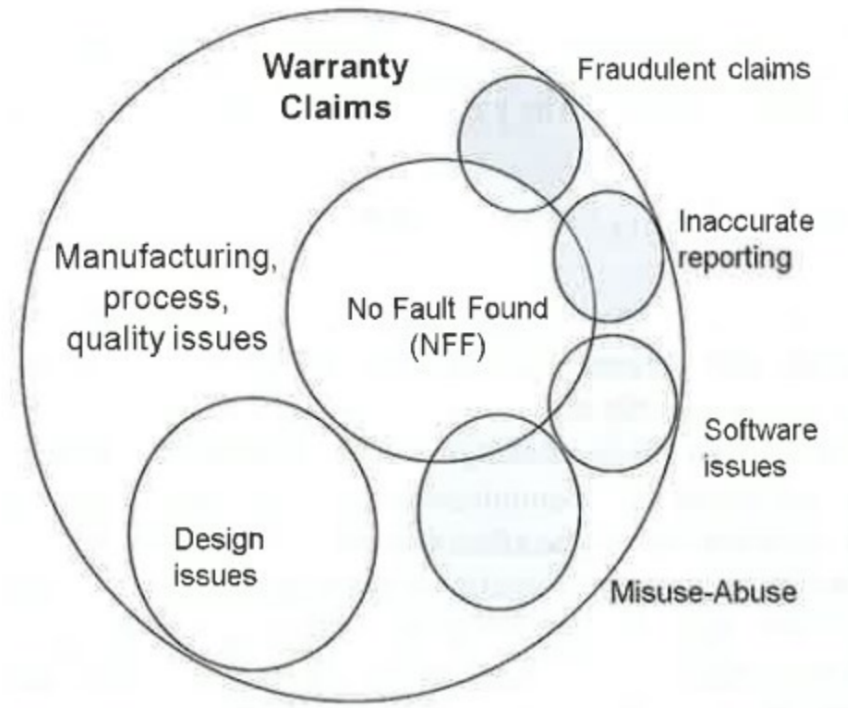


Figure 3.7 *Root causes for warranty claims. [17]*

Challenges in warranty data usage is that the devices are sold, bought and claimed at constant rates. The warranty data increases as a function of time. This also means that the warranty periods are not fixed to the calendar year, but more likely as the product age is used. For product age, usually the start of warranty period start, when device is delivered, but for some cases, the device cannot be used straight away, and it is stored, or sold again. To warranty data, this formulates a challenge, as the product age is calculated from the delivery moment, but the time the device was used is much shorter time. Also vital information about the wear out failures is left outside warranty data, as the wear out period usually begins sometime after warranty ends. The acquired data also fails to take into calculations those failures that are not reported to the manufacturer. There is some uncertainties at the data gathering, but when digitalization progresses, more and more data could be gathered for warranty analysis. For the calculations from warranty data speaks the natural use of device, and non-accelerating environment. [9, s. 348-355]

3.3.2 Testing

Reliability testing of devices is a wide area, and the amount of possible tests vary from very simple to highly complex tests. Many different mechanisms for failures, and slight change in testing environment or stresses might push the system over the strength limit. When choosing the right test for right system, the first thing to do is to define the reason for the test. Why testing is done, and what is the wanted data output from test. Is test for weakness in device, does test results need to be comparable with other tests, or is the goal for the test loads of data to calculate life time estimations.

Reliability tests are like any other tests and can be divided by their nature in two distinct test types: qualitative and quantitative tests. Qualitative tests aim for deeper understanding of a system. Data gathered is abstract and the test subjects can be specifically made for the testing purposes, as qualitative test tries to validate and to reveal weakest points, from a relatively small sample size. Quantitative tests on the other hand represents tests that have larger sample size, and the tested devices are not generally made for the test. This means that the tested samples are usually part of a bigger lot, or random samples from produced device. Data gathered from quantitative tests are used for example to calculate lifetime, and reliability of a system. The important difference on these tests are that qualitative tests try to improve of the system where as quantitative tries to gather information from it. [18]

Even though there is lots of reliability test used in an industry, there is some common practices for tests. What goes in reliability, the developers are usually interested in faults happening in later in device's lifetime. Acceleration of aging is used with almost every test, with an exception of very safety critical applications, where the uncertainty of acceleration cannot be accepted. For industries that produce consumer goods, the acceleration of aging is a good tool for product development process, as it decreases the total time of reliability testing which again gives faster time to market, and lower product development costs. Time to market is more critical in a fast developing industries like electronics, and transportation industries than more slowly developing manufacturing productions like building technology or agricultural work. Few examples of reliability tests are HALT and ALT-testing. [19, s. 123-136]

HALT stands for highly accelerated life test, and the primary reason for doing HALT type of testing is to reveal weakest points on design. This makes HALT mainly a qualitative test, as the main purpose of the testing is to achieve the deeper understanding of a device under test. This test is used in a design phase of the product development process, as it reveals faults on design, it is not used for verification purposes. HALT is accelerated test, this means that when using HALT, there is some accelerator involved. Usually this accelerator is high temperature as it adds energy to the system and this way causes more stress. There is also possibility to use variable temperature. This cyclic test causes more stress to the tested device, as cyclic temperature brings not only the high temperature, but also the gradient of the temperature. HALT is used to find faults in design, and idea to use HALT is to bring out the weakest components and designs. The faults can be for example failures in ball bearings in late life, or critical changes in viscosity of a compound. The test is used usually with as high level of complexity of the system as possible, as it is relatively fast test when applied correctly. When defect is detected in design the defect should be analyzed for criticality and after the analysis designer might need to work on a solution. In test, the fault is somehow bypassed and test is continued. For weakest part type of testing there is no need for high amount of test subjects, as the testing grows fast in size and in time. [20] [21]

ALT is an accelerated life test and it is usually done with a longer periods than HALT as it does not accelerate as much. Alt is used mostly to gather a big amount of data on more devices, as the amount of reliable data is vital in calculating a system's or subsystem's life expectancy. ALT is usually accelerated with a temperature cycle or static temperature as it is easier to calculate lifetime for real component, when the amount of different accelerators are smaller. ALT brings out a variety of faults that are more probable to occur in a lifetime of a device, than the faults found with more accelerated HALT. As a quantitative test method, ALT is used to achieve failures in device. This data is again used to calculate the possible life expectancy. As with ALT the uncertainty of the fault mechanism is smaller than with the HALT, as the stress levels are much smaller in ALT. [22]

To support a reliability growth in design, a very common test in a high reliability system is used. The idea of burn in is to artificially age the system, so that the early failures can be caught before the system is installed into a customer's system. The burn in is not as straight forward as it seems, as all products does not need to be pre-aged before use. Not all systems suffer from early failures as much as some others do. This is why it is important to understand the system as a whole. When burn in does not reveal any or very few failed systems, it might decrease the maximum reliability of the system - a very parameter that it should be increase. Objective of the burn in is to minimize the failure rate and maximize the system lifetime, after the delivery to the customer. This is done by removing as much as possible of the freak population of various reasons, while keeping the test time as short as possible. There is a mathematical equation that calculates the positive and negative effects of burn in, and gives a value for how long it is valid to burn in a single product so that the test brings value to the company. To justify the use of burn in testing in manufacturing, a large population of systems needs to be analyzed, and if the analysis reveals majority of early failures, the system should be ran through burn in before sending it to the customer. This analysis is highly dependable of multiple different parameters, such as company policy and quality goal of the products. The most important point against burn in testing is the cost. Testing and the equipment needed for this kind of large scale testing costs money and it should be carefully analyzed if the positive impact of burn in exceeds the negative ones. Other reasons include lead time and the quality/reliability goal for the product. The negative side-effect is also that the testing reduces the lifetime of a healthy population. [1]

By utilizing testing at the right time, and by using right tests, the results are delivered at the right time in a design process. Often the standard design process designs the system, and after the system has few prototypes the planning of the tests start. By using HALT, a systems weaknesses can be revealed and fixed quite fast. Reliability tests should not be overlooked in any case, even they tend to last longer than functional tests.

3.3.3 Reliability Predictions Based on Standards

Based on published reliability data of the components, failure rate of the systems can be calculated to some extent, as there is many challenges to tackle when calculating reliability data from multiple data sources. Standards prediction is used most efficiently during the planning and proposal phase of the project. Some of the most used standards are MIL-HDBK-217-F, IEC-62380 and Telcordia SR-332.

MIL-HDBK-217

MIL-HDBK-217-F is the revised version of the reliability statistic and failure rate data for electronic components. It is a collection of electrical failure rates by the United States military. It presents two different ways for reliability calculations: part count and part stress, where part count method is an earlier stage method where stress for part is assumed to be somewhat average. [23]

$$\lambda = \sum_{i=1}^{n} N_i \pi_{Qi} \lambda_{bi} \quad (3.4)$$

where n is the number of part categories, N is the quantity of ith part π_{Qi} is quality of ith part and λ_{bi} is base failure rate of ith part. As can be seen, the part count model does not take into account environmental or temperature stress in the design and because of this it is not applicable to a late design phases, as the model does not take enough parameters into account. To use MIL-HDBK standard later in design process, a parts stress based mathematical model is used. It uses the 3.4 as a base, but further develops the λ_{bi} as shown in 3.5.

$$\lambda_b i = \pi_Q \pi_E \pi_t \pi_L [C_1 \pi_T] \quad (3.5)$$

Where $\pi_Q \pi_E \pi_t \pi_L$ are factors for quality, environment, temperature and learning respectively, C_1 is a complexity factor. Also various other factors is used in specific applications, such as a packaging factor is used with integrated circuits and cycle count with memory circuitry. [23]

Some controversy has been laid against MIL-HDBK-217 for it has not been updated since 1994, and contains an outdated information, also some of the technologies have progressed so that the standard does not represent the technology good enough anymore. Other controversial things are that the standard does not calculate the all the factors affecting reliability, including EMI and transient overstress to name a few. Also some of the parameters are not backed by the experience from modern devices. [23]

217Plus and PRISM

To develop the outdated MIL-HDBK-217, The Reliability Information Analysis Center (RIAC) have made upgrades to the old standard. This is seen as important, because MIL-HDBK-217 is not actively developed, and lacks on modern component values as well as it produces quite pessimistic results. MIL-standard produces pessimistic results, because the failures are modeled so that component is affected with different π values, and these factors multiply. It is observed that all different environmental values does not affect to all failure mechanisms, and this is why the MIL-standard gives somewhat pessimistic results. RIAC argues in their standard, that over 78% of all failures are caused something else than component based, resulting to the need for more specific reliability calculation model. [24] While MIL-HDBK uses a multiplicative modeling on component, the PRISM uses more refined model, which combines the multiplicative and additive methods for π factors. Failure rate model for PRISM-model is presented in equation 3.6.

$$\lambda = \sum_{i=1}^{n} N_i \sum_{j=1}^{m} \pi_{ij} \lambda_{ij} \tag{3.6}$$

where n is the number of part categories, N_i is the quantity of the ith part, m is the number of failure mechanisms in ith category, π_{ij} is the π factor for the ith part category and jth failure mechanism and λ_{ij} is the failure rate for the ith part category and jth failure mechanism. [9]

PRISM also adds a possibility of adding non-component variables, such as software failures. The RIAC calculations tool also can calculate predecessor system values and component level test data to more precisely calculate reliability data. Further development is made from PRISM in form of 217Plus, which has same mathematical approach, but the part type failure rates are increased with connectors and optoelectronic devises. [9] [24]

Telcordia SR-332

Telcordia's standard is based on Bellcore standard TR-332, which in turn was based on MIL-HDBK-217. Telcordia is modified from military standard to more usable in small electronics, commercial applications and telecommunications industry, this is done by adding a field experience from telecommunications to the standard. [9, p. 138] Telcordia standard takes into account following factors, when calculating failure rates: operating temperature, electrical stress, quality and environmental conditions. [25]

For reliability calculations, Telcordia offers three different methods, where Method I is similar to the MIL-HDBK-217 part count method, where is assumed that the failure rate of the device can be derived straight from a failure rates of the components consisting in the device. Method II takes into account a possible laboratory data for life time test. This data includes sample size, generic FIT (failure in time), test time and quality factor of test device. Also in the Method II can implement burn in procedure in calculations. Lastly the method III includes the field data for more accurate estimation. SR-332 concentrates more to the early life of the systems, and applies so called first year multiplier -factor, that accounts to the early failures of the system in a failure rate predictions. Not only that but the standard also credits the burn-in testing by reducing the first year multiplier, when system has undergo the burn in. [25]

Using the Standards Based Calculations

By using standards based reliability and life time calculations, the life can be calculated in some extent. With products on power electronics, many standards fail to rise the challenge in power electronics' parameters, as the standards are relatively slowly updating [23] and power electronics, especially IGBT (insulated gate bipolar transistor) modules has been around from early 1980. This means that the information from the older standards is irrelevant.

At early product development process, the standard, with what the calculations are done, does not matter as much as in further in process. At early process, the calculation includes so much estimation, changes and uncertainty, that error is not primarily caused from the standards. When comparing the standard's databases for components, the MIL-HDBK-217 clearly lacks some of the component categories that are present in other, standards derived from it. Siemens SN29500 and Telcordia SR-332 seems to have wider database of electronics with low power consumption, whilst PRISM and 217Plus seems to support more high power components than the first two standards. [23] [24] [25] [26]

At later in the product development the accuracy of the product design rises, as well as current, voltage and other stress ratings. This causes the error for estimation and uncertainty to lower, and the wanted accuracy of failure rates to rise. It is important that all the data can be implemented in this kind of calculations, and the clear need for this has been seen with all presented standards, except the MIL-HDBK-217 and Siemens, in some extent due the fact that many of the components are based on field data and not the estimation of the manufacturers. In 217plus the predecessor system, Bill of materials and either field data or test data can be used as a part of failure rate of the system. Telcordia uses only the part count in Method I, or part count and either the test data or field data in methods II and III. While the support reliability calculations give during the process, the standard used should be constant to ensure confidence in the data. Manninen [17] also argues that, the outcome of the reliability calculation changes visibly when using different reliability standard. Thesis claims also that both 217Plus and Telcordia resulted a metrics quite in line with the warranty data acquired from the systems, even though there was some controversy in the calculation methods of the warranty data and its validity.

3.4 Data Analysis

One of the ideas of reliability engineering is to make educated guesses to the future, by using early data of a system. This means that confidence based on our data and testing is important for a future calculations. Challenges of early calculations are that all the information needed for modeling the reliability is not present at the time. [9, p. 177] Because of this, reliability engineering relies a lot to statistics, probabilities and known models for system failures. [27, s. 7-10]

After testing the device, the data acquired from the test should be analyzed, and censored properly, to make proper outcome possible. Next step after gathering the data is the validation: is the data from right system, and is it possible to be valid.

To gather valid data, the tests and warranty data should be about the defect at hand. Of course there is not only one failure-type and sorting these failures is an important task in a sense of data validation. Too small sample size or too big simplification might also possess threat to data analysis. Censoring is a good tool to rule out either wrong mechanisms or to censor failure free components to reliability calculations. [27]

To handle the valid and censored data, the data is analyzed and fitted to probabilistic distribution. Because of the large amount of distributions, the fitting can be a tedious job. Luckily, most electronic failure mechanisms are possible to fit into either two parameter Weibull- or one parameter exponential distribution. Both of these represent continuous distributions, even though acquired data is usually discrete. This is for the reason, that when data points are very small relatively to the whole time, discrete data points can be approximated as continuous. These distributions are discussed on more detail later in this thesis. [27]

For reliability calculations and data usage, there are multiple challenges, with a different parts of the data analysis process. Firstly, gathering the right and accurate data affects greatly on results. This data gathering can be done either during product development process, derived the known technology's previously gathered data, or gather data from the manufactured devices, and actively improve the reliability of an active devices on sale. Of course, the most reliable data could be gathered at testing facilities, because most of the stresses of the system is known. For warranty data, the environmental effects could easily been overlooked, if system does not have an accurate sensors which monitor the local environment. For faster product development, the reliability needs to be taken into account before warranty data arrives from customers. Even though the warranty data is usually good meter for achieved reliability, for system improvement it is achieved too late. [17] [2, p. 205] To derive reliability data from older systems, and reusing the validated subsystems is a good practice, and decreases the time and money for data gathering of the system. In this method it is to be remembered that the communication of the subsystems needs also to be tested for reliability, and intersystem communication should not be overlooked. [2, s. 62,63]

When data has been gathered, the raw data should be analyzed. Before a very deep analysis, some work is needed to be done to the data. Censoring is used in both warranty and testing data. Depending on a sensors and timers at the system, warranty data could provide either with an accurate data of the system use, or the data could be only when the failure was noticed by the user. Of course, smaller amount of the acquired data, less data to analyze. For test data it is much easier to provide exact data on failures as at the testing environment can be constantly monitored. Depending on the problem at hand, censoring of some kind is needed to reduce the unwanted and wrong data from the gathered data group. This censoring can be of left-, right-, random, and interval censoring. Censoring the data is a powerful tool in life estimation, especially with accelerated life testing (ALT), where tests can take a while to finish. With censoring, an early failures of the system, wrong failure mode can be disregarded and test time can be decreased. [27, s. 211-215]

Right censoring is used when the amount of data desired is gathered, or when the test or system has achieved a usage set beforehand. There is two subcategories in right censoring, called type I and type II censoring. In type I censoring the experiment is stopped at predetermined time, and all the failures that happens after this time is censored, as we know that data is above this time value, but it is unknown how much. Type II censoring on the contrary is for the amount of failures in test, where time of test is unknown in beforehand. For right censoring, the event that creates the data point does not happen for some reason. Left censoring is used when the interest is clearly at the later in devices life. One example of left censoring in testing is burn-in tests, where test subjects are exposed to aging before the aging test. This means that data could be gathered before the set censor limit, but only the failures after this limit is gathered and analyzed. In interval censoring, the data is between known boundaries, and these intervals can be multiple in one test. The interval censoring is used with a discrete data of critical measurements: the exact time for failure is not known, but failure is known to happen in between two known times. When sample size is significant, the continuous tracking is not always possible. This results in interval censoring. In this type of censoring, the unknown value is known to be between some two different values. In reliability calculation's point of view, interval censoring is more significant when the interval is relatively large when compared on the whole test time. Lastly there is random censoring, also known as non-informative censoring is statistically independent of failure time. Good example of random censoring is a test for specific failure mechanism, and critical failure happens without the observed failure mechanism, this data point needs to be randomly censored. [27, s. 211-215]

Reliability data can be faulty for a few different ways. According to ISO 5725 [28] the general term that is describing data value to its true value is called accuracy. Accuracy is again divided to trueness and precision. Precision is a parameter which tells how repeatable and how reproducible the measurements are. Whereas trueness is a more systematic failure caused by fault in measurement system, or in a testing method. The precision is a parameter how much there is variance in a consecutive measurements. This means that the measurements can be either true or precise, neither or both. [28] Visual presentation of trueness and precision is in figure 3.8.

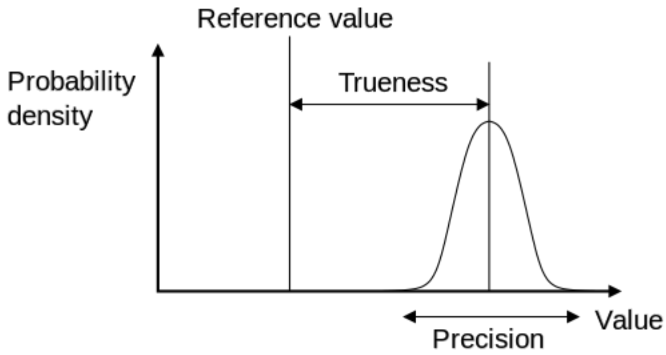


Figure 3.8 *Trueness and precision with probability density. [29]*

Example of low trueness in a reliability engineering is a test that makes an unnatural failure mechanism occur during testing. Usually this is done by applying too high stress that is not occurring naturally to the system. High temperature, or condensed liquids are examples of these kind of possible non-occurring environmental stresses. Example of low precision is test that has multiple different failure mechanisms working during testing. Usually this is caused by either poor design on system, or poor design on testing, as poor system tends to break down with different mechanisms, where as poor test might add too many of different kinds of stresses on the system. Increasing accuracy can be achieved in multiple ways: censoring, planning tests and maturing design before testing. Also burn-in type testing before the real reliability test can be of help. [28]

Confidence is a value that tells how valid the data is. Reliability engineering aims for an improvement of product reliability and exact knowledge of that reliability in certain system. Often with data analysis, a few challenges arises. There might be too much data to analyze everything or the data will not be present when the reliability data is required. Confidence bounds can be told as one sided bounds or two sided bounds. [30] These bounds are presented in a figure 3.9.

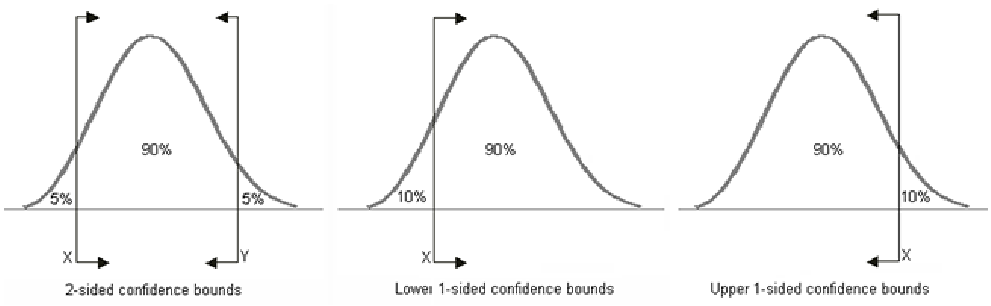


Figure 3.9 *Different types of confidence bounds. [31]*

All different bounds presented in 3.9 has their individual usage in reliability engineering. Two sided confidence is used as a parameters to tell, in which confidence the manufacturer promises for the parameters to be in certain tolerance. In short two sided confidence bounds are promise of certain tolerances. Lower side confidence bounds in middle of figure 3.9 is used with survival. Usually with survival, the confidence is given to certain time, or in special cases in other measured aging methods. [30] For example, to a system, a lower confidence limit of 0.90 at $t = 20\ 000h$ which states that after 20 000h only 10% of population has broken. Upper side confidence bounds can again be used with parameters of events, like that there is a 0.9 confidence at certain current that the fuse will burn.

3.4.1 Distributions

In life data analysis, reliability engineer tries to predict the reliability and life of all similar products by small sample size. Important part of that process is selecting a lifetime distribution which will fit in a lifetime of a product. There are many distributions, but some does not generally predict life distribution as well as others. Some distributions does predict, and those are commonly used for life estimation of a system, examples of these are Weibull distribution and not so used, but an interesting model of exponential distribution. To ensure good distribution choice a past experiences and a goodness of fit -testing is used.

Weibull distribution is a 3-parameter distribution, and it is one of the most used distributions in reliability due to its flexibility and the fact that many failure mechanisms present in modern electronics are Weibull distributed. Weibull distribution is most commonly presented in a equation 3.7: [18]

$$f(T) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \tag{3.7}$$

Where:

$$f(T) \geq 0, T \geq 0 \text{ or } T \geq \gamma \text{ if } \gamma \leq 0, \beta, \eta \geq 0, -\infty \leq \gamma \leq \infty$$

In equation 3.7, β is known as shape parameter, η as scale parameter and γ as location parameter. Usually Weibull distribution is reduced to 2-parameter model by setting $\gamma = 0$ because the aging usually starts at $T = 0$, in all but very few exceptional cases. β, or shape parameter is presenting a shape of a distribution. When $\beta \leq 0$ the shape of a probability density function reminds more of an exponential distribution, and when the shape parameter grows, starts the distribution remind more of a normal distribution. This difference is seen in a figure 3.10.

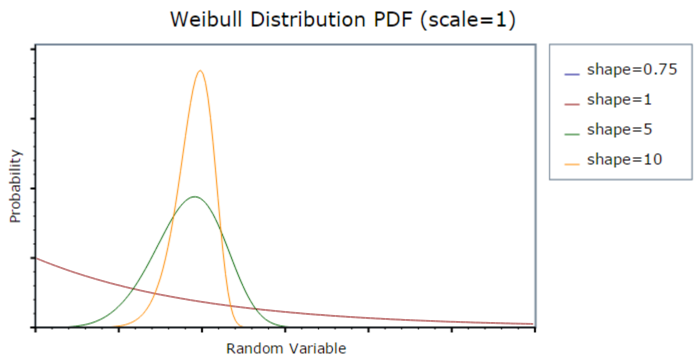


Figure 3.10 *Change made by shape parameter [32]*

The η, or scale parameter stretches the probability distribution function. Because of the integral of probability density function is always 1 in a reliability calculations, this means also that the peak will decrease. The changes of scale parameter is drawn in a figure 3.11.

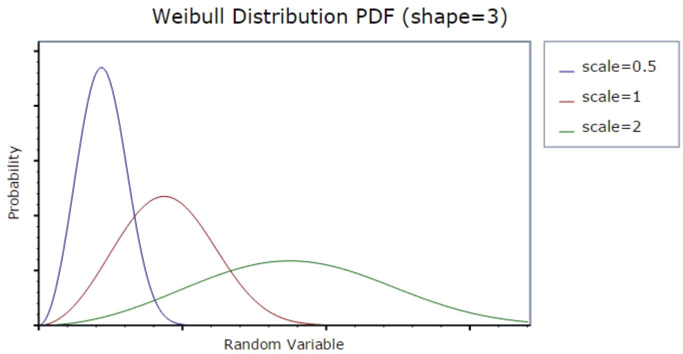


Figure 3.11 *Change made by scale parameter [32]*

Because of the flexibility of a Weibull distribution, it can model not only decreasing and increasing failure rate but constant failure rate as well. This again means that with proper distribution of failures, the Weibull distribution is able to model whole life cycle of system. That is one reason it is used as much. [27, s. 104-107] [1, s. 420-421]

Exponential distribution is a worth knowing as it is used to model behavior with a constant failure rate. Because of the simple mathematical basis of exponential distribution, it can be easily misused. The 1-parameter exponential distribution probability density function is: [18]

$$f(T) = \lambda e^{-\lambda t} \tag{3.8}$$

where:

$$t \geq 0 \text{ and } \lambda > 0.$$

In equation 3.8 λ is constant failure rate, measured in per unit and t is operating time in a same unit as λ. Different failure rates produce different probability density distributions and some are presented in figure 3.12.

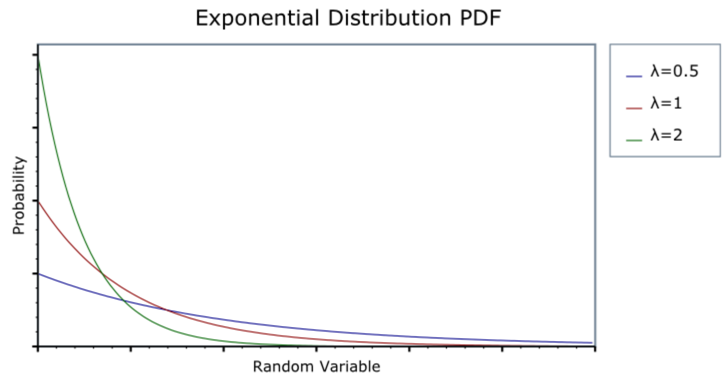


Figure 3.12 *Change made by failure rate [32]*

Because of the constant failure rate of distribution, exponential distribution if an ideal in modeling a devices' failures in useful life, as these tends to be of a constant in nature. When using this distribution, it is important to understand that the events that are observed needs to be independent from each other, and there should not be possibility that these events happen at same time. [1, s.419-420]

3.4.2 Load-Strength Analysis

Load-Strength analysis, or stress strength analysis is a tool for assessing strength of materials and the interference between the materials and the system. In load strength analysis, the load and strength are understood as with their widest possible senses. Load can be anything that affects the system: voltage, centrifugal force or temperature, for example. Also strength can be understood at the same premises, as the analysis pairs the designated load to the equivalent strength. Usually strength is some resisting physical property, like hardness or adhesion. This relation is also known as stress-strength analysis. Traditional design follows the principle that the minimum strength of the system needs to be higher than the maximum load it endures, to stay away from the failures. Also some other reliability design rules, for example derating can be used to further increase the gap between load and strength. [9, s. 120-130] [2, s. 181-183]

Usually the load and strength of products are not fixed values, but are distributed statistically. Goal of a good design is that there is ample of space or margin, between load and strength. These distributions are presented in 2.3. If the two distributions overlap, like in figure the failure occurs. Usually, when following good design practices, this means that the weak device is subjected to the very high loads. Area where these two distributions overlap is often called load-strength interface. With the known distributions for both load and strength with mean and standard deviations, the reliability to the product with the current load can be calculated. Challenge of the calculation is that the load and strength are rarely easy to use, as the properties are not often possible to measure reliably, or are not practical to measure. It is also to be noted that the degradation of strength usually happens when device is used, and that causes the strength distribution to move towards the load distribution. If this movement is recognized in design phase the designer should take this into account, and increase strength of the device, so much that the degradation does not connect load and strength distributions. [9, s. 120-130]

To increase the safety margin, or the separation of the two distributions, a design can utilize the burn in testing. It will find at least some of the weakest device, the devices at the low end of the strength distribution. This skews the distribution, but increases the median life of the population. [9, s. 120-130]

Of course the use of the burn in will decrease also the life of the good population that undergoes the test. More of the burn in is talked later in the thesis. Effect of the burn in is depicted in figure 3.13 where the effect of burn-in is pictured. Burn in has also other effect, as this type of testing ages the system and causing strength degradation. [9, s. 120-130]

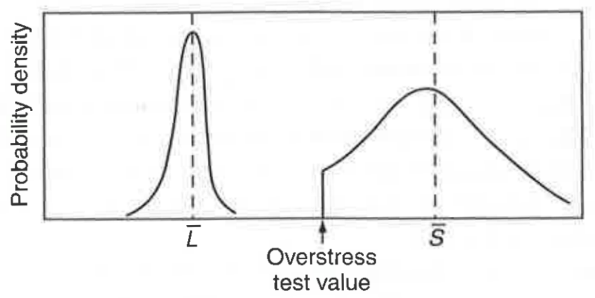


Figure 3.13 *Weak population has been removed by burn-in. [9]*

There is some applications, where load strength analysis can be used, but when many different environmental stresses effects to the single component, the load strength analysis is slow and complicated to use. This analysis can be most effectively used to the single failure mechanisms, where the mechanisms is known, and well documented. Examples can be of material strengths under constant load, and temperature dissipation from device's casing. [9, s. 120-130]

3.4.3 Degradation Analysis

Degradation analysis comes into use when the total failure in system is not wanted, or the failure mechanism is such that it supports the degradation analysis rather than instant failure. Other major positive fact is that degradation analysis and testing takes less time than either test to failure or test to success, as the physical changes are observed during degradation testing. Examples of these mechanism are corrosion and loss of conductivity, which develop with time. With the test data, extrapolation of the data is done by using mathematical models, usually linear, exponential and power models. [33]

To effectively use degradation analysis, degradation testing must be done, as this kind of testing are somewhat different from accelerated testing. Similarities to accelerated testing are vast: test parameters need to be connected to measured system parameters, and causality needs to be clear as the poor quality is not valid reason for subject to degrade in degradation analysis. With the test ongoing, the parameters are measured in fixed intervals. These measurements are plotted, and when enough measurements, data will be extrapolated to a certain time. Usually this means the reliability goal. With extrapolated data, normal reliability analysis methods can be used to get the probable lifetime of the system or the reliability on certain moment. [33]

The testing and analysis has some pitfalls that needs to be addressed, especially if comparing to the accelerated testing. Firstly the system parameter needs to be paired well with the environmental stress, to produce most highly confidential results. Secondly the trend from measurements needs to be logical and support the extrapolation. Lastly, with extrapolation is important not to stretch the data for too long, as it increases the inaccuracy of the measurement. [33]

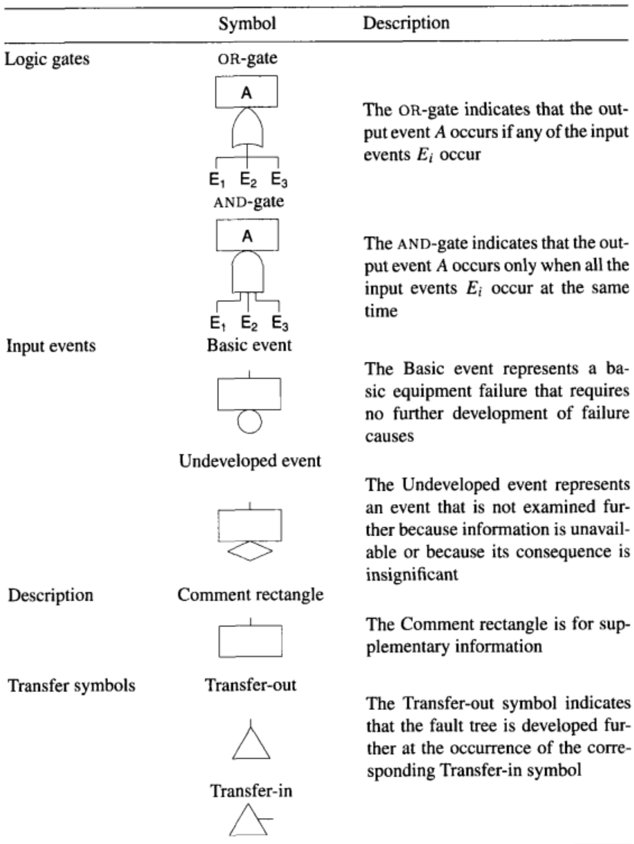
Degradation testing and analysis is a good tool for fast analysis of single failure mechanism. Extrapolation and test uncertainty decreases the confidence, but the speed from test start to results are much faster than HALT. Also the subject measurement cannot use destructive methods to analyze the sample, which is a major limitation for the various failure mechanisms. On the positive side of degradation analysis and testing is that the failure mechanism is much more like the physics of failure, than the accelerated testing results, increasing the confidence. Because the degradation is not concerned about the failures itself, but more of the change that the test subject endures during the testing, the degradation analysis might prove usable on highly censored tests, where many subjects does not break at all. [33]

3.5 Fault Tree Analysis

Fault tree analysis is used for non-conformities in system, but also predicting what are the consequences of design failure. It was first developed by Bell Telephone Laboratories at 1962, and further improved by The Boeing Company. Boeing developed the technique further and also developed computer programs that can be used in both qualitative and quantitative fault tree analysis. Fault tree analysis is now one of the most used reliability and quality technique, particularly in safety systems. In simple terms, fault tree analysis is a logic diagram that visually connects the critical events of the system to the causes that might cause this effect. [2, s. 118-126]

Outcome of the fault tree analysis can be qualitative, quantitative or even both. The quantitative tree resembles in analysis part quite well the similarly built system block model, so the quantitative analysis is not covered in this thesis. Steps necessary to construct the fault tree is the same regardless the analysis method. Results can be a list of all the causes possible for the specified critical event, or the possibility of that critical event to happen. [2, s. 118-126]

Fault tree analysis is a binary analysis, where the event either happens or does not happen. In the analysis time is not considered, but the connections between event and causes. The analysis is also deductive, where the analysis starts from the event, called top event and layer by layer back traces the possible root causes of the event. There might be only one event leading to the top event or there might be additive effects of multiple causes. The analysis goes as long as the analyzer is satisfied in a level on detail in cause. The lowest level causes are called basic event of the fault tree. Graphical representation of the most used static gates is presented in a figure 3.14.



	Symbol	Description
Logic gates	OR-gate	The OR-gate indicates that the output event *A* occurs if any of the input events E_i occur
	AND-gate	The AND-gate indicates that the output event *A* occurs only when all the input events E_i occur at the same time
Input events	Basic event	The Basic event represents a basic equipment failure that requires no further development of failure causes
	Undeveloped event	The Undeveloped event represents an event that is not examined further because information is unavailable or because its consequence is insignificant
Description	Comment rectangle	The Comment rectangle is for supplementary information
Transfer symbols	Transfer-out	The Transfer-out symbol indicates that the fault tree is developed further at the occurrence of the corresponding Transfer-in symbol
	Transfer-in	

Figure *3.14 Gates of Fault Tree Analysis [3]*

First step of fault tree analysis is definition of the problem and setting the boundary conditions. First step can naturally be divided into two clear substeps: definition of the critical event and definition of the boundary conditions. Top event needs to be clear and well defined event for maximal value in analysis. The definition should cover at least time, location and the event type. For example a failure in IGBT-module (answering what) in phase W, upper transistor(answering where) when after 2 years of use(answering when). To clarify the scope of the analysis the boundary conditions needs to be defined. Physical boundaries, initial conditions, external stresses and level of resolution all belong to the boundary conditions in terms of failure tree analysis. Physical boundaries sets the line between what belongs to the system, and what is left out. Initial conditions means those conditions that the system is at the beginning of the analysis: options, problems and capacity all fall in this category. External stress means the stresses from outside the system, lightning, floods, human actions. Lastly the level of resolution means that level of depth the analysis goes, by setting this boundary too low, the analysis might not reveal enough in depth to really address the problem, and by going into too much detail, the analysis goes fast into too great. [2, s. 118-126]

Second step is a construction of the fault tree. The building starts always on the top event, on the top event, clearly described in first step. Idea is to list all causes connected to the event, and describing them as one would describe top event. All the causes should then be divided in and listing all the reasons for the top event to occur. After recognizing the causes for top event, an event, whether it is a top event or undeveloped event element, causes should always carefully analyzed to reveal, if the causes are the right resolution level, the event is determined as primary failure. If the cause is too vague, it is set to be as secondary failure, and in need of further evaluation. Lastly the gates are designated depending on the relation needed between causes, by using logical components presented in 3.14. This step is repeated until all secondary failures are evaluated to the point that the causes are all primary failures. Example of the finalized fault tree before the analysis is presented in a figure 3.15

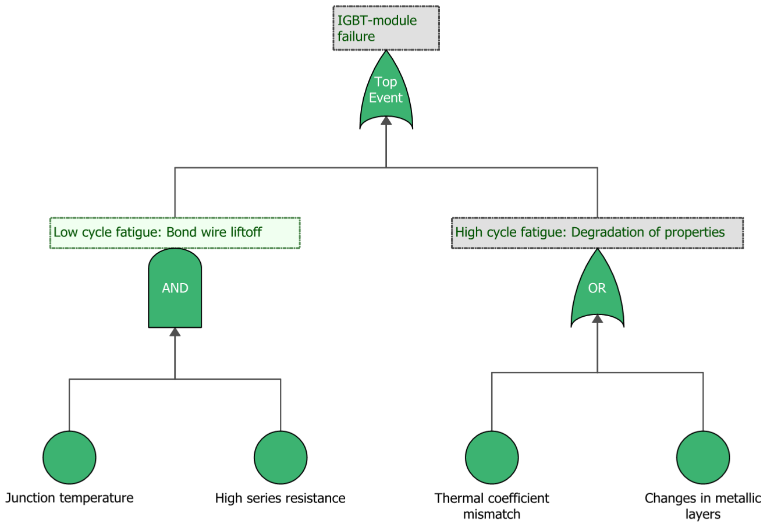


Figure 3.15 *Example fault tree.*

As can be seen in figure 3.15 all the failures are marked as primary failures with no undeveloped elements. It also shows that even though the reasons for missing signal can be traced further than this fault tree shows, the causes are within the scope of the system. [2, s. 118-126]

Third step identifies the minimal cut and path sets. This means that by analyzing the fault tree model, a valuable information of the failure combinations can be achieved. The cut set in fault tree is defined in [3] as follows: Definition 3.1 a cut set in fault tree is a set of basic events whose occurrence (at the same time) ensures that the TOP event occurs. A cut set is said to be minimal if the set cannot be reduced without losing its status as a cut set. [2, s. 118-126]

The order of the minimal cut set is calculated with a lowest number of basic events needed to TOP event to happen. For relatively small and simple trees the minimal cut set analysis can be done without algorithms, but analysis for more complex systems often needs an efficient algorithm. [2, s. 118-126]

Last step is a qualitative analysis is based on the criticality of the failures. Criticality is defined through the minimal cut sets, and is dependent on a number of basic events in the cut set. The number of basic events, or the order of the cut set defines the cut set importance, as the cut set of order 1 is often more critical to the event than cut set of order 2. Order 1 cut set means that as soon as the one basic event happens the TOP event happens, where as in order 2 cut set both of the two basic events needs to happen to trigger TOP event. When analyzing large trees, the ranking in orders are also checked to ensure right criticality assessment. Ranking of the cut sets can be done with dividing the basic events into three subcategories: Human error, Active equipment failure and Passive equipment failure. Human error is seen as more frequent than active or passive equipment failures, and active equipment failures are more inclined to fail than passive equipment. This of course is just an assumption, and the exceptions can occur. [2, s. 118-126]

When used in right places, failure tree analysis can be used to assess and observe critical events in the system. It is clear that over use, and too broad boundaries hinder the results from the analysis. This method can be supportive to the FMEA process, as the event-cause relation can be observed in more detail.

4. COMPUTER AIDED DESIGN AND SYSTEM MODELING

Technology based companies face the inevitable change on the ways of working. Computer aided design can hasten the development of the new devices, and offer new possibilities to increase the products parameters like reliability and usability. To get the best out of the development of computers, a new set of programs and methods are possible to implement straight into the design process.

The PCB design can be automated with a quite small effort, if the components are modeled, the computer is able to place components, wire, and analyze the system. Also much of the structural integrity to stresses, temperature dissipation and effect of the magnetic fields can be modeled. Use of computers to decrease waste, and increases productivity, which both are signs of a modern design process. Reduction of waste, especially time and money is important, to keep the company competitive against other companies from the same field. Simulation can be cost effective way to replace part of testing. Of course all failures cannot be simulated, simulation model might not be accurate enough, or the model is too complex to discover the failures. Some testing is needed, but the amount and type of testing can be replaced and modified with the use of simulation.

Modeling of the modern systems can be tedious to do without aid of the computers, as the information of the model complexity and parameters is hard to control without automated system. Also with multidisciplinary team the design team information needs are quite different and with computerized system, all the information can be sorted as how important it is to the user.

In next chapter simulation is presented as a part of the design process. Also some ways to model the system to support the whole product development process. Simulation concentrates on probabilistic simulation, and structural simulation of FEA. Later the system block modeling is covered.

4.1 Simulation

As computational knowledge develops, also possibilities to simulation increases. When substituting the real tests, with simulation major waste reduction can be achieved. Nominally the testing of the new product takes a big part of design time. This is especially true when reliability tests are in question, as they tend to last longer due to the decrease in confidence, when acceleration is increased. Also from the results of reliability tests might rise the need for change, as faults are found.

When all the most critical parts are verified and functioning as early as possible, the chance for costly redesign is reduced, and the increase in development speed is achieved. Usually this means, that the need for resources shift from testing to simulation, and from later in design phases to earlier spots.

To assess the need for simulation it is important to understand the business and the products. For low complexity, low reliability part, the simulation modeling might just increase cost, as the goal for the design is not high reliability device. For high reliability systems, and subsystems, with high goal for mean life, the simulation might ease the risk in early design phases, as many different things can be tried out, without putting much effort and money on the concept and prototypes.

In next chapter, the numerical Monte Carlo method is presented, and after that, a Finite Element Analysis. Monte Carlo method is a numerical way of simulating the process. It can take input's probability distribution into account, and produce a probable outputs for multiple inputs. FEA is mostly mechanical modeling method. It can be used to solve changes in a material structures, by dividing model into mesh, and calculating the mesh's deformation or stress with linear equations.

4.1.1 Monte Carlo Simulation

Monte Carlo is a method, which has many applications in engineering field. The method is mainly used in three different areas: Numeral integration, optimization and as a method to simulate probability distribution's cases. In reliability engineering, the most used way of Monte Carlo is with probability distribution's draws. With it the simulation model can estimate the natural fluctuation, or standard deviation of reliability distribution, and from that project the estimated reliability. [1, s.273-274]

Idea is to iteratively evaluate deterministic model, by suing random inputs. If the nature of our deterministic function is correct, the output represent real situation with the system. And because the function is deterministic, the pseudorandom inputs of same limits will deliver similar output to some extent, as the truly random inputs are not available with computers. [9, 108-119]

Process of Monte Carlo simulation follows similar path every time. First, a problem is defined. By defining what is studied, and what is expected from the simulation, a clear consensus of methods and parameters can be achieved. After definition, a parametric model of a challenge is needed. Parametric model connects the output to one or multiple inputs of the simulation. Mathematically this can be given as: $y = f(x_1, x_2, ..., x_n)$. When output is bind to inputs, these inputs needs to be defined. Every input should have its own probabilistic distribution. Also amount of runs per defined inputs, as it effects on accuracy and confidence of the simulation. When simulation is set up, testing can begin. Test starts by generating random numbers of predefined amount. These numbers are set as an inputs and the output is recorded. This test is repeat m times and after the testing results are analyzed along with accuracy and confidence of test. [9, 108-119] This process is depicted in figure 4.1.

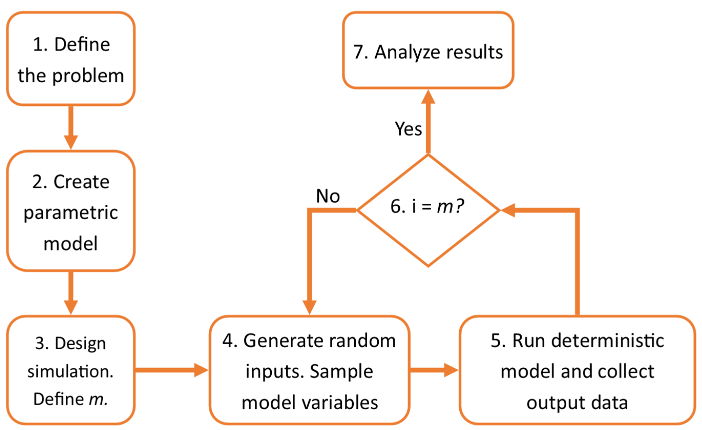


Figure 4.1 *Monte Carlo Process as a flowchart, adapted from [9]*

Advantages of Monte Carlo simulation is that it is relatively easy to use, and it has low level of complexity. The Monte Carlo simulation can work with all the distributions on input systems, and at all cases the distribution is not even necessarily be mathematically presentable. This simulation is ideal for systems with high uncertainty, and simulation works despite the complexity of the models. Another important advantage is that Monte Carlo has is that it takes the probabilistic approach when used in what if scenario, where inputs are more static values than probability distributions. [9, 108-119]

Monte Carlo simulation has also some disadvantages. Even though the electronics and computational capability develops at high speed, also the models for Monte Carlo increases in complexity. To the model this is not a problem, but the amount of calculations increases so that the time to calculate complex model can be quite large. Other point is that the Monte Carlo method does not take into account the facts that modeling system, and its inputs can have dependencies, where inputs are not independent, even though the model expects that. [9, 108-119]

Monte Carlo is a simulation, which could be used to check effects of a multiple independent parameters to a single system. This can be used widely on the field of reliability, with for example load-strength analysis or degradation analysis. With LS-analysis, simulation can calculate the effect on component's parameter drifts thus gaining important information about the development of a system in a long run. With degradation analysis, Monte Carlo can calculate probabilities of failure when device has been used. This kind of data can be vital to high reliability device's development. Monte Carlo simulation is specific, even though it can be used in various situations, its effect often stays small due the needs of an extensive analysis with it. Also the measurement error from when data was gathered might add so much uncertainty to the results that good decisions is hard to make based on Monte Carlo.

4.1.2 Finite Element Analysis

Finite element analysis, is a numerical method that has been traditionally used with solid part mechanics, but with increase in computational power and development of software, it can be used with variety of different physics based problems. In area of reliability, FEA can be used with traditional structural analysis as well as dynamic analysis caused by external vibration. The FEA also can be used to produce thermal analysis to analyze the internal temperature gradients, and their development. [34]

To do a FEA, first the part or component is needed. This part can be virtually any part of interest, but complex parts with cavities are much harder to model than the solid parts. This model, so called "physical model" is set as a boundaries to the system, and simplifying the analysis. Then this physical model is modified so that it can be solved by FEA. Modified physical model is then discretized to FE-Model, by approximating the model outlines. This forms a solid three dimensional mesh. Physical model and mesh are represented in figure 4.2.

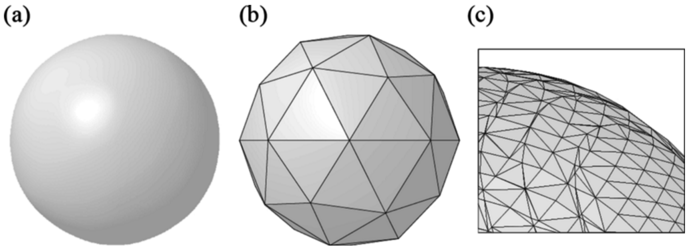


Figure 4.2 *Physical model in figure (a), simple mesh model at figure (b) and more complex mesh model at figure (c) [35]*

Mesh is formed by elements, and corners of these elements are called nodes. By increasing the amount of nodes the simulation model increases in accuracy. This can be observed in 4.2 by comparing the subfigures (b) and (c). By increasing the amount of nodes, the next step of FEA is going to be more challenging, as the amount of linear calculations also increases. To simulate the change in system, a calculation is done to every element. Linear equations with displacements are formulated, and within these equations the nodes of the system are marked as unknown. After the formulation the linear equations are solved. Last part of FEA is to obtain the results and critically analyze them. [34]

The FEA is incredibly efficient when modeling solid materials. Also fluid mechanics and electromagnetic environments can be considered in some finite element modeling (FEM) packages. Because the FEA is used throughout the engineering fields, it has lots of support, and different applications to use. By using the FEA the engineer can visualize the effects on stiffness and component thickness, which in turn helps at minimizing component costs, reducing waste, and decrease time from re-design. [34]

Increase in complexity as a form of nodes can slow the analysis, as the computer needs more power to calculate the linear equations. Also the model needs to represent the real life counterpart quite well, as changes between the model and part might skew the results on some degree. In some models, the thread of the hole is often not modeled, but if the threaded hole is in close contact with thermal expansion, it might cause some challenges in a long run, for example loose connection at the thread. [34]

In the future the FEA can be effectively implemented in a computer aided design software (CAD), to further increase the design speed, and cutting the waste of time by allowing CAD program to analyze the FEM, during the design process. Also the increase in computational power increases the possibilities in high complexity parts, by using parallel computing, or supercomputers. In the future the mesh created before the analysis can be automatically change, allowing more flexible design, and more accurate analysis for example in failure events. [34]

Finite element analysis is a powerful tool to use in mostly mechanical problems, and mechanical structure and boundaries are one of the first specs that are defined. Also in electronics, the casing defines greatly the size of PCBs and other electromechanical components, so it is important that the mechanical design is going strong from the beginning, when fast time to market with electrical device is desired.

4.2 System Modeling

As modern electronics are quite complex, the design is most often done in smaller parts. These parts may consist of functional entities or physical structures, and together they form a functional device, that fulfills the design parameters. Dividing the design into smaller parts supports the FMEA process, failure analysis and reliability calculations to name a few. For designers, the smaller designs are more easily handled, and if these parts are seen as an integral part of the system, the time and effort put to them are more efficient. Modeling the system as a block diagram can clarify the devices' weaknesses and help designers to understand in where the unreliability in their design comes from. [1, 28-33]

4.2.1 Series Model of Reliability

The most basic part of block diagram is system with two independent components, which both have constant failure rate. Failure in either of these components will result in failure in the whole system. This system is represented in a 4.3.

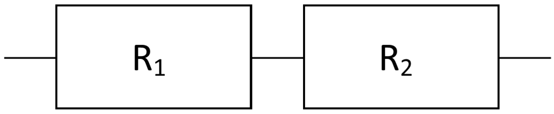


Figure 4.3 *Two components in series*

If R_1 and R_2 are reliabilities of the two components in 4.3, the system reliability is R_1R_2 and in general the reliability of n number of blocks can be presented like in 4.1

$$R = \prod_{i=1}^{n} R_i \tag{4.1}$$

This model is the simplest on which parts interact with each other and is nondependent on what level of design the system is. This model only covers the component failures, but for example the interface, or use of device can cause failures, and for these failures, the block depicting this type of failure rate is needed, or the probabilities needed to include in the already placed system blocks. [27, s. 17-25]

4.2.2 Redundant Systems of Reliability

In design not all structures are worth the same, some function-critical structures are more critical to the operation, than structures that allow some feature to work properly. To support a highly reliable device, either a highly reliable parts needs to be used, or implementing redundancy in these structures to generate more reliably working system. Redundancy can be divided into two different functions: active and passive redundancy. The redundancy is to prevent performance decline under the specification limits and both, passive and active redundancy tries to prevent total operation loss. [27, s. 17-25]

Passive redundancy usually means that the failure of the one redundant part does effect on the performance of the system, but the system is still operational. Examples of this are load sharing of marine motors, where failure in one of the motors does not cripple the whole vessel, but greatly decreases its maneuverability or velocity. In passive redundancy there is no component, that actively checks the performance, or there is no backup system to use when component fails to operate properly. [27,

s. 17-25]

Active redundancy means that the system usually monitors itself while operating. An active redundancy means that there is a backup system, which is fully capable to take over the system without performance deterioration. Usually actively redundant systems consist of three distinctive parts: Automatic fault detector, automatic fault isolator and automatic reconfiguration. These components together make an actively redundant system capable to independently decide whether it is broken or not. [27, s. 17-25]

In next paragraphs are presented some of the simplest models for redundancy and reliability calculations for these models. In figure 4.4 is presented the simplest kind of redundant system, which is composed of two independent systems in parallel.

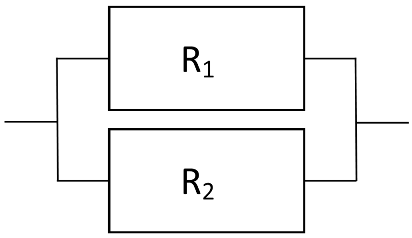


Figure *4.4 Components in parallel*

In this model, the system is considered operational, when either of the two or both functions. If reliabilities of the components are R_1 and R_2 the probability can be written in

$$(R_1 + R_2) = R_1 + R_2 - R_1R_2$$

this can be rewritten as

$$1 - (1 - R_1)(1 - R_2)$$

And this can be generalized for parallel redundancy as

$$R = 1 - \prod_{i=1}^{n}(1 - R_n) \tag{4.2}$$

As redundancy increases cost of the design, it also increases the reliability of the system, but for simple, yet critical systems the increase in cost usually pays off in increased reliability. [27, s. 17-25]

More sophisticated systems can make use of so called m-out-of-n redundancy, where m systems total of n is needed for proper operation. These kind of configurations are commonly used in power station's generators, and other applications, where the continuous operations is needed. This system type makes possible to maintain and repair the part of the system not in use at the time. The reliability of the system, with n equal and independent systems, can be written as [27, s. 17-25]

$$R_{sys} = 1 - \sum_{i=0}^{m-1} \binom{n}{i} R^i (1 - R)^{n-1} \tag{4.3}$$

As one can imagine, the complex system can span out to very complex reliability block model and presented models are only small base for how the real electrical system could behave in this kind of modeling. Various examples can be taken from aircrafts where hydraulic power systems have at least 2 parallel lines for same functions. Some safety and high reliability digital circuits utilize the majority voting circuitry, where n amount of systems deliver their interpretation of the outcome, and the majority of votes are decisive, causing system being more tolerant to failures than single voter. Usually the most complex systems are seen in safety critical systems. [27, s. 17-25]

4.2.3 Reliability Block Diagram

System modeling and reliability block diagram can be of use in many different times at product development process. By modeling a system as a functional blocks makes grasping the parts involved an easier task. When system is modeled as a blocks, each block can be handled as a single system, and its parameters like reliability can be individually assess. This division can be made so that each PCB is different functional block. This makes the presentation and analysis of different challenges rising at the development process easier.

When calculating of system reliability, a division of blocks can ease the task. When some of the system is completed, the reliability engineer does not have to know every reliability metrics, but the incompleted can be approximated. When approximating only one block, the work is much easier than the approximation of every single component on PCB. This saves time and resources, as the work done is much smaller than for calculating every single part's individual reliability. When analyzing the blocks in early phases of design process, a predictions for reliability from the standards can be used. For example Telcordia's SR-332 can be used in a way to produce output without knowing much of the PCB.

5. COMPONENT REQUIREMENTS ANALYSIS

One clear place, where reliability of the system is built, is component choices. Market has often a multiple different manufacturers for similar components, and even though the components might seem to be similar, there is multiple things to consider. By analyzing carefully the component properties, some clear failures can be averted, along with costly redesigns. When designing system, a new parts should always analyzed for functionality, quality and reliability, before using them in a high-reliability systems. By using components already used in previous products, that function properly a good amount of time can be saved, same is with used subsystems. When using components in critical parts of the design, some tolerance analysis is in place to ensure the satisfactory outcome on finalized product.

For high reliability product, the critical components are vital to detect, and act accordingly. Often testing is costly, and limited resources needs to be divided to achieve maximal benefit. When acquiring and testing new components, it is important to understand the stresses the component endure, and the criticality of the component in hand. Example of these kind of critical components for system operation are IGBT - modules, which are used in many power electronic devices. Often one of the most expensive components, the IGBT module needs to be properly tested, analyzed and derated to achieve high reliability device.

Division between critical components and non-critical components is always a challenge, when majority of components are needed for even a satisfactory function of product. One way of analyzing criticality is through the FMEA process, which can output statistic for possible risks in design process. Of course this data can be skewed but often trends are clear enough to make decisions from. Maybe the best bet for criticality is from warranty data. It contains much of the information from previous product families, and can be used to find trends in failures. Lastly the way of analyzing criticality is connected with unit cost. By analyzing expected cost for system bill of materials, the most expensive components are often derated least thus being most vulnerable for degradation of reliability and poor performance. When choosing critical components, a designer's intuition and silent knowledge should not be overlooked, as designer is often expert on this specific area.

5.1 New Part Analysis

Practice of new data analysis is important as the designer should be able to choose from various different suppliers, and the aim for choosing one is to get the best product for the money. This is quite difficult, if the data got from suppliers greatly differ. For example if one suppliers tells that their product has upper 10% life in 20 000h, and other supplier tells that their system's 20% life is at 15 000h. Also different ways of measuring can be used. Usually based on standards, but also these values vary greatly depending on the standards. Ways to deal this imbalance in the received data, depend highly on the prestige of the company and also the monetary value of the possible trade. Smaller companies must often just try to compare differently given values, and try to make the best out of challenging situation. For bigger companies the standardization of data from suppliers is the answer to this challenge and can save time, money and testing resources.

Depending a lot of component type, the testing of the new component can be quite different, not only in functional testing, but degradation and reliability testing too. Testing of critical and expensive components, which performance is more critical to the device's operation should be more carefully addressed than the non-critical components with low stress. Tests for especially components enduring or generating heat should be carefully addressed as heat is one of the most challenging environmental stresses in modern devices. Other component group to address is the components with relatively high cost. Usually this types of components are more likely to be less derated, and the parameters of the component is closer to its operational limits. This is because for good revenue the cost of device should be as low as possible, while fulfilling the reliability, functional and other requirements. When cost cuts are done to the device, it is easier, and usually most efficient in monetary terms to reduce the investment in high-cost components, even though this usually reduces reliability, and lifetime of the device.

When acquiring totally new components that has not been used in any devices some basic tests should be done. Functional testing to verify the component's values, this should also reveal the tolerances in the component. To ensure the tolerances and parameters, functional testing should also be done in product's maximum and minimum operating temperature. This is the bare minimum that every component should go through. For short, every component should be tested so that it operates normally in device's operational limits, as electrical components vary from actuators to programmable logic controllers, it is not in this thesis scope to design every component type's test routines. For critical components, and temperature dependent components the reliability test is recommended, to figure out, what is the life of the components in the system, in real conditions, and does the manufacturer's documents comply with the results. With reliability tests also aging should be addressed, more likely the critical values, that might degrade and at later life of the component can't achieve the parameters the new one could. This means that the device might fail to operate at later life in customer's premises. [2, p. 188]

It is argued by Liu [5] that the now de facto styled testing and quality assurance against standardized tests are not going to be the main type of quality assurance in near future, as the electronics and electrical devices develop to more and more sophisticated systems. In the future the quality and reliability assurance is demonstrated by tests made by manufacturer, and that standards of today, will evolve to more guiding documents over a documents that clearly tells how the assurance of quality has been done. As this development goes on, it is ever more critical that the sourcing and designers understand the reason and possibilities of testing. The engineers need to understand what a specific test reveals about the product, and what the most important aspects of the said tests are. The DfR supports this development, as the designer need to take more responsibility for the reliability design, and at the same time the understanding about different tests increases. Even now the standards cannot keep up the pace in updating the reliability values in all the electrical components. And the increase in integrated circuits in PCBs when silicon handling develops increases the challenges of keeping up the reliability information up to date. The industry starts to shift from standardization of testing, like MIL-STD or IEC to more guiding documents, resulting in a need for understanding of reliability and quality calculations in all major companies. This shift does not happen in a year, but in near future this is one possibility where the industry shifts. [5]

It is important to company that it can compare two similar products on similar parameters. This is not possible at all times, but the more critical the component, the importance of the possibility of comparing increases. Especially with reliability metrics, where reliability of the component can be represented in quite many ways:

FIT(failure in time), MTBF(mean time between failures), MTTF(mean time to failure), λ. Also the calculation can change, and if the reliability values are not based on field data, which they rarely is, the results can change depending on program, reliability specialist or even by sheer luck. One possibility to handle this is do the reliability test in-house, but it is expensive and time consuming, which leaves no other choice than to trust the reliability metrics. One thing to improve the reliability metrics on new components is to standardize the reliability metrics demand, while contacting the manufacturer of the components. If the document has clearly defined reliability values, defining how the reliability needs to be measured, and what kind of information is needed. Of course if the parameters are different than the component manufacturer already has, this might not get the warmest of welcomes. But it is the one of the few things that can be done in relatively easy.

As new parts are used, some kind of testing is always needed. For passive and other simple components, this is relatively easy process. For more sophisticated components the functionality can be quite challenging to test. Also the degradation and aging must be taken care of to ensure proper function also at later life. This means that the component manufacturer that has high prestige, and the company sees it as a reliable partner is more likely to be favored over the new possibility. Companies also should gather and keep the information of the component manufacturers that are "trusted" or that produce the components of the required quality. This tends to make companies more dependent on few supplier, which in turn might be bad.

5.2 Component Selection

When talking about electronics, the reliability of the system consists mainly on components' reliability. This is why the component rating, and parameters are in the vital part of device reliability. No device is reliable, if the components are not high quality and reliable. That's why it is important to understand the impact that the selecting components have on an overall product. Reliability itself is no easy subject, as many different parts have effect on final product: quality, environment, electrical parameters, up/downrating and stress balancing. Component quality has two different meanings, where the more familiar is that the component satisfies its stated or implied needs, the other however is the ranking system of electrical component by intended working temperature. Environment and electrical parameters put the component under certain stresses, while up and down rating of controls the environments and reliability of components.

The commonly used style for differentiate the electrical components' temperature range is following: the smallest range is with components of commercial use. These components are usually guaranteed to ensure temperatures from 0 to 70 degrees Celsius, and are used by commercial manufacturers on everyday electronics like toasters and televisions. Usually this means also cheaper price than the wider temperature range components needs possibly more testing, validation and higher quality of parts. Mid-range of components are called an industrial components, which offers a wider range of use temperature from minus 40 to 85 degrees Celsius. These components are mainly used by industrial users, which need a more robust and more reliable systems that lasts for a longer time than consumer grade goods. Lastly is the high end temperature range, a military grade, that endures -55 to 125 degrees of Celsius these types of components are used for highly robust, and reliable systems, as the component cost will rise when robustness and quality grows. Along with military use, also power plants and airplane industries might use this types of parts. This is just a broadly accepted grades, and not an industry standard, so different manufacturers can use more specific ranges, including extended and automotive ratings. [10]

One important part of component selection is to use component rated in a right temperature. As mentioned in before, a temperature is one of the main reasons a device, especially transistor based components fail to operate. Supplier tests its components, and sets some limits to the components' usage. These limits includes, but are not restricted to maximum and minimum operating temperatures, and at least absolute maximum temperature. Operating temperature limits are the upper and lower limits, which the system is guaranteed to operate. Absolute maximum is a destruction limit, which usually means, that when over the limit the component will break and is not operable again. When operating over the limiting temperatures, the manufacturer usually does not extend their warranty for broken components. Same principles goes with the current, voltage and power limits. Usually the overstress shortens the lifetime of the component and by controlling the real stress against the suppliers intended stress the component can be put to more stressful place for reduced reliability and less stressful environment for extended reliability. [10]

Uprating is a term, where component's property is increased to the point where it might not be intended to be used by the manufacturer, but it can operate. Uprating is not a reliability tool, in a sense, that the reliability tends to decrease as the system parameters goes beyond manufacturer values. But the uprating is used widely, mostly because by using same component in many places, a design can save from procurement and testing costs as buying in bulk is usually cheaper, especially if the amount of buying is otherwise small in quantity. There is a multiple ways to uprate components: by parameter conformance, stress re-balancing and re-characterization of components. Parameter conformance is a method, where component is tested, if its parameters stay during higher stress levels, thus being possible to use over the limits the manufacturer is designed the component to function. Usually the components uprated with this method are low complexity components, easily tested for functionality. Parameter conformance is also the cheapest way of uprating components. Re-characterization is a method to extend the usable stress limits to a certain amount while the parameters of the system degrade. Parameter degradation is controlled by series of tests, to ensure that the standard deviation of the parameter drift is controlled, and within acceptable limits. Finally the stress balancing, which is solely a tool for temperature control. In stress balancing to increase the either ambient or junction temperature, a tradeoff has be made. Component parameter that is connected to the power of the component, usually input voltage, or frequency, is decreased, so that the temperature can be increased. [10, s. 39-71]

Derating is a pure tool for reliability, and it aims to decrease the possibility that any component in a system is affected by greater stress it can handle. In a simple way, derating aims for robust design against stresses. Derating has a two different approaches. One is to reduce the stress level the component endures. Other is to select components in a way, that robustness of the components against these stresses is higher. Often the stress is one of the following; electrical-, thermal-, mechanical- or chemical stress. Electrical stress consists usually voltage and current levels and transients in these levels. Thermal stress is mainly affecting with a temperature level, or the temperature cycles. Chemical stress is corrosion and erosion caused by different compounds. and finally the mechanical stress is vibrations, shocks and thermal expansion causing the strain. [1, p. 139]

One of the most straightforward ways of derating is to decrease the stress component endures during the use. Often components can benefit for using them under the rated values. Benefits include lower stress levels, increased efficiency, and better ability to handle transients. When increasing the quality of the component, it effect straight to the reliability of the said component. At appendix A. is presented a comprehensive list for parameters for derating and also the suggested derating values. For example the film capacitor is suggested to choose in a way that the rated DC (direct current) voltage is multiplied with a factor of 0.8. These kind of derating guidelines are common and based more or less to the experience and deductive reasoning. There is also relation with the stress and lifetime of a component, and when used in higher stress levels the lifetime decreases. By derating components, the useful life for components can be increased. [1, p. 139]

Derating and uprating are not challenging or complex tools for properly rate components, but before these tools are used, the principles behind their effects is good to understand. They both are based on inverse relation of stress and reliability. As a reliability point of view the derating increases it, but only if the stress chosen has a causality to the probable failure mechanism. For example hermetically sealed component is not susceptible to problems to internal humidity. Uprating on the other hand usually decreases the reliability, as the components are used outside the operation limits. Sometimes this is justified, as some of the manufacturers are not manufacturing MIL-grade products, due the cost of testing those, but the industrial-grade components sold by the same manufacturer can endure the MIL-grade environments. In this case, the uprating can be done without the loss in reliability. Still, usually using uprating, engineer should be quite careful, not to faultily measure the values. [10]

5.3 Tolerance Design

Tolerance design is a tool which has strong basis in a DFSS process. Tolerance design bases its effectiveness to the reducing the product variance. Tolerance itself is defined in Merriam-Webster as an allowable deviation from standard. This means that when component has tolerance for certain value, the value might change within the tolerance limits. Some applications and devices needs a smaller tolerances, where as some can cope with higher tolerances. The tolerance amount in electrical passive components tends to be ±10% or even higher, whereas machined mechanical parts the tolerance might be smaller than ±.5%. Usually there is a relation between the tolerance and cost. Often enough the cost increases when tolerance decreases. This is easy to understand as the increase in the level of detail needs better equipment and takes often more time.

Tolerances can be divided into two distinct categories: absolute tolerances and statistical tolerances. Also when taking into account all the tolerances in the system, either worst-case or statistical summing can be used. There is also more complex methods for more complex systems. Tolerances can be thought as an acceptable range for some characteristic. Form, size, location, or orientation are tolerance types in mechanical structures whereas voltage output, current input and frequency have electrical tolerances. By giving the tolerance as:

$$\mu \pm \Delta \tag{5.1}$$

where μ is an average of the value and Δ is the tolerance. Equation 5.1 gives the fast glance of quality can be assessed, along with the general sense of values. Of course small tolerances gives the illusion of the quality of the product. It is vital to understand if the tolerance is set with absolute or statistical tolerance. In absolute tolerance, all the components that is outside the tolerance are discarded. This method means that all the components are inspected thus increasing the cost for manufacturing. Other mean is statistical, which decreases the amount of testing. Statistical method uses the sample components, with what the average μ, standard deviation σ and distribution is determined. When the process capability is given in statistical method, a tolerances have some probability of being faulty. Because all the components does not need to be measured in statistical tolerance measurements it is cheaper and more used method especially with large number of products. [36]

When manufacturer delivers the tolerance metrics they matter only little until the components are part of the system. Tolerances needs to be considered according the near components or as a part of subsystem. This rises the need for tolerances to be measured as a part of something larger, a total tolerance for multiple components. This summation can also be made with two different ways: Worst-case and statistical. With worst-case the tolerances of the parts are thought to be within the tolerance limits, but every tolerance is set as it supports the values to be unbearable. Example of this in electronics can be a voltage divider constructed with resistors, which tolerances can be as big as 10%. This means that when two components are within tolerance limits, the measurement value can vary as much as 20%. Mathematically this can be written as $\Delta_{total} = \Delta_1 \pm \Delta_2$. Of course this amount of uncertainty about measurement is often not acceptable, and more accurate components needs to be used. Other method, a statistical tolerance summation, is again more forgiving as a design method. This is because it does take the variance of the components into account, but it does not expect the worst outcome. Of course this method is more useful with statistical tolerances, as absolute tolerances make statistical approach of summation difficult to estimate. When summing statistical tolerances, it can be mathematically represent as ${\Delta_{total}}^2 = {\Delta_1}^2 \pm {\Delta_2}^2$. This means that the statistical should give more optimistic, and often realistic view on tolerances of the system. Recap of the tolerance types and summation methods are presented in figure 5.1 [36]

Summation method	Tolerance type	
	Absolute	Statistical
Worst-case	Every piece within tolerance	Some products out of tolerance. Often small percentage.
Statistical	Difficult to estimate	Fraction in tolerance related to components' fraction in tolerance

Figure 5.1 *Tolerance types and summation methods according to [36]*

Presented methods of summation are applicable to simple shapes, and systems. Often a linear relations between components are needed to analysis for being successful. When analyzing more complex systems, 3-dimensional models or variability from different sources, these models are not extensive enough. To approach more demanding system, a few different ways to handle the situation exists. Some approaches uses the experimental nature, and applies acquired experience into the design. This needs an extensive understanding from the field including accurate data. Also the analysis needs to be assessed with care. Second method includes computational models in a form of Monte Carlo, discussed earlier in this thesis. This simulation can be used to test different combinations of components and environments, by using a large number of simulated test samples. Lastly the method of tolerance design which aims for decrease in variance in the final product. [36]

In the tolerance design the variance ${\sigma_{total}}^2$ is a combination of system's variances, multiplied by proportionality constant η, which is often called sensitivity. Tolerance design experiment aims to visually produce such output that the each parts effect on final variance is clearly visible. This process is most effective with subsystem tolerances, as the degrees of freedom grows with each different component. Size of the experiment is between $n+1$ and 2^n, where n is a number of components in the system. Process starts with an experiment matrix, pictured in 5.2.

Treatment condition	Component			Measured response
	A	B	C	
1	+1	+1	+1	Y1
2	+1	+1	-1	Y2
3	+1	-1	+1	Y3
4	+1	-1	-1	Y4
5	-1	+1	+1	Y5
6	-1	+1	-1	Y6
7	-1	-1	+1	Y7
8	-1	-1	-1	Y8

Figure 5.2 *Experiment matrix of a subsystem. Adapted from [36]*

At figure 5.2 topmost row has all the components of the system, A B and C. One component can take more than one column, depending on the amount of dimensions the component have. For each component dimension also the tolerance variance is plotted. This can be either $+\sigma$ or $-\sigma$ and is marked with +1 or -1 respectively. In each row, a one combination of component levels are plotted, and at measured response column an outcome is marked. From the matrix, all the single variances by different component dimensions can be calculated, because the amount of equations is larger than the amount of components. In this example, a matrix is sized after 2^n, but this is not necessary, the needed amount is affected by complexity and structure of the system. After the calculation of variances, a next table can be produced. This is represented in figure 5.3. [36]

Source	σ	Variance	%	η
A	0,04	20	26,7	12500
B	0,02	40	53,3	100000
C	0,02	15	20,0	37500
Total	-	75	100	-

Figure 5.3 *Key results calculated from experiment matrix. Adapted from [36]*

As seen in figure 5.3, all the sources are represented, and their individual variances are calculated. With this presentation, main contributor for variance can be seen. Of course, when contributions for total variance are close to each other, other factors such as reliability and cost should be analyzed, but by improving highest contribution, it is probable to have highest improvement to product variance. To predict the change in variance, the individual sensitivity can be calculated from the table, as:

$$\eta_i * {\sigma_i}^2 = \text{contribution to } \Delta^2 \tag{5.2}$$

As sensitivity does not vary with tolerance, the new contributions can be calculated by the 5.2. This can give coarse effect of tolerance into total variance. This is quite fast method for assessing the variance of the final product, and to calculate expected changes with change of tolerance. [36]

Tagauchi, the developer of tolerance design method, has suggested that the tolerance should be determined as a tradeoff between quality loss and cost. This suggestion is highly linked with a mechanical design of the product, as electrical characteristics does not necessarily affect as linearly to the product, as mechanical variation does. Tolerance design itself also is based on mechanical devices, decreasing the usability in electrical systems, but set aside the mechanical point of view, a worst case and statistical tolerance analysis can be used to analyze the effects on cost cut and parameter values in critical components. Especially the worst case analysis can be at the effective with critical components, and it should be used with IGBT-modules and its driving circuitry. Non critical components can be allowed to be designed with statistical tolerances, as the failure rate and overrating because of the tolerances are still uncommon.

Tolerance design is an important part of design process, as it ensures that even when the system's component parameters varies. Tolerance can be outputted as an absolute value, or as a statistical model. Absolute values puts all the components into tolerance limits, and ensures the proper values, whereas statistical tolerances allow some portion of components to be over the tolerance limits. Tolerances in system can be summed with two different techniques: worst case and statistical. Worst case method assumes the worst possible tolerance at the component, and statistical assumes the extreme tolerances being very unlikely to appear. Designing the tolerances and the limits, a Tolerance design can be used. It needs some experiments to output a proper result. Other method to calculate and analyze tolerances of complex systems is a Monte Carlo method which can utilize simulation and computer models.

6. CONCLUSION

Objective of this work was to present possible methods and tools that the reliability engineer can utilize, while working on a new product development process. This thesis aimed to find and present methods that are the most useful for increasing, or estimating the lifetime of a system. Applying reliability tools, and designing a high reliability device is no easy task. Due the great amount of different reliability tools, including those, that are designed primarily on quality, choosing the right tool for a right job is quite tedious. To implement the reliability from the beginning, the old way of putting the reliability on top of the device needs to develop. Starting the reliability growth at the testing phase is just too late.

For successful design, and implementation of reliability a one fact kept rising from the material. A dedication to the use of certain tools is needed. If there is no willingness to develop reliability design further, it does not matter what tools are available. At the future it might be useful to divert resources for reliability development from different teams, and from different backgrounds. The increase in understanding of reliability metrics can improve the designer's ability to affect the end result. This reliability knowledge should not be only on designer level, but it needs to be raised to the knowledge of a managers, as they control the resources.

Based on the thesis' data the full implementation of Design for Reliability methodology can't be proposed at current time. Despite the fact that the idea behind the DfR is very well thought, the change is too large to pull through without major investments. Because the DfR is a toolbox, some of the tools can be utilized without overhauling whole design process. Few tools to look more into with a pilot project are: FMEA, Mission profiles, and degradation analysis alongside with degradation testing. FMEA is constantly used and every time, users learn a little more about it. Use of FMEA needs a little help and guidance, but it is worth doing. When testing new devices the results often stops where test stop, and based on this thesis, it should not be that way. The ability for degradation analysis should be considered when beginning new tests for reliability. Often with a small changes in test setups, a degradation analysis can be made. Also one named person for making the extrapolations is needed for consistent analysis.

When choosing components, the mission profile should be considered. It would be useful, if more accurate mission profiles were used with harsh environments, where company knows their systems are implemented into. In the building of the mission profiles, a lots of data can be gathered from customers, but also digitalization and connectivity can improve data gathering from the use site. By analyzing the use environments and user profiles, a more reliable system can be designed, increasing in profit, quality and customer satisfaction.

Digitalization and increase in computer aided design is a field that should be looked more into. Along with mechanical stress modeling of FEA, thermal and electrical models can also make the design process faster. Monte Carlo simulation should be known, but implementation just because it can be used, is not the way to go. If possibility present itself for efficient use, it can be worth the learning, but the possibility for using the Monte Carlo should not be actively pursued.

Important thing is that the basics are clear, there is no advantage to implement a tool or method to product development process, or to change the process, if the company is not committed to the change. Even if the engineers know the possible good ways of working, and possibilities to develop more efficiently and make more reliable device, it is important that the people managers and upper management understand and support the change in the process. Enough resources should be allocated to the change or to learning new things. If some changes are to be made, there should not be any rush, and the resources should be available for development of the reliability design.

APPENDIX A. COMPONENT DERATING GUIDELINES

An extensive listing for most used electrical components derating values.

Device	Part Type	Derating Parameter	Derating leve
Capacitors	Film	DC Voltage	60 %
		Ambient or Case Temperature	90% derated for Ripple Current
	Ceramic	Ambient or Case Temperature	90% derated for Ripple Current
		DC Voltage	90 %
		Surge Current	80 %
		Ripple Voltage or Current	80 %
		Temp from Max Limit	10C
	Electrolytic, Aluminum	Ambient or Case Temperature	90% derated for Ripple Current
		Surge Current	80 %
		Ripple Voltage or Current	80 %
		DC Voltage	80 %
		dv/dt when rated	80 %
		Temp from Max Limit	20C
	Tantalum	DC Voltage	60 %
		Ambient or Case Temperature	80 %
Connectors	AC or Dc	Voltage Pin to Pin, Pins to ground/shield	80 %
		Contact Current	80 %
		Insert Temp (°C) (Delta T from Max Lim	80 %
Diodes	Signal/switch	Forward Current	75 %
		Forward Surge current	80 %
		Ambient or Case Temperature	80 %
		Reverse Voltage, Peak	90% <100V & 80% >100
		Max Junction Temp	80 %
		Power Dissipation	60 %
	Zener	Ambient or Case Temperature	80 %
		Max Junction Temp	80 %
		Zener current	75 %
		Forward and Reverse Surge Current	80 %
	Transient suppressor	Average Current	65 %
		Max Junction Temp	105C
		Average Forward Current	65 %
	LED	Max Junction Temp	105C
		Power Dissipation	60 %
	Schottky/Positive	Intrinsic Negative (PIN) Reverse Voltage	70 %
		Max Junction Temp	105C
		Forward Current	65 %
	Power rectifier	Reverse Voltage	70 %
		Max Junction Temp	105C
Inductors	Pulse Transforme	Operating Current	80 %
		Dielectric Voltage	50 %
		Hot Spot Temperature	20% below rating of insulation
		Operating Current	60 %
	Coils	Dielectric Voltage	50 %
		Hot Spot Temperature	20% below rating of insulation
Insulating materials	All Applications	Voltage Withstand, (Dielectric Strength)	80 %
		Temperature Rating	80% or 100C whichever is less
Integrated circuit	MOS Digital	Supply Voltage (VDD)	70 %
		Ambient or Case Temperature	100 %
		Frequency (% of Max Spec)	80 %
		Output Current	75 %
		Fan Out	80 %
		Max Junction Temp	80 %
	MOS Linear	Input Voltage	70 %
		Frequency (% of Max Spec)	80 %
		Output Current	75 %
		Fan Out	80 %
		Max Junction Temp	110C
		Supply Voltage	+/-5%
	Bipolar Digital	Frequency (% of Max Spec)	80 %
		Output Current	75 %
		Fan Out	75 %
		Max Junction Temp	100C
		Supply Voltage	90% for devices rated up to 18Vdc max, and 80% for devices >18Vdc
	Bipolar Linear, Including Voltage Regulators	Ambient or Case Temperature	100 %
		Input Voltage between inputs and between inputs and ground (Peak)	90 %
		Input Voltage	70 %
		Frequency (% of Max Spec)	80 %
		Output Current	75 %
		Fan Out	75 %
		Max Junction Temp	110C
	Microprocessors	Supply Voltage	+/-5%
	MOS	Frequency (% of Max Spec)	80 %
		Output Current	75 %
		Fan Out	80 %
		Max Junction Temp, 8-BIT	125C
		Max Junction Temp, 16-BIT	125C
		Max Junction Temp, 32-BIT	100C
		Supply Voltage	+/-5%
	Bipolar	Frequency (% of Max Spec)	80 %
		Output Current	75 %
		Fan Out	75 %
		Max Junction Temp, 8-BIT	110C
		Max Junction Temp, 16-BIT	110C
		Max Junction Temp, 32-BIT	100C
	Memory/PROM	Supply Voltage	+/-5%
	MOS	Frequency (% of Max Spec)	80 %
		Output Current	75 %
		Max Junction Temp	125C
		Max Write Cycles (EEPROM)	105
	Bipolar	Fixed Supply Voltage	+/-5%
		Frequency (% of Max Spec)	90 %
		Output Current	75 %
		Max Junction Temp	125C

Device	Part Type	Derating Parameter	Derating level
Fuses	Chip or Through Hole	Rated Current	50 %
		Voltage	90 %
Opto	Photo Transistor	Max Junction Temp	105C
	Avalanche Photo Diode	Reverse Voltage	70 %
	Photo Diode, PIN	Max Junction Temp	105C
Printed Circuit Board	Glass or FR4	Operating Temperature	110C or 80% of glass transition temperature, whichever is less
Resistor	Composition	Power Dissipation	50 %
		Temp from Max Limit	30C
	Film	Joule Rating for Inrush Limiting Resisto	80 %
		Power Dissipation	50 %
		Temp from Max Limit	40C
	Thermistor	Power Dissipation	50 %
		Temp from Max Limit	20C
	Wirewound Accurate	Power Dissipation	50 %
		Temp from Max Limit	10 %
	Wirewound Power	Power Dissipation	50 %
		Temp from Max Limit	125C
	Thick/Thin Film	Power Dissipation	50 %
		Voltage	80 %
		Joule Rating for Inrush Limiting Resisto	80 %
		Temp from Max Limit	80C
Thermistor	Chip or Through Hole	Maximum Current	80 %
Thyristors	All SMT and Through Hole	Ambient or Case Temperature	80 %
		Max Junction Temperature	80 %
		Peak forward blocking voltage	80 %
		Peak reverse blocking voltage	80 %
		Turn-Off time	Guardband allow 140% of maximum
		Static dv/dt	80 %
		Reapplied dv/dt	Does not exceed derated static dv/dt
		Commutating dv/dt	60 %
		Forward RMS Current	80 %
		Forward average current	75% Max
		Rate of rise of anode current di/dt	80 %
		Fusing current I2T	80 %
		Forward Surge current	80 %
		Latching Current	Guardband allow 120% of min
		Holding Current	Guardband allow 120% of min
		Average of peak gate power	70 %
		Peak Gate Voltage or Current	85 %
		Reverse Gate Voltage, Peak	60 %
		Isolation Voltage for isolated case devic	80 %
Fans	Tube Axial Ball Bearing	Airflow Rating	80% for Aging
		Voltage	90% to 100% unless otherwise specified by manufacturing
		Operating Temperature	80 %
Transistors	Silicon Bipolar	Power Dissipation	60 %
		Ambient or Case Temperature	80 %
		Voltage (Peak) Vce,Vbe,Vcb,Vds,Vgs	80 %
		Ic, Collector Current	80 %
		Base Current, Peak	80 %
		Breakdown Voltage	85 %
		Max Junction Temp	125C
	GaAs MESFET	Power Dissipation	60 %
		Breakdown Voltage	70 %
		Max Junction Temp	100C
	Silicon MOSFET	Power Dissipation	65 %
		Breakdown Voltage	70 %
		Max Junction Temp	110C
Transistors (RF Pulse)	Silicon Bipolar	Power Dissipation	60 %
		Vce, Collector-Emitter Voltage	70 %
		Ic, Collector Current	60 %
		Breakdown Voltage	85 %
		Max Junction Temp	125C
	GaAs MESFET	Power Dissipation	60 %
		Breakdown Voltage	70 %
		Max Junction Temp	100C
Switches	All SMT and Through Hole	Resistive Load Current	75 %
		Operating Cycles	< 100% of rated @ 10 years
		Ambient or Case Temperature	80 %
		Capacitive Load Current	75 %
		Inductive Load Current	40 %
		Contact Power	50 %
Varistors	Surge Arrestors, and MOVs	Operating Voltage	80 %
		Joule Rating	80% calculated
		Operating Temperature	80 %
Wire	Stranded or Solid Conductor	Maximum Working Voltage	80 %
		Temperature Rating	80% or 100C whichever is less

Figure 6.1 *An extensive listing for most used electrical components derating values. Adapted from [37]*

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