RELIABILITY METHODOLOGY STUDY
OF
A CONCENTRATED PHOTOVOLTAIC SYSTEM

by

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DEDICATION

This work is dedicated to my lovely wife Alaa R. Mohamed,
To my parents Jassim and Lotfyah Mohamed,
And to my children Abdullah, Khalid and Sana.

All I have and will accomplish are only possible due to their love and sacrifices.

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ABSTRACT

Reliability as an engineering discipline has grown in importance in systems development and manufacturing since its inception in the 1950s. This growth in importance is driven by several factors, including increasing complexity and sophistication of systems, public awareness of and insistence on product quality and availability, new laws and regulations concerning product liability, government contractual requirements to meet reliability and maintainability performance specifications, and profit considerations resulting from the high cost of failures. Such failures lead to increased costs for warranty programs, increased rate of repairs, and loss of sales because of decreased customer satisfaction.

Reliability engineering is the discipline of ensuring that a product or system will work properly during a specified period of time. Therefore, the aim of reliability engineering is to delay the failures and then to maximize the life of the product.

Studying the reliability of renewable energy systems in particular became more important in the last decade because of the need to find long life reliable substitutions to fossil fuels. One of these systems that recently has gained increasing interest because of research and development in the field of sustainable solar energy systems is Concentrated PhotoVoltaic (CPV) systems. These advancements could enable:

1) Higher conversion efficiencies,
2) Lower capital costs, and
3) Better reliability than competing products.

The CPV system architecture creates the potential for higher conversion efficiencies as contrasted with other sustainable solar energy systems such as flat plate PhotoVoltaic (PV) system. Because CPV systems require significantly less silicon than other sustainable solar energy systems, their resulting lower capital costs was viewed as the technology's major potential advantage over flat-plate PV, particularly for utility-scale applications. That argument has become less relevant with the dramatic reduction in silicon prices over the last several years.

Increasing the reliability of the CPV systems could potentially significantly decrease the cost of electricity produced by these systems. If so, this could have a great influence on the economy and the cost of life especially in areas that have substantial amount of solar radiation like Arizona in the United States. Therefore, the present research explores various extent reliability methods, synthesizes a new method, and applies that method to a specific CPV design. The results show that applying this method to the design of the considered system should result in a significant improvement in CPV system reliability. Finally, the present research considers the opportunities for extending this work on different types of systems including software systems.

CHAPTER 1: INTRODUCTION

1.1 Overview

Reliability as an engineering discipline has grown in importance in systems development and manufacturing since its inception in the 1950s after the World War II where reliability became a subject of study because of the relatively complex electronic equipment used during the war and the rather high failure rates observed (Ebeling, 2010).

This importance is driven by several factors, including increasing complexity and sophistication of systems, public awareness of and insistence on product quality and availability, new laws and regulations concerning product liability, government contractual requirements to meet reliability and maintainability performance specifications, and profit considerations resulting from the high cost of failures. For example, today's systems are more complex than systems in the 1950s as evidenced by the commercial jetliner the Boeing 737 consisted of some 600,000 total parts (Boeing, 2014), whereas the most recent Boeing jetliner (i.e., the Boeing 787) consists of about 2.3 million parts per airplane (Boeing, 2017). Public awareness and insistence of product quality and availability is evidenced by water crisis in Flint, Michigan where shortage in reliability study of the city water distribution system led to tainted drinking water that contained lead and other toxins (ThinkReliability, 2016).

The government is demanding developers meet reliability performances measures such as that for international market entry into the United States, CPV manufacturers are required to test and certify their CPV modules through an accredited Nationally Recognized Test Laboratory per UL Subject 8703, the official U.S. standard for CPV modules and assemblies (Robusto & Rai, 2013).

Profit is related to reliability where any manufacturing industry is basically a profit-making organization and no organization can survive for long without minimum financial returns for its investments. There is no doubt that the expense connected with reliability procedures increases the initial cost of every device, equipment or system. However, when a manufacturer can lose important customers because his products are not reliable enough, there is no choice other than to incur this expense. How much reliability cost is worth in a particular case depends on the cost of the system and on the importance of the system's failure free operation. If a component or equipment failure can cause the loss of a multimillion dollars' system or of human lives, the worth of reliability and the corresponding incurred cost must be weighed against these factors. For the producer, it is a matter of remaining in the business. However, his business volume and profit will be substantially increased once his reliability reputation is established. (Aggarwal, 1993)

The main objective of studying and analyzing the reliability of any system is to answer the following questions.

1. Is the system reliable enough to be relied on for a certain working time?
2. Which component of the system can fail or needs to be maintained?
3. How can the reliability of the system and its components be improved?

(Ebeling, 2010)

The answers to the foregoing questions is depends on the following these more fundamental issues:

1) Calculation of the reliability of the system,
2) Comparing the calculated reliability to user's demands for reliability,
3) Determine how long system will maintain a certain reliability value,
4) Determine the budget and required procedure to maintain this reliability,
5) Determine the life time of the system, and
6) Determine if it possible to extend this life for a pre-decided time or terminate it in a certain. (DoD, 2005)

The critical impact of reliability is understanding the risk that failure of the system (in whole or part) creates adverse consequences for the environment, economy and humans associated with this system (Johansson, Hassel, & Zio, 2013). The most obvious examples are the reliability of the nuclear power plants, aircrafts, and airspace shuttles, the catastrophic damage that can be resulted from lack or miscalculation the reliability of such systems, as an example Fukushima nuclear accident has brought reliability concerns sharply into the public eye, people are anxious to know more about the chances of similar accidents occurring in the future, and the potential impact (Kuo, 2011).

From this prospective, we can see that studying reliability is not only essential for the product or system itself, but in most cases, has great impacts on the life and environments.

1.2 Scope of the Work

The emergence of a new system design calls for careful consideration of its reliability because reliability is of fundamental importance in judging the usefulness of a system, one case in point is the recently publicized Xbox issue, which has cost Microsoft more than a billion dollars in warranties (Mettas, 2010).

Reliability is extremely design-sensitive, very slight changes to the design of a component can cause profound changes in reliability, which is why it is important to specify product reliability and targets before any design work is undertaken. This in turn requires early knowledge of the anticipated service life of the product, and the degree to which parts of the product are to be made replaceable, as an example; for electrical and electronic systems, parts tolerances, drift characteristics, electrical stress and environmental stress can have a major impact on system reliability and on the individual failure modes of various system components. (Blanchard & Fabrycky, 2011)

Reliability prediction from design is less important for existing systems than for emerging new designs because existing system reliability maybe understood from analysis of maintenance and repair records (Ebeling, 2010). For example, the general architecture of the personal transportation automobile has been largely unchanged since Kettering invented the first electronic ignition system for automobiles in 1911 (Jeffries, 1960). As a result, the more than 100 years of automobile maintained and repair data, as well as the existing methods of studying reliability apply to studying the reliability of automobiles. For fundamentally different system architectures as is the case for emerging new system designs, the situation is much different. (NNDB, 2017)

A particularly important area for new systems designs is in renewable energy. (Erdinc & Uzunoglu, 2012). Public awareness of the need to reduce global warming and the significant increase in the prices of conventional energy sources have encouraged many countries to provide new energy policies that promote the renewable energy applications. Such renewable energy sources like solar, geothermal, wind, and water energies. Studying the reliability of renewable energy systems in particular became more important in the last decade because of the need to find long life reliable substitutions to fossil fuels (Erdinc & Uzunoglu, 2012).

Renewable energy is the purview of the office of Energy Efficiency and Renewable Energy (EERE) in the Department of Energy (DOE). The DOE's EERE office implements a range of strategies aimed at reducing our reliance on oil, saving families and businesses money, creating jobs, and reducing pollution, like using the solar energy. The DOE recognizes this, and in fact DOE supports the development of innovative, cost-effective solutions that allow increasing amounts of solar energy to integrate seamlessly into the electricity grid while mitigating associated risks. Such solutions can improve system reliability and encourage widespread deployment of solar technologies. That is why DOE requires all R&D studies they fund to include a reliability study for their new system. (DOE, 2014), (U.S. DOE SunShot Concentrating Solar Power, 2012)

One of these systems that recently has gained increasing interest because of research and development in the field of sustainable solar systems is CPV systems. These advancements could enable:

a) Higher conversion efficiencies,
b) Lower capital costs, and
c) Better reliability than competing products.

The CPV system architecture creates the potential for higher conversion efficiencies as contrasted with other sustainable solar systems such as flat plate PV system. Because CPV systems require significantly less silicon than other sustainable solar systems, their resulting lower capital costs was viewed as the technology's major potential advantage over flat-plate PV, particularly for utility-scale applications. That argument has become less relevant with the dramatic reduction in silicon prices over the last several years (Stalcup & Angel, 2012). CPV converts light directly into electricity in the same way that PV does. The difference of CPV regarding the PV stands in the addition of an optical system that focuses direct sunlight collected on a large optics area onto a small solar cell. The optics area to the solar cell area ratio is called geometrical concentration or simply concentration level whose dimensional units are typically referred to as suns or X. The technology of the CPV consists of assembling multi-layer junctions (three in recent CPV modules) on a single small space area chip to increase the efficiency of the absorbed spectrum of the sunlight, this will gain the solar cell power transferred efficiency (Algora, 2016).

By concentrating sunlight on higher-efficiency converters, CPV increases energy production per unit area. CPV's lower silicon requirement was viewed as the technology's major potential advantage over flat-plate PV, particularly for utility-scale applications (Stalcup & Angel, 2012).

The CPV industry is largely pre-commercial, and the technology currently represents a small fraction of the total PV market but most CPV systems are able to leverage recent advances in

commercial high-efficiency multifunction PV technology. Additional beneficial characteristics include capacity factors of up to 41% (versus 27% for flat-plate PV), stable performance in high-temperature environments, and potential reductions in water and land requirements. These features, combined with low-cost and locally sourced commodity materials and the ability to utilize existing manufacturing infrastructure for fast scale-up, may allow the CPV industry to more quickly capture market share.
In fact, TIMS Research declared that CPV represented 27% of the U.S. market by 2016 (TIMS Research, 2016.)

Other market research firms project that global CPV deployment will be a more modest 500 MW to 850 MW annually by 2017 (SPV Market Research/Strategies Unlimited, 2016).

1.3 The System of Interest

The present research focused on one example of an emerging new CPV system design, namely REhnu, Incorporated's second generation CPV system. REhnu specializes in developing and manufacturing CPV systems, and developed said system under contract to the DOE, which required an analysis of reliability new CPV system according to the DOE regulation standards. CITE (REhnu, 2013)

The REhnu second generation CPV system therefore became a convenient subject for the present research in the analysis of reliability for emerging new systems. This study is considered that system as a case study to consider extent methods, synthesis a new methodology for the reliability analysis of such systems using commercial reliability software tools, and applied it to the case study system. Figure 1 (an original photograph) illustrates the CPV system.

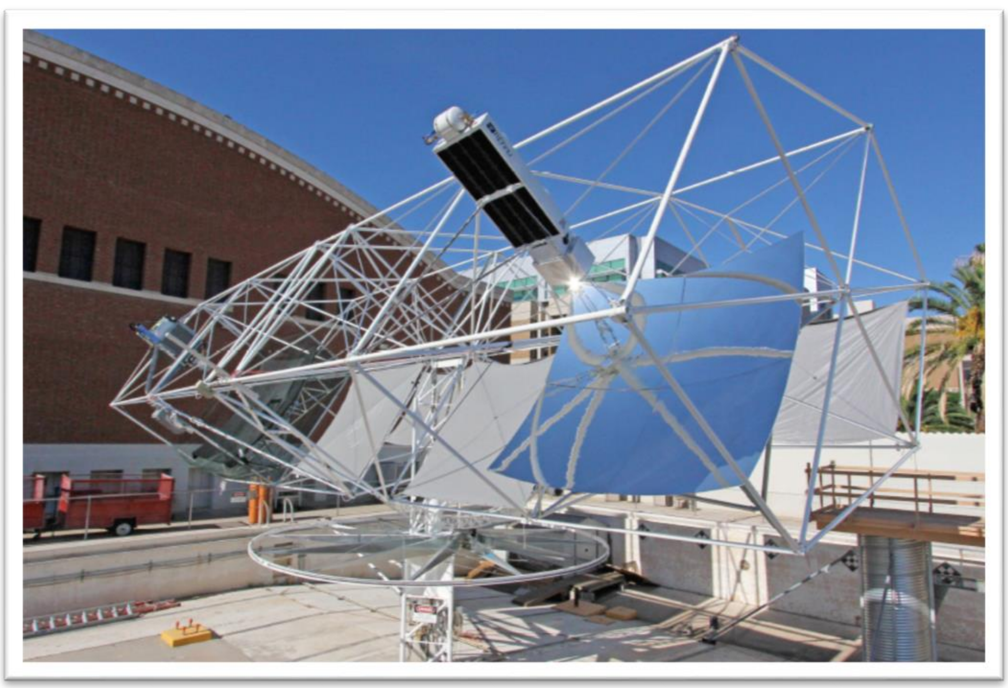


Figure 1: REhnu Second Generation CPV

The REhnu second generation CPV system use lenses and mirrors with tracking system to focus the sun's energy on multifunction cells that convert a large portion of the solar spectrum into electricity than the single-junction cells used in conventional flat-plate PV. This principle of operation is illustrated in Figure 2.

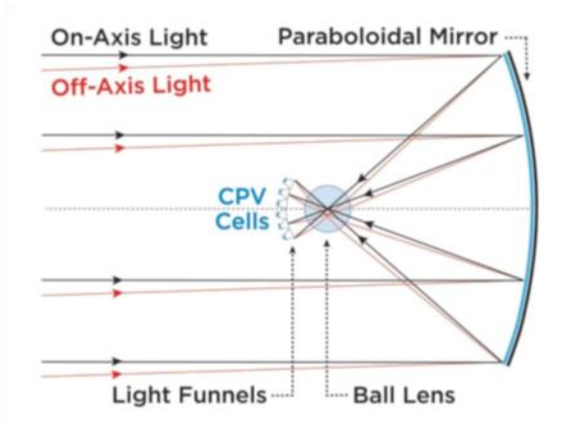


Figure 2: REhnu Second Generation CPV Mechanics and Operating Principle

The main elements of the CPV systems under study of this research are the Primary Optical Element (POE), reflector, receiver subsystem, thermal subsystem, Balance of the System (BOS), and mechanical subsystem (Algora, 2016).

The following paragraphs discuss each element in turn.

The POE redirects the incoming parallel light rays from the sun to a focal point where the receiver is placed. The POE in the REhnu second generation CPV system is a ball lens as shown in Figure 3.

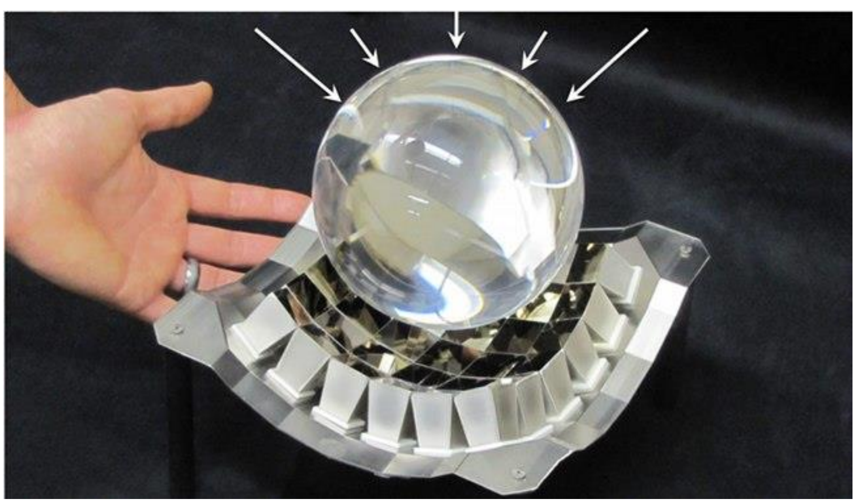


Figure 3: REhnu Second Generation CPV Ball Lens

The 3.1 meter–square paraboloidal mirror reflector is a dish shaped mirror reflector which reflects and concentrates the sun rays on the POE. The length of one side of the square mirror is 3.1 meters.

The receiver subsystem is shown in Figure 4. The receiver includes the solar cells and all associated components that are pre-assembled to it including the secondary optics reflectors and heat sink.

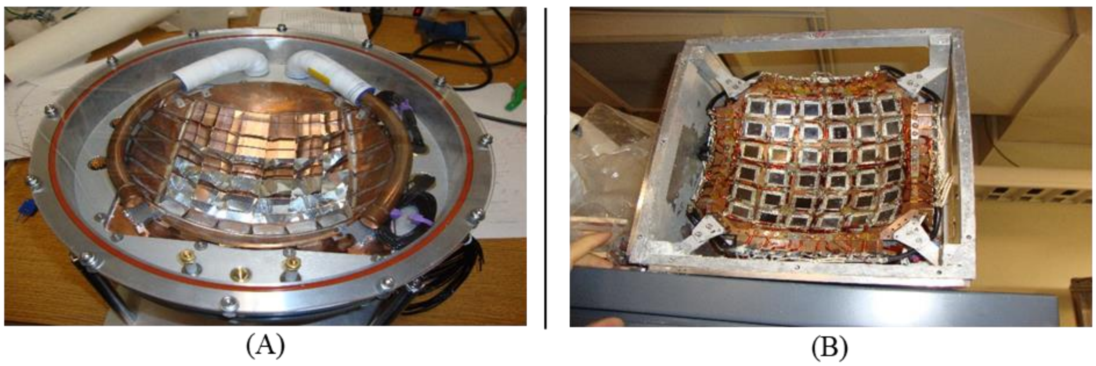


Figure 4: CPV Receiver Showing (A) Inside the Housing and (B) With the Solar Cells

The thermal subsystem is shown in Figure 5, this includes the heat sink/spreader which dissipates the extra heat produced by each solar cell. The heat sink/spreader is a thick copper finned plate bonded to the Carrier (i.e., Funnel Bowl) which is the thermal attachment that also acts as initial heat spreader. The thermal subsystem also includes the external heat exchange subsystem shown in Figure 6 to dissipate the heat of the thermal attachment to external environment. The external heat exchange subsystem consists of radiator, coolant pump, copper pipes, funnel cooling frame, and external fan.

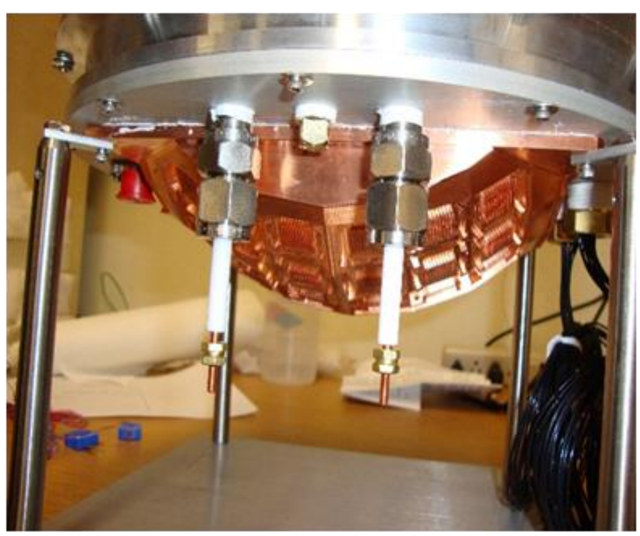


Figure 5: CPV Funnel Bowel Cooling Frame

Figure 6: CPV Heat Exchanger

The BOS of this CPV system shows in Figure 7 is the electrical and electronic components of the system. This consists of the following: main control board, inverters, UPS and batteries, analog to digital (A/D) converter board, and electrical sensors.

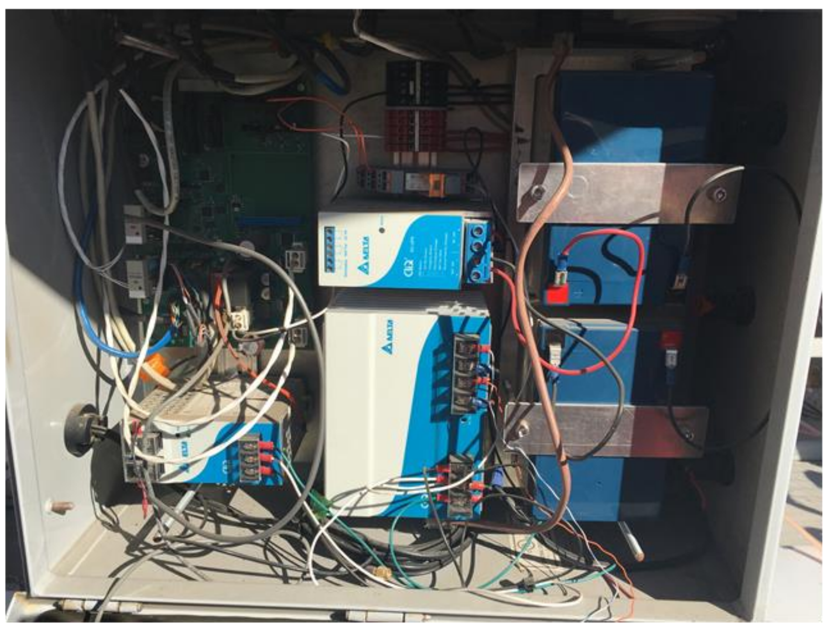


Figure 7: CPV Balance of System

The Mechanical Subsystem consists of the chassis and tracker as shown in Figure 8. The chassis envelopes the receiver and provides the structure onto which the rest of the components mount. The tracker that encloses the all subsystems and provide the required track movements to follow the sun beam by means of servo motors and mechanical drivers.

(A) (B)

Figure 8: CPV Mechanical Subsystem Showing (A) Chassis, and (B) Tracker

1.4 Overview on Concentrated PhotoVoltaic (CPV) Reliability

Reliability is an engineering discipline, using specifically developed standards and tools, whose objective is to help design engineers and maintenance organizations achieve and sustain reliable and safe systems (Algora, 2016).

IEEE describes the discipline in the following manner (IEEE 2009): "Reliability is a design engineering discipline which applies scientific knowledge to assure a product will perform its intended function for the required duration within a given environment. This includes designing in the ability to maintain, test, and support the product throughout its total life cycle. Reliability is best described as product performance over time. This is accomplished concurrently with other design disciplines by contributing to the selection of the system architecture, materials, processes, and components -- both software and hardware; followed by verifying the selections made by thorough analysis and test."

Therefore, the computation of a CPV system design's reliability is a matter of importance because:

a) To develop a long life CPV system with less failures and maintainability,
b) To increase the availability and therefore the total efficiency of the system, and
c) Analyze the safety and risk management of the system.

CHAPTER 2: LITERATURE REVIEW

This chapter is consisting of three parts. The first part provides an overview of reliability and those aspects of reliability that are particularly important to the study of CPV system reliability. The second reviews the fundamental concepts of reliability, namely formulation of the statistical forms of the reliability function and other related functions such as the failure rate function. The statistical relationship between these functions is exposed in this part. The third part of this chapter explores the suitability of nine well-known reliability methods for the needs of the CPV system reliability problem. The exploration presents each method using a graphical language commonly used in systems engineering called the Structured Analysis and Design Technique (SADT) to expose the application and pros and cons of each method.

2.1 Overview on Reliability

The development of PV systems requires a high initial investment cost, so these systems must have long life cycle and have high working reliability to cover these costs. Flat panel PV system designers realized this fact from the beginning and they worked to study and develop the reliability of these systems, so that they now have the required advanced technology to ensure the reliable working of these systems for a period of 30 years sufficient to provide a warranty and ensure a 5% degradation limit. (Algora, 2016)

In contrast, the technology of the CPV module is still relatively new and needs more study and research about the reliability., The documented collection for the reliability data of the CPV modules started in 2005 (Algora, 2016) to cover some commercial development, and this is a short period compared with the big stack of accumulative data that is available about the flat pad PV systems. The study of the CPV reliability is essential in reducing the cost and increasing the availability of the CPV system.

As introduced, the system under study is the second generation CPV system developed by REhnu Company in the Steward Observatory Laboratories in the University of Arizona funded and financial supported by the US Department of Energy (DOE) (Stalcup, 2012).

This research centers on the reliability of a system. This study does not examine the reliability of a specific piece or component, and precisely when it will be replaced or will need to be maintained. Study of component reliability is of great interest to manufacturers of parts or components, as well as marketers or research centers interested in developing product life and make it more efficient and less maintenance and cost (METTAS, 2010). This kind of study is very common and hence numerous research and studies exist in this area for a wide variety of components. The variety of options of selecting the required components to build the systems or subsystem in this area can be wide, many and confusing for developers (Berg, 2010). They can choose the very high-quality components that enjoyed high reliability in their product, but subject to the following considerations. (Aggarwal, 1993)

1) This will be at the expense of cost.
2) This may not have the part or piece of high quality which is compatible with the rest of the system.
3) The combination of parts for a system consists of several components of high quality and reliability cannot ensure that the reliability of the total system is equal to or higher

than the reliability of its parts due to the extreme circumstantial conditions of the installation of these parts and their integration with each other.

For example, consider an example of a simple traditional subsystem, a source heat dissipation system consists of a radiator, coolant, pump, source of heat to be dissipated, and pipes. The developer of this system can choose the components of such system that have very high quality and reliability (this will be of course at the expense of cost), but the position of the pump to the radiator may be a factor in reducing the lifetime and reliability of the pump that selected with high reliability at the design stage.

While there is no single commonly accepted and appropriate methodology for analyzing and developing the reliability for the whole CPV system, there are methods for components of the CPV system. In contrast, this study examines reliability from the point of view of the entire system, i.e., the product. Table 1 summarizes the extant CPV reliability literature from the point of view concerning CPV components (like CPV solar cell, thermal units, and BOS) versus CPV system.

Table 1: Summary of Extant CPV Components Versus CPV System Reliability Literature

	CPV Components	CPV Systems
Importance of Reliability for CPV	(Algora, 2016)	(IMS, 2016)
Methods	(Núñez, González, & Manuel Vázquez1, 2011)	No suitable literature, hence the motivation for the present research
Minimum Reliability Requirements	(IEC62108, 2010)	(IMS, 2016)
Testing Requirements	(IEC62108, 2010)	(Robust, 2016)

The way that is used to study and analyze the reliability of the CPV system is based on answer these three questions.

1. Is system reliable enough to be relied on for a certain working time?
2. Which component of the system can fail or needs to be maintained?
3. How can the reliability of the system and its components be improved?

(Ebeling, 2010)

Numerous research publications show that many companies that develop or manufacture a system are interested in studying *Design for Reliability* (DFR), that is the reliability of their product when it is under development and how to reduce the failure rate or potential hazards in the future (Murthy, Rausand, & Østeras, 2008); (METTAS, 2010); (Birolini, 2007); (Lee & RongPan, 2017).

Furthermore, after systems are fielded, their owner/operators often feel the need to assess reliability during operations and sustain; this is termed *Utilization Reliability*. Utilization Reliability (UR) assesses whether system or product has met its reliability objectives to:

a) identify unexpected failure modes,

b) record fixes,
c) assess the utilization of maintenance resources, and
d) assess the operating environment. (DoD, 2005)

Several reliability methods exist which may be used for the purpose of utilization reliability. In order to assess reliability in this stage of system life cycle, it is necessary to maintain an accurate record not only of failures but also of operating time and the duration of outages. Systems that report only on repair actions and outage incidents may not be sufficient for this purpose. (DoD, 2005) Figure 9 explains the need for DFR and Utilization Reliability in system life.

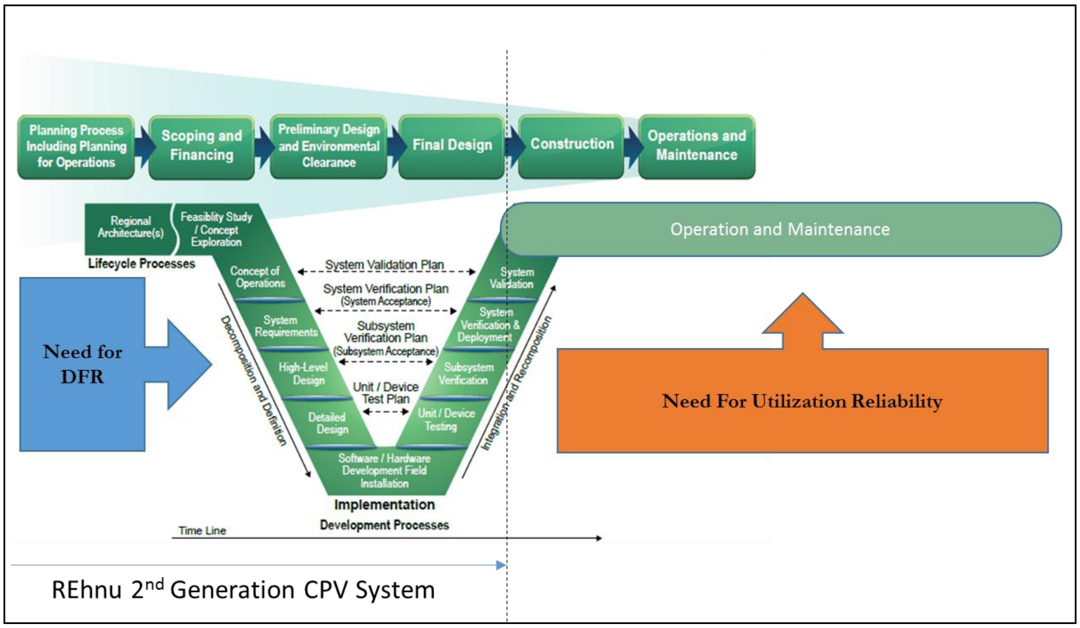


Figure 9: Design For Reliability and Utilization Reliability in System Life

One objective of studying the reliability in the phases of the system life cycle is to analyze the reliability of the system and its component is to certify if this reliability fits the requirements of the system. If the resulting reliability parameters are not sufficient to qualify the desired requirement, the reliability of the system has to modify by applying reliability improving methods to enhance the system reliability. (Ebeling, 2010)

From this concept, this research considers two terms for reliability study: *Analyzing Reliability*, and *Improving Reliability*. The Analyzing Reliability considers about computing the reliability parameters by applying defined methods to express the probability of failure. (Rausand & HØyland, 2004)

Analyzing Reliability of a system based on a wide range of assumptions and boundary conditions like defining the objective of the analysis, determine the level of detail required, and which operational phases are to be included in the analysis (e.g. DFR or Utilization Reliability). This study is important to:

a) To verify system meets requirements,
b) To certify the system meets standards, and
c) To collect data for future designs. (Rausand & HØyland, 2004)

While the Improving Reliability study intends to leverage and enhance the reliability parameter by surfacing failure modes and implementing effective corrective action. (Feiler, Goodenough, Gurfinkel, Weinstock, & Wrage, 2012). The Improving Reliability implemented by accepting current reliability as an input and consider the alternative system design to improve this input considering some limitation like the cost. The goal of this improvement is to improve customer satisfaction, and to reduce maintenance and sustainment costs. There are different architectures to achieve this goal, like:

a) Improve components,
b) More /fewer components, and
c) Change interfaces. (Feiler, Goodenough, Gurfinkel, Weinstock, & Wrage, 2012)

From the above discussion, the research worked on reliability on four aspects shown in the Table 2.

Table 2: The Needs for Reliability for the CPV System

	Analyzing Reliability	Improving Reliability
Design for Reliability	Needed for CPV	Needed for CPV
Utilization Reliability	Needed for CPV	Needed for CPV

2.2 Reliability Engineering Fundamentals

Reliability Engineering is defined to be the discipline of determining the probability that a component or system will perform a required function for a given period (Charles & Ebeling, 2010). This is the formal definition for the reliability, and the industrial definition is that the capability of providing function or service when requested.

To determine reliability in an operational sense, some aspects must be considered:

1) Specify the intended function unambiguously to know if a product works properly or has failed,
2) Identify the unit of time (clock time, operating hours, or cycles), and
3) Specify the working condition of the system to do the reliability analysis, more stress on the conditions or environment of systems' parameters decreases the reliability of the system.

(Algora, 2016)

As the reliability defined by probability of no failure, using probability and statistics is necessary to determine the reliability of the systems. The main probability functions related to the reliability are:

a) Failure probability density function (pdf) i.e., $f(t)$,
b) Cumulative Distribution Function (CDF) of the failure i.e. $F(t)$ or namely, the integral of the pdf,
c) Reliability function i.e. $R(t)$,
d) Failure rate or hazard function i.e., $\lambda(t)$, and
e) Mean Time To Fail (MTTF) i.e. $E(T)$.

The time to failure (t) is the random variable associated with the probability density function for reliability study of this research. Recall that the random variable is the variable that takes on numerical values in accordance with some probability distribution. The value of $f(t)$ will increase if the failure of the system increases in a small interval of time.

The pdf, $f(t)$, has these two properties:

$$\int_0^\infty f(t)dt = 1 \quad \text{where} \quad f(t) \geq 0\text{, and}$$

The cumulative distribution function (CDF) of the failure distribution (also called the *unreliability*), is normally used when failure probability is being computed, it is the population fraction that has failed at instant of time t. So, the $F(t)$ is the probability of falure until an instant of time t, can be put in the following function:

$$F(t) = \int_0^t f(t)dt \quad \text{where } F(0)=0,\ F(\infty)=1$$

The reliability function, $R(t)$ is normaly used when reliability is being computed, it is the population fraction that has not failed at an instant time t. $R(t)$ the probability of success is the complementary to $F(t)$, and it can have formulated as:

$$R(t) = \int_t^\infty f(t) = 1 - F(t) \quad \text{where } R(0) = 1, \text{and } R(\infty) = 0$$

The failure rate or hazard rate function $\lambda(t)$is often used in reliability. It gives the failure probability but only of the surviving products. Also, it gives information about the periods in the life of the product or the system, or we can say that the failure rate function indicates the frequency with which surviving products will survive.

$\lambda(t)$ has units of failure per unit time (e.g.: failure/hour), can be formulated as:

$$\lambda(t) = \frac{f(t)}{R(t)}$$

Mean Time To Fail (MTTF) i.e. $E(T)$ formulated as:

$$MTTF = \int_0^\infty tf(t)dt \quad \textit{, or} \quad MTTF = ET = \int_0^\infty R(t)dt$$

The failure rate function gives information about the life cycle of the system or component, the form of the failure rate function is shown in Figure 10, and it calls the bathtub curve because of its shape. In this figure we can recognize three periods in the life cycle of the system.

1- Early (Infant Mortality) failure period or (Burn-in): In this stage the failures is happened due to the malfunctions of manufacturing, and the product will have Decreasing Failure Rate (in practice, this is often referred to as DFR, not to be confused with the acronym of Design For Reliability in this work).

2- Constant (random) failure period or (Useful Life): This stage lasts most of the product life and starts directly after the first stage. In this stage, the product has an almost Constant Failure Rate (CFR).
3- Wear-out failure period: In this stage the materials wear out and degradation occur at increasing rate, and the product will have Increasing Failure Rate (IFR).

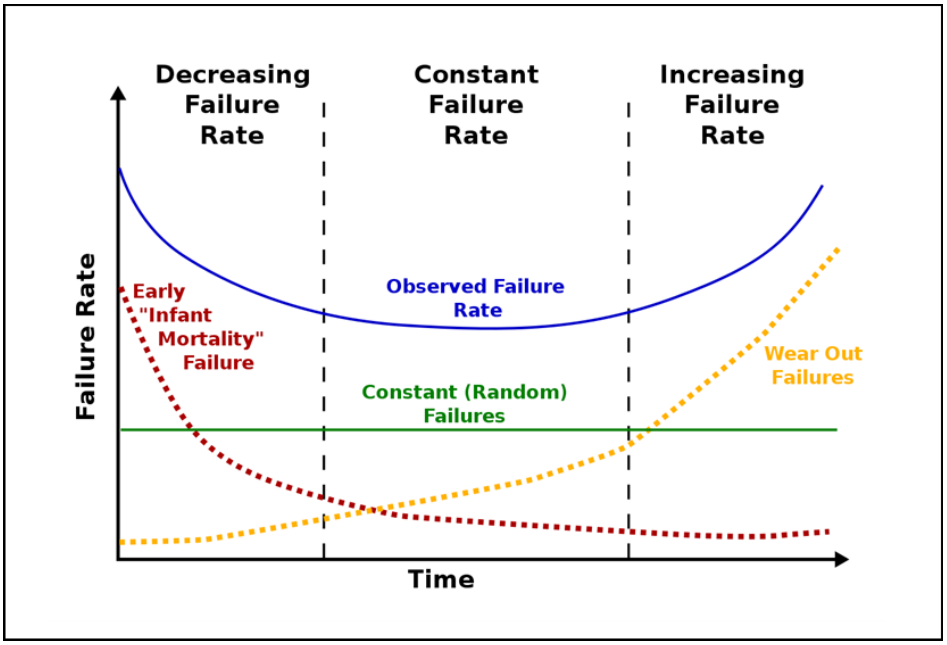


Figure 10: Failure Rate Bathtub Curve

2.3 Methods for Reliability

Every industry views the analysis and consideration of reliability differently. This has especially affected the development of different methods used to analyze reliability. The methods are not necessarily very industry specific, but they have been developed from the specific need the industry sees to address system failure.

Although industry clearly considers reliability in sustainable solar systems important, (Aggarwal, 1993) the CPV industry has no standards for reliability methods. IEC62108 standards specifies the minimum requirements for the design qualification and type approval of CPV modules and assemblies suitable for long-term operation in general open-air climates, but does not specify required reliability methods. IEC 62108 standards do discuss a reliability strategy, which states that reliability analyses should be integrated in the design phase. The standard explicitly states there is no specific guidance for the setting and allocation of reliability requirements in the CPV industry, which would be part of a reliability method. The standard establishes a goal for CPV system designers to allocate reliability down to the component level and verify do the standard required testing under the standard's specified environment. (IEC62108, 2016)

The methods used at a certain point of the life cycle will depend on how the product is manufactured, its intended use, and how far into the development it is, but in any case, these do not apply to the CPV system (Stalcup, 2012).

In the earliest development phases, preliminary studies of the reliability can be performed, while in phases where the product is materialized, physical tests become possible.

For a product produced in large numbers, for instance an iPhone 8, tests leading to destruction may be used. Prototypes can be developed at little expense and depending on the product's size the tests may be performed by employees bringing the product home. When the product is of such a scale or cost like the CPV systems and its related structure, destructive testing is harder to apply. (Mark Spencer, 2010)

Non-destructive testing is in use, but these rather prove the ability to perform than the failures. One such test is Factory Acceptance Test (FAT), whose main goal is to confirm that all parts of the system functions as intended. Alterations may be done after this test in case of unacceptable results.

The CPV industry is a very good example of how specific conditions might demand more of the system reliability for custom made products than standard product. In this industry it is likely that the products are of a large scale, expensive and made to order.

Depending on the CPV proposed lifetime, a product can be required to operate for many years. Due to new developments increasing the field's lifetime, a product can be demanded to last even longer than originally planned. All these factors increase the importance of reliable designs. The lack of real-time data is a difficulty shared with the aerospace industry, while the extension of planned time in use is a trait shared with the nuclear industry. An example is France which in 2012 extended the life of two nuclear plants ten years, from the previous expected thirty years to forty. This can be both dangerous and press the systems towards their wear-out phases.

Thorough and precise methods for reliability are thus needed to confirm that the extended life is acceptable.

The more commonly applied methods for the analysis of system reliability are not made to suit all phases of a product life cycle (Berg, 2010). Nor can they include every aspect of interest to an analyst. All methods need certain inputs and produce specific outputs (Berg, 2010). The outputs of one method may be the input of another. Some of the methods are more overlapping, but necessary together for the output they give (Berg, 2010). Other can stand alone at a specific point in the life cycle, but will not give the most useful outputs without the help of a later method analyzing them. The methods are not necessarily stuck to one single phase, but can be updated throughout the life cycle. A good example is the Failure Mode and Effects Analysis (FMEA) which exists in several formats, and can be useful in many phases.

The methods described in this chapter are some of the more well-known tools used by reliability engineers. All of them are applied across most industries, depending on product type. Which method one ends up with should depend on the life cycle phase, the desired outputs, the product and the available resources? A methodology for DFR must contain a selection of different reliability methods based on their ability to complete each other.

Early in the life cycle, the method choice will be constrained by the existing information about the product. Many parts may not be specified, and changes will probably occur later on. During later phases, the input to the analyses can be found from other similar products, methods performed in the previous phases and tests. Depending on the cost, size and utilization of an item, certain methods may not be applicable at all.

Some of the methods are already used together in specific types of analyses, in order to develop a specific overview of a product. One such method is the reliability, availability and maintainability (RAM) analysis. This uses Fault Tree Analysis (FTA) and Reliability Block Diagram (RBD) among other methods.

Each method will be presented through the Structured Analysis and Design Technique (SADT). SADT was one of the first methods for the graphical specification of requirements, SADT enables the representation of complex systems by means of hierarchically ordered diagrams, and can be used for the actual analysis of existing systems as well as for defining the requirements of new systems (Krönin, 2017).

As shown in the Figure 11, there are five main elements in the SADT model as follows. (Rausand & HØyland, 2004)

1) Function: Is the method which is to be performed.
2) Inputs: Are the energy, materials and information needed to perform the reliability method.
3) Mechanisms: Are the people, facilities and equipment needed to perform the function.
4) Controls: Are elements for a reliability method influence the execution of an activity but are not consumed, like standards, requirements, demands and budgets.
5) Outputs: are the results after the method has been used.

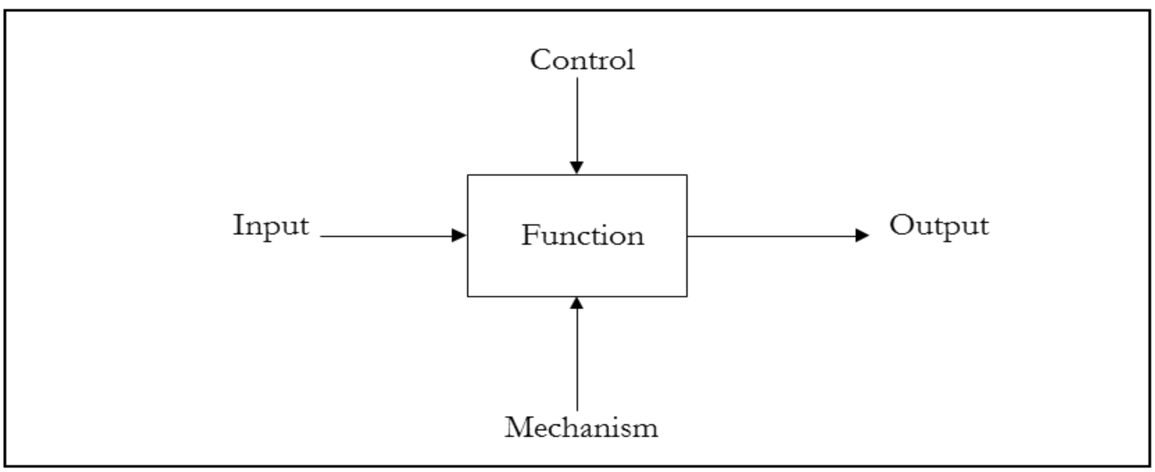


Figure 11: Structured Analysis and Design Technique (SADT) Model

The following discussed provides an overview of the basic method, then itemizes the required input, the mechanism, the control and lastly the output.

Using SADT as a tool to evaluate the applicability of a method can be preferable when there is a need to act in accordance with specific constraints and demands for the desired outputs. If a reliability program is desired, the SADT can show which methods may follow one another to complete each other and the reliability picture. It is for example evident in this chapter that FMEA and FTA are useful together in order to show both simple and dependent failures.

2.3.1 Preliminary Hazard Analysis (PHA) Reliability Method

In the beginning of the product life cycle little information is available, unless the product is a new generation of another product. The reliability analyses performed at this stage cannot demand too much input. Their output, on the other hand, must to give information which increases the knowledge about the product features. An analysis which can be performed early is PHA. This method is a semi-quantitative analysis which helps identify potential hazards and accidental events, ranks the events according to severity and considers hazard controls and follow-up actions (Rausand, 2005). PHA was developed by the US army and has later spread through to other industries. Another slightly different type of PHA, with the same objectives and need for inputs, is HAZard IDentification (HAZID).

The PHA procedure consists of four steps; PHA prerequisites, hazard identification, consequence and frequency estimation, risk ranking and follow-up actions (Rausand, 2005). All parts of a system or product must at first be considered in a search for hazards. This includes failure modes, known maintenance operations, safety systems and potential human errors. The frequencies and severities of each hazard should be considered and classified in classes ranging from “improbable” to “frequent” and from “negligible” to “catastrophic”. Figure 12 **Error! Reference source not found.** illustrates the PHA Reliability Method using SADT.

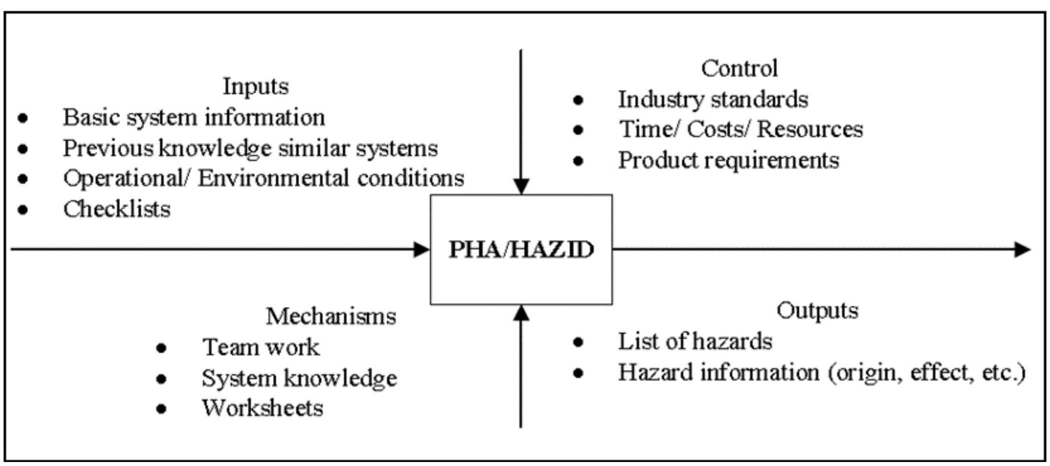


Figure 12: SADT Applied to Preliminary Hazard Analysis Reliability Method

<u>Inputs</u>

Any information about the system; design plans, concept definitions etc. is useful input. Checklists can be followed to remember all elements which are to be studied and what is to be studied about them. Other inputs such as risk information and block diagrams may come from similar existing systems (Stapelberg, 2009).

Mechanisms
The mechanisms of this analysis are based on team work. The members should complement each other with different backgrounds and knowledge, enabling a more complete review of the whole system. If little information can be obtained, useful techniques for the retrieval of inputs can be what-if techniques and brainstorming (Rausand, 2005). These techniques are based on imaginative thinking and are generally thought efficient for team work.

Control
In some industries there are standards describing how the PHA is to be performed and which outputs the final report should include. The main part of demands to the analysis will be given by the organization it is performed for. This will depend on the limitations of time and costs given to perform the analysis. All product requirements which have been established can be considered, both as input to the analysis, and as controlling the main focus of the analysis. (Ødegaard, 2003)

Outputs
A PHA will produce a list of all hazards considered, including where they may originate from and a ranking of how grave the event's occurrence can be. The latter will be very useful for later reliability analyses, if some hazards need to be prioritized above others. To present the outcome of the PHA, a worksheet is made. This worksheet is standardized in several industries and will give a clear perspective of the different hazards connected to the system studied. There are few, or sometimes no differences between the worksheets of the HAZID and the PHA. The worksheets will mostly depend on the systems and the organizations that employ the analyses (Ødegaard, 2003).

The PHA method is not sufficient to study and develop the reliability of the CPV system because it focused and worked in the early preliminary stage of the system design and the method does not address on how to improve the reliability of the CPV system during the whole life of the CPV system which is in the point of interest of this research. (Rausand, 2005)

PHA addresses part of the DFR needs such as early in the concept of operation or high-level requirements of a system life cycle when there is little information on design details but not in detailed requirements, high-level design or detailed design. Further, PHA does not support the need for Utilization Reliability of the CPV system because it is not extensive method. (Valis & Koucky, 2009)

2.3.2 The HAZard and OPerability (HAZOP) Reliability Method

The hazard and operability study (HAZOP) was first published in the late 1960s for Imperial Chemical Industries (ICI) and further developed and published for the ICI Petrochemicals Division in 1974 (Swann & Preston 1995). It is a structured and systematic method, performed as a team work with members specialized in different areas necessary to understand the defined system (IEC 61882 2001).

The objective is to identify the potential hazards in the system and the possible operability problems, for instance causes for operational disturbances and deviations (IEC 61882 2001).

An attempt is made to find all possible deviations from the intended design of the system. The search is performed through the use of a number of guide words triggering the imagination of the team members. An example is the word “More” which is supposed to bring the thought to a problem where the deviation is an increase compared with the intended design. If it is used for a component received amount of radiant power, “more” could mean that a CPV solar cell accepts a higher radiant flux than intended. Figure 13 shows the SADT applied on HAZOP with listed inputs, outputs, mechanisms, and controls.

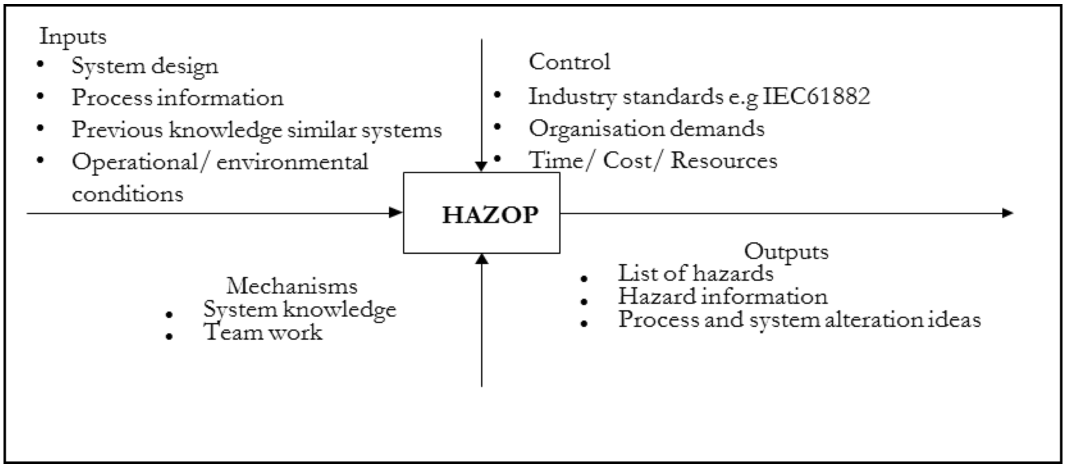


Figure 13: SADT Applied to HAZard and Operability Reliability Method

Inputs

The input to the HAZOP is the system design and the operational information for the system. If similar systems exist, hints may be acquired for the guide words. A HAZOP study can be done in several life-cycle phases, but is recommended performed just before the design is fixed. The design should then be detailed enough to contain the information needed to answer the guide words (IEC 61882, 2001).

Mechanisms

In order to perform the HAZOP, team work is necessary. Together, the members should agree on the guide words and how the system is to be studied. Little is needed to perform the HAZOP and depending on the extent of the study, the analysis may be performed within a small-time frame. (Ødegaard, 2003)

Control

To control the analysis, the IEC 61882 (2001) is a good instrument. Any specific demands for the output of the analysis will also be of interest. The design drawings can be utilized as a proof of whether the identified problems are realistic or not.

Outputs

When the HAZOP has been performed, the outputs are used for improvements in the design, and to alter routines in the operation. HAZOP can be performed for several purposes, and is very useful for the discovery of problems to watch out for in the manufacturing phases. (Ødegaard, 2003)

The HAZOP reliability method is not applicable to a new prototype of system design because one of the inputs is the previous knowledge of similar system and this input is not exist in the case of the new generation of the CPV system.

2.3.3 Structured What-If Technique (SWIFT) Reliability Method

The Structured What-If Technique (SWIFT) is a brainstorming technique where a team search for hazards through questions like "What if...?" and "How could...?" (Ratzinger, 2007). It was originally developed for the chemical process industry and is today also used in other industries, for instance the aircraft industry. SWIFT mainly considers systems at higher levels, either the complete system as a whole, or a sub-system. The technique is an alternative to the HAZard and OPerability (HAZOP) study as it is less time consuming and costly. These two methods do not operate on the same level of detail. It is thus possible to use them as complementary studies (MoD, 2010). Figure 14 showing the SADT model for SWIFT Reliability Method.

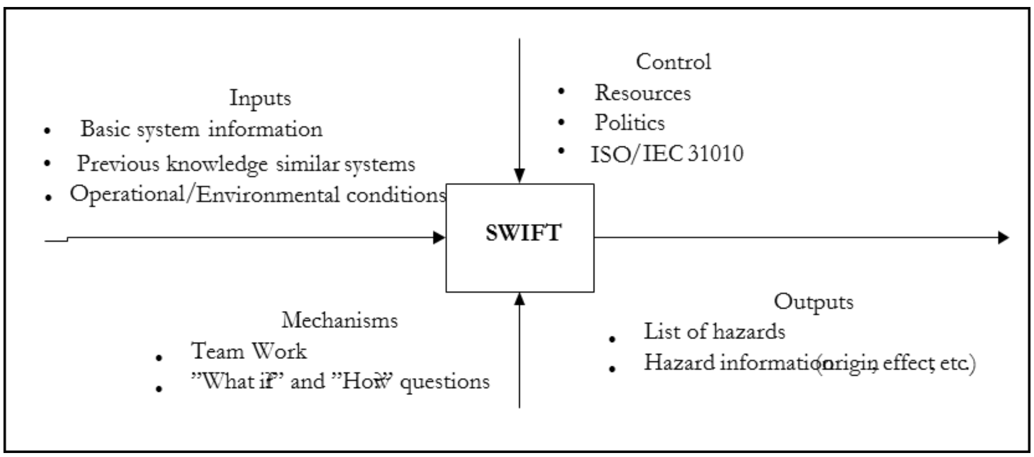


Figure 14: SADT Applied to Structured What-If Technique Reliability Method

SWIFT is easy to use through all phases and for many purposes, for example as a study of a manufacturing process.

There is no specific standard for the SWIFT technique, but it is mentioned in the ISO/IEC 31010 (2009). The normal procedure includes a definition of the activity and problems of interest, a generation of what-if questions and responses, and a report on the findings. If the method is performed after a PHA or HAZID, many hazards will already be known. The SWIFT could then go further into the question of how the hazard would affect the system, and whether the rankings made were correct.

<u>Inputs</u>

To perform a SWIFT analysis, it is necessary to have a basic system description, a definition of the activity, and some problems of interest. These inputs, along with a checklist for which elements one should study, would give all the information needed. (Kritzinger, 2007)

Mechanisms
The mechanisms of this method are the chosen team. It is very important for the success of the analysis that the team members have sufficient experience with the system and the technique. They must also be able to understand the output of other analyses performed before the SWIFT. The technique itself is a mechanism through the questioning. (Ødegaard, 2003)

Control
Controlling factors are few for the SWIFT. It does not demand much time or cost to perform it, nor has it been standardized. The main controlling factors would thus be the resources and whether any political issues affect the questions asked. The latter may happen in most reliability analyses and is troubling if it leads to the exclusion of failure considerations with dangerous effects. This method is described in the ISO/IEC 31010 (2009) standard which also shows it against other techniques.

Outputs
Outputs from the SWIFT are hazards, their causes and possible effects. Together with other hazard identification tools it can provide a good overview of the problems possibly faced by the system. This can be used as inputs to FMEAs, FTAs and other reliability analysis methods. (Ødegaard, 2003)

A negative aspect of the SWIFT which is not suitable to use in the CPV system is that a failure problem is likely to stay unnoticed if the team fails to ask the correct questions because this method depends mainly on the brainstorming technique and the teamwork skills to ask sufficient comprehensive questions (Valis & Koucky, 2009). Another problem is its inability to produce quantitative results which can answer the more complex risk-related questions which is one of the main interest of this research.

SWIFT is prone to human error, because it is a systematic, team based study, utilizing a set of 'prompt' words or phrases that are used by the facilitator within a workshop which is particularly a risk in unprecedented or relatively new systems such as CPV (Valis & Koucky, 2009).

2.3.4 Reliability Growth Method

Reliability growth is a physical test method. The intention is to improve the reliability through a test analyze-and-fix technique. A component will be tested under increasing amounts of stress until failure. The test results are then analyzed and if they do not satisfy the requirements, improvements will be made. This process continues until the reliability requirements are met with as Figure 15 shows (Murthy, 2008).

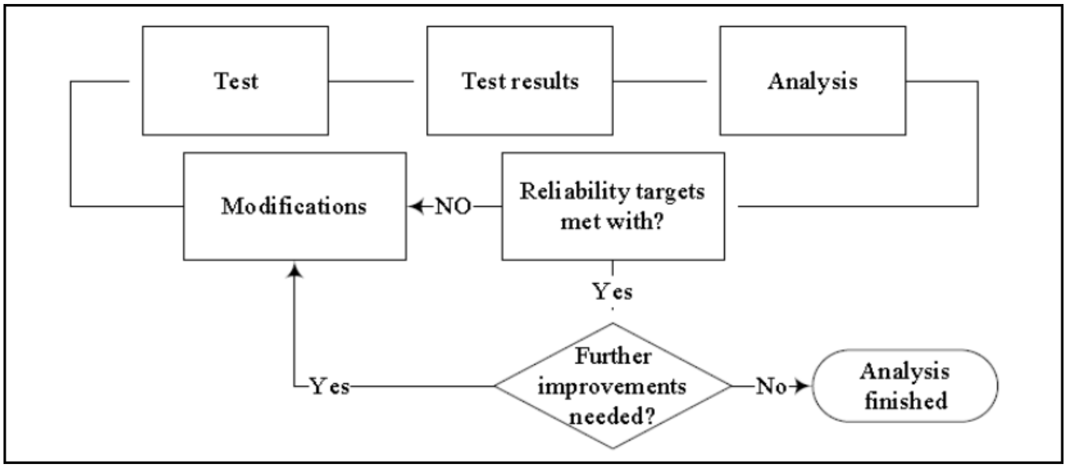


Figure 15: Reliability Growth Process

For products that are very expensive and built as one-of-a-kind, it can be hard to perform reliability growth tests. Reliability growth is meant to lead to a failure, which cannot be accepted for the overall product in this case. Sub-systems and components which are not expensive and time consuming to develop can, on the other hand, be subject to the tests. (Ødegaard, 2003)

What a reliability engineer must be aware of is that the amount of "runs" which are performed in the reliability growth process has an effect on the outcome. For every run, the component or system is pushed further towards failure. This must be considered in the analysis as the previous load can mean that the system fails in run three, although it can handle more stress than what it was subjected to. (Ødegaard, 2003)

As reliability growth tests usually are performed as early as possible during the product's physical life, little knowledge is available. The results of the tests must therefore be studied carefully by analysts with good understanding of the necessary physical and mathematical analyses, and an ability to make sound judgments (Blischke & Murthy, 2000). The following section describes the Reliability Growth method as shows in Figure 16.

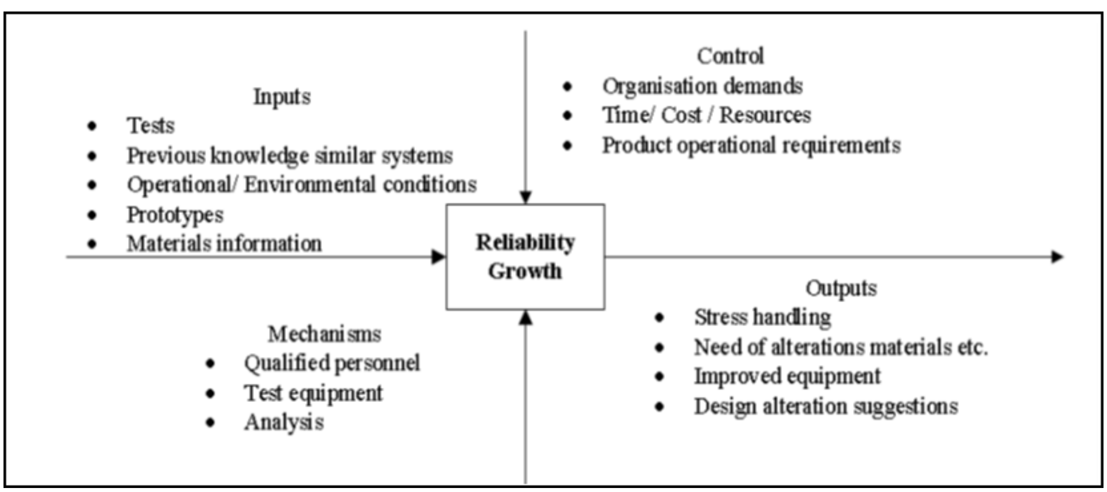


Figure 16: SADT Applied to Reliability Growth Method

Inputs

To perform the reliability growth test, prototypes of the components and the results of analyses performed implying necessary testing will be needed. Other information will be the outer limits a type of material can handle under stress, and how the tests are performed. (Ødegaard, 2003)

Mechanisms

To perform the tests, qualified personnel is needed. Proper equipment and laboratories with good environmental conditions for the tests are also necessary mechanisms of this method. Some of the more important factors for a successful reliability growth test are good management, tests that give comprehensible answers, the ability to identify the root cause of failures, effective corrective actions and valid reliability assessments (Berg, 2010).

The reliability found in this type of analysis is based on how the system responded to the testing and corrections. It is therefore vital that the measures taken are thought-through and sensible.

Control

Control of the reliability growth tests will depend on resources, time and money. The number of runs will vary with time and resources. The organization developing the system may also have some demands concerning which tests the system should undergo and the conditions they should be performed in, for instance specific temperatures. IEC 61014 (2003) suggests programs for reliability growth and may be followed both as a mechanism and as control.

Outputs

The main outputs will be how the tested elements handle the stresses they are subjected to and whether alterations must be done to the production of the system. If the reliability growth tests are used on materials in a very early phase, the output might be used as inputs to the design phase when the materials are chosen. (Ødegaard, 2003)

In the CPV industry and other industries where the products are the prototypes, reliability growth tests are restricted. The tests must then be performed on components that can be tested to failure and are not too expensive for this purpose. What the analysts have to remember in this case is that the results from component tests may not give all the answers. When the component becomes a part of the complete system, the possibility of new failures might occur that were not found through previous testing (Berg, 2010).

2.3.5 Failure Modes and Effects Analysis (FMEA) Reliability Method

Failure modes and effects analysis (FMEA) is a systematic technique for the study of failures. It was developed in the 1950s by reliability engineers for the study of military system failures (Rausand & Høyland, 2004).

FMEA is meant to be an input to the design process, enabling alterations of problems before the design is too settled. In order for this to be possible it is suggested that the FMEA is performed as early as possible in the development process. As the development progresses, it is possible to keep filling in the failure information. This can be useful for other reasons than reliability, for instance safety and maintenance. The FMEA can be extended to include a criticality ranking of the different failures. In this case the criticality ranking is a combination of a severity measure set for the failure mode and its frequency of occurrence (IEC 60812, 2016). The extended FMECA is called a Failure Mode, Effects and Criticality Analysis (FMECA).

The FMEA is usually a bottom-up analysis, where as many components, assemblies and subsystems as possible are included. To begin the analysis, a study of how each part may fail is done (Rausand & Høyland 2004). This should be followed by the study of why they occur, what their possible effects are, and how they can be detected. It could also be studied how the failures might be compensated for and whether they are dangerous or not. Figure 17 showing the SADT for the FMEA reliability method.

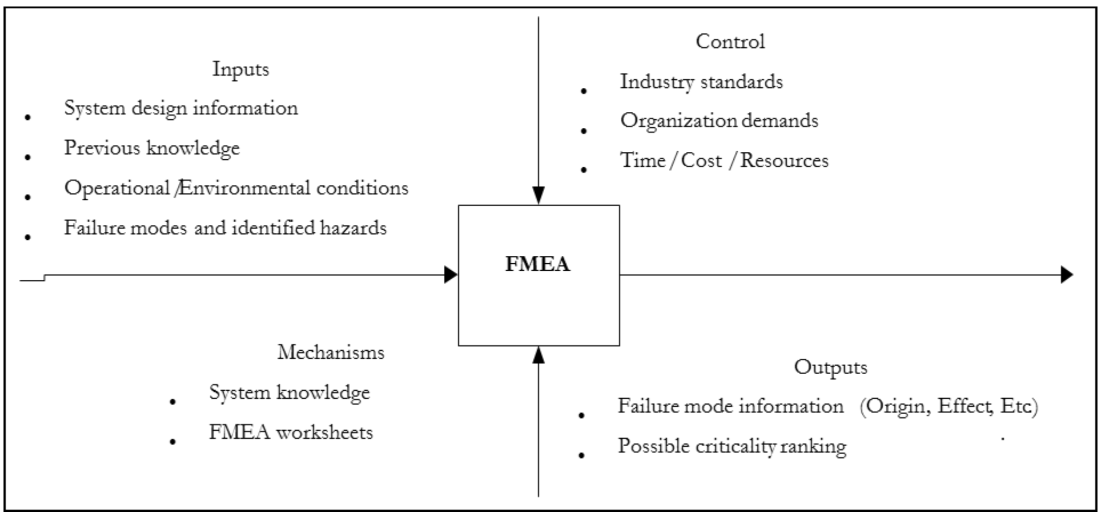


Figure 17: SADT Applied to FMEA Reliability Method

<u>Inputs</u>

To perform the Failure modes and effects analysis, it is necessary to have an overview of the system. The main inputs to the FMEA are system design drawings, functional breakdowns, and a list of the possible hazards and failure modes found in previous analyses. If criticality is added, information about the failure frequency should be obtained as well. (Ødegaard, 2003)

<u>Mechanisms</u>

The FMEA demands an understanding of the development and consequence of a failure. Worksheets are used to keep the results of the analysis in a logic and comprehensible format. These can be adapted to each FMEA, but will normally include the columns in Table 3. Although the analysis can be performed by one person alone, it is believed that team work is the most suitable. This is due to the magnitude of possibilities in the design which may lead to failure (IEC 60812, 2016).

Table 3: Failure Mode, Effects and Criticality Analysis (FMECA) Worksheet

Function	Operational mode	Failure mode	Failure cause or mechanism	Failure detection	Effect of failure	Failure frequency	Severity ranking	Criticality	Risk reducing measures

Control

The FMEA has spread to almost all industries and has been developed for several other purposes than product reliability, for example project management. Among the standards and handbook explaining the method and its application is IEC60812 (2016). Based on the industry and the relevant standard, it is possible for an organization to develop its own guidelines. Another possible means of control is to evaluate the impact the analysis has on the design. If the analysis is performed untimely, its effect may be hard to notice, but some useful outputs can still come of it.

Outputs

The FMEA gives a good overview of the different issues to watch out for in the design and during the system's operational phase. It can function as an input to several analyses, for example Fault Tree Analysis and Reliability Block Diagram (RBD). The listing of the criticality of the failure modes may be used to decide necessary alterations in the design and maintenance tasks during the operational life. With a thorough analysis, the worksheets will give a clear overview of the system, its failure modes and their effects. This will be useful throughout the product life cycle and in future projects. (Ødegaard, 2003)

Although the FMEA is well incorporated in most industries, including the CPV, there are criticisms against it. For example, the method itself is time consuming, especially if absolutely all component failures are examined to the same level of detail (Rausand & HØyland, 2004). Another limitation is that the method only focuses on one failure mode at the time, leaving it unsuitable for the study of dependent failures. It is thus a possibility that systems with a fair degree of redundancy are insufficiently analyzed because FMEA does not provide any assessment or discover complex failures involving combination of failures, which is not recommended in this study that is looking for sufficiently reliability analyzing method. (Joshi & Joshi, 2014)

While these criticisms of FMEA raise questions about its suitability for CPV, it is possible that it could be applied with some benefit, perhaps in concert with other methods.

While the basic procedures for conducting FMEA in the DFR and Utilization Reliability are the same regardless of the focus of the FMEA, some of the tactics are different if it is Design FMEA (DFMEA) or Process FMEA (PFMEA). The Table 4 highlights the key differences between the two. (Carlson, 2014)

Table 4: Design vs. Process FMEA Analysis

Criteria	DFMEAs	PFMEAs
Primary Objectives	To uncover potential failures associated with the product that could cause: • Product malfunctions • Shortened product life • Safety hazards while using the product	To uncover potential failures that can: • Impact product quality • Reduce reliability • Cause customer dissatisfaction • Create safety or environmental hazards
The basis of the review	A blueprint, detailed product schematic or prototype	A process flowchart or detailed traveler
How potential failures of intended functions are evaluated	Identifying and assessing potential risks of the design requirements	Identifying and assessing potential risks with process operating parameters and meeting product specifications
The evaluation criteria for Detection ratings usually focuses on:	An evaluation of the ability of design controls (related to the product or process) to prevent or detect mechanisms of failure	An evaluation of the ability of process controls (mistake-proofing, fail-safes, gages) to prevent a failure mode (or cause) from occurring or detect the effect of a failure if a failure has occurred

2.3.6 Fault Tree Analysis (FTA) Reliability Method

Fault tree analysis (FTA) is a deductive method where the analyst starts with the final hazardous event and traces it back to the original failure) by constructing a Fault Tree. (NUREG-0492, 1981) A Fault Tree is a graphic depiction or model of the rationally conceivable sequences of events within a complex system that could lead ultimately to the observed failure or potential failure. (NASA, 1999a). It was first introduced for the safety evaluation of the launching system for the Minuteman I missile in 1962 (HØyland & Rausand 2004). Later improvement has led to a very extensive use in most industries where risk and reliability studies are performed. One reason may be the method's ability to give an overview of an entire system based on a few problems (NUREG-0492, 1981).

For reliability purposes, it is important to start the FTA development as early in the product life cycle as possible and update it concurrently with the design development (IEC 61025, 2006). As the original hazard is traced back through the possible contributing failure events which lead to it, the contributors are put into boxes and connected. The connections are based on whether a failure can occur alone or not in order to induce the next event. Underneath the failure, an and- or an or-gate is placed to describe the connection between the contributors. The final level in the Fault Tree is normally at the component level, but this is optional.

As the bottom-level is entered into the tree, the contributor's failure rates or probability of occurrence can be included. If all the necessary estimates for this level are obtained, it is possible to estimate the failure rate or probability of the occurrence of the top event. This will be done by following the gates from the bottom and up to the top. FTA is helpful when a system is complex with many potential failures leading to a larger problem (NASA, 1999a). It is easy to read, while systematic in its approach. Figure 18 showing the SADT model for the FTA reliability method.

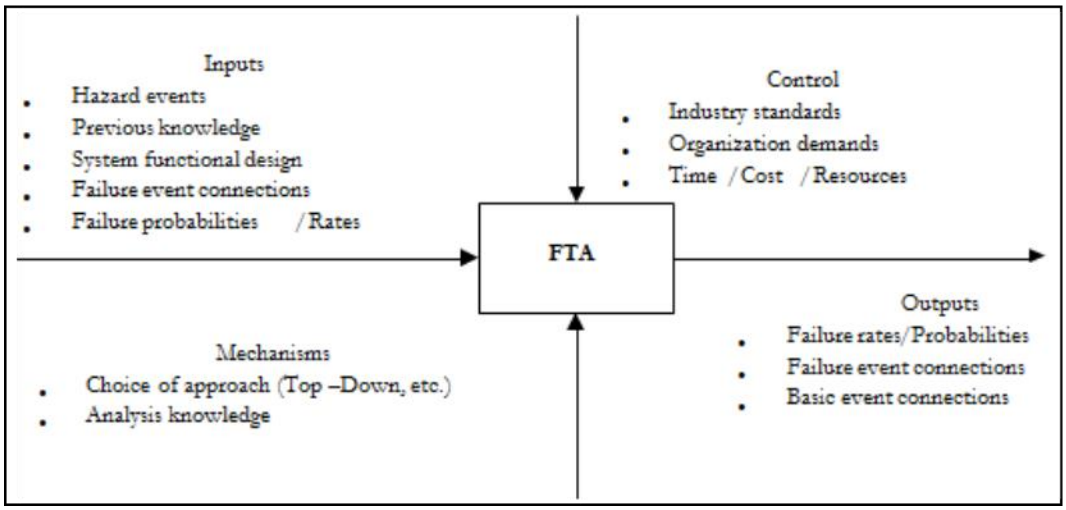


Figure 18: SADT Applied to FTA Reliability Method

Inputs

The top event will be chosen from the previous hazard identification analyses, while the system design is needed to trace the contributors. As the design becomes more detailed, more contributors may be discovered. To calculate failure rates and probabilities for the top event, estimates for the basic events are required (IEC 61025 2016).

Mechanisms

The FTA can be performed by one analyst alone, but a very thorough knowledge of the system is needed. In cases where the systems are too complex for one person, it is recommended that a team is used (IEC 61025 2016). As the fault trees may become too large to be drawn up manually, it can be very useful to work with computer tools, for example ReliaSoft ® by HBM Prenscia Inc. These tools are often also able to calculate the failure probabilities and failure rates for the top event, and discover the minimal cut sets.

Control

There are several standards and guidelines existing for the FTA, for example IEC 61025 (2006) and Again the procedure should depend on what the organization demands of it. How far down it goes will therefore be decided by the organization's need. A reasonable manner in which it is possible to see whether the fault tree is reasonable, is through comparison with system breakdown structures.

Output

The output from the FTA can be used to improve the design, evaluate the possible preventive measures against failures and give input to RBD. As the fault trees show the effect one undesirable event has on the system as a whole, it is possible to evaluate whether preventive measures, or design alterations are the best. The failure rates and probabilities calculated in the FTA can become useful for the estimation of Mean Time To Failures (MTTFs).

Using FTA reliability method in the early of the CPV system life would be useful but is not completely sufficient to use the FTA without getting some of the FTA required inputs -such as hazard events, failure event connections, and failure probability/ rates- from another method of reliability analysis (Joshi & Joshi, 2014).

It is likely therefore that pairing FTA with another reliability analysis method would satisfy the need to analysis CPV system reliability.

2.3.7 Reliability Block Diagram (RBD) Reliability Method.

RBD presents the connection between the different components fulfilling a particular system function. The purpose is to show how the system can function or fail depending on the specific components. Where a fault tree has been made, a transformation to an RBD may be possible, and vice versa (Høyland & Rausand 2004).

To create an RBD, three types of system information must be studied:

a) Functional systems architecture data,
b) Component reliability data, and
c) Mission times/Operating times. (NASA, 1999c)

When an analyst has these data, he or she can determine the relationships between the components as either serial or parallel. The components placed in a k-out-of-n (k-o-o-n) relationship, where the system functions even when some components fail, will also be noted. An RBD is easy to understand through its graphical representation. When a diagram of this type is presented, it can prove why parallel structures generally are considered stronger than series structures. In the former, the system's ability to function depends on its strongest link, while in the latter it will depend on the weakest.

The creation of the block diagram can only start after the difference between success and failure has been established (IEC 61078 2006). As there are possibilities for a system function to be in a state less than 100%, but higher than 0%, one could say that success is above 80%. When this is done, the system can be divided into blocks that are linked according to how the information passes through the system as shown in Figure 19. By applying reliability information to each block, pivotal decomposition may be used to calculate the system reliability. RBD is a series of blocks connected in parallel or series configuration. Each block represents a component of the system with a failure rate. Parallel paths are redundant, meaning that all of the parallel paths must fail for the parallel network to fail. By contrast, any failure along a series path causes the entire series path to fail.

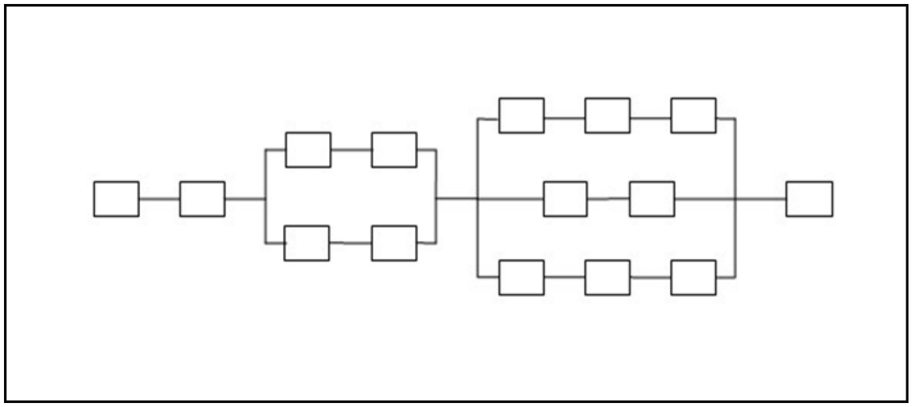


Figure 19: Example RBD

Inputs
The inputs to the RBD are system design, failure definitions, k-o-o-n relationships and redundancy information. A fault tree can be turned into an RBD and the other way around, but the RBD is the easiest to read with respect to the connections of components, assemblies and subsystems (Rausand & Høyland, 2004).

Mechanisms
In order to perform the RBD, knowledge about the system is needed, both concerning its composition and how the elements work together. If the system is very complex, including k-o-o-n structures, switches and parallel structures, it is useful to perform the analysis in a team. RBDs can become very large and complex, and it is thus helpful to employ computer simulation programs like the Reliasoft ® (HBM Prenscia Inc., 2017) used later in this research. Such a program will keep the information separate and facilitate calculations such as component importance and overall system reliability.

Control
What controls the method is the interest of the organization ordering it and the design progress. The decision of what a success is will be decided by the system requirements. Creating the RBD, the design is the basis and it is thus also the main element which may show that the RBD is put together as it should be. Any changes in the design should be a reason to update the RBD. The RBD is described together with Boolean methods in IEC 61078 (IEC61078, 2017), which may be used for control of the performed RBD.

Outputs
One useful type of output from the RBD is minimal cut sets showing the smallest number of failed components leading to the loss of a system function. This can help the understanding of the weakest links within a system. If the RBD is used to find the system reliability and component importance, it could be entered into other analyses, or used to compare with previous studies. The downside with the RBD is that it cannot be used for repairable systems (Rausand & Høyland, 2004). These should be analyzed through Markov diagrams, which are described in Rausand and Høyland (2004). Figure 20 showing the SADT model for the RBD reliability method.

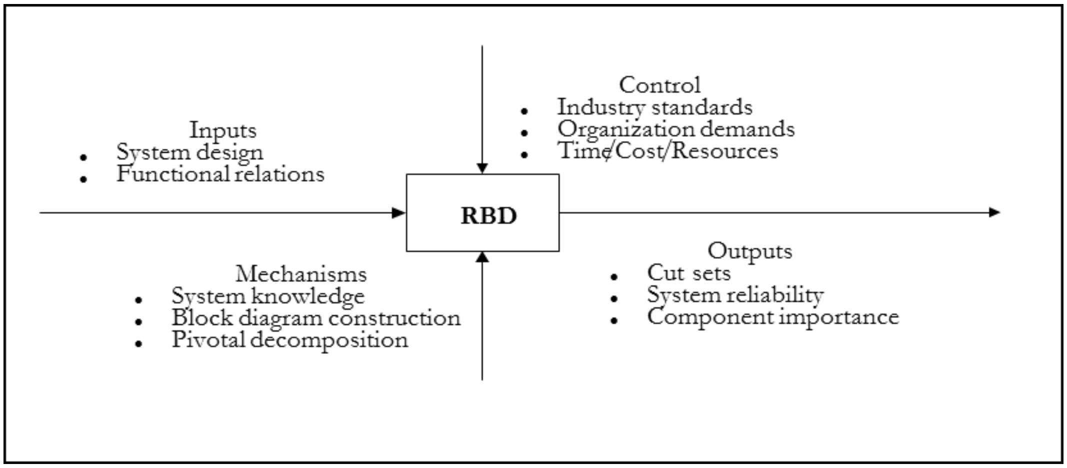


Figure 20: SADT Applied to RBD Reliability Method

Using standalone RBD for analysis of CPV reliability will not give sufficient information about the system's reliability without having enough information about the relationships between the failure(s), effects of a failure on the other parts of the system, and cause(s) of these failure(s) (Berg, 2010).

As this information required by RBD can arise from other Reliability methods such as FTA and FMEA, it is possible that RBD could play a useful role in analyzing CPV system reliability.

2.3.8 Accelerated Life Testing (ALT) Reliability Method

Accelerated life testing is a method where an object is forced to fail. Failures are induced by submitting the product to stresses it will experience during its operational life, but at a larger scale. A reliability engineer is interested in failure data for the operational life, for example failure rates. The main problem with such data is the time it takes before a failure. Databases can be useful to obtain failure data, but they rarely consider the differences between the operational conditions of the items that have failed (Murthy, Rausand, & Østeras, 2008). Accelerated life testing can therefore be a solution both to the environmental differences and the time it takes to obtain the data.

The tests for this method can generally be split into two categories; qualitative and quantitative tests. The former is useful for the detection of failure modes and failures, while the latter gives input to life predictions and failure data, for example MTTF (Murthy, Rausand, & Østeras, 2008). Qualitative tests are primarily made to pressure the product to failure and provide results fast. Example of such tests is the Highly Accelerated Life Test (HALT). In such test do not necessarily employ time as a measure and it can thus be hard to say something about the life time of the product.

Quantitative tests can be divided in two; accelerated usage rate tests and overstress acceleration tests (DoD, 2005). The first is convenient when the products are not in continuous use, such as dishwashers and coffee machines. Possible testing methods would then include using the products with an elevated frequency.

As with reliability growth, custom-built products might not suit this type of testing. The components and sub-systems which are easy to produce and inexpensive can be tested instead.

A very important aspect of this method is that the reliability engineer must be aware of what type of product he or she handles. A product which is in continuous use should not be subjected to accelerated usage tests. For a product which is turned on and off, it might be interesting to use both accelerated usage tests and overstress acceleration tests. For qualitative tests, it must be evaluated whether it is likely that the product will be subject to increasing stress over time. Applying SADT on ALT demonstrated in Figure 21 and explained after that.

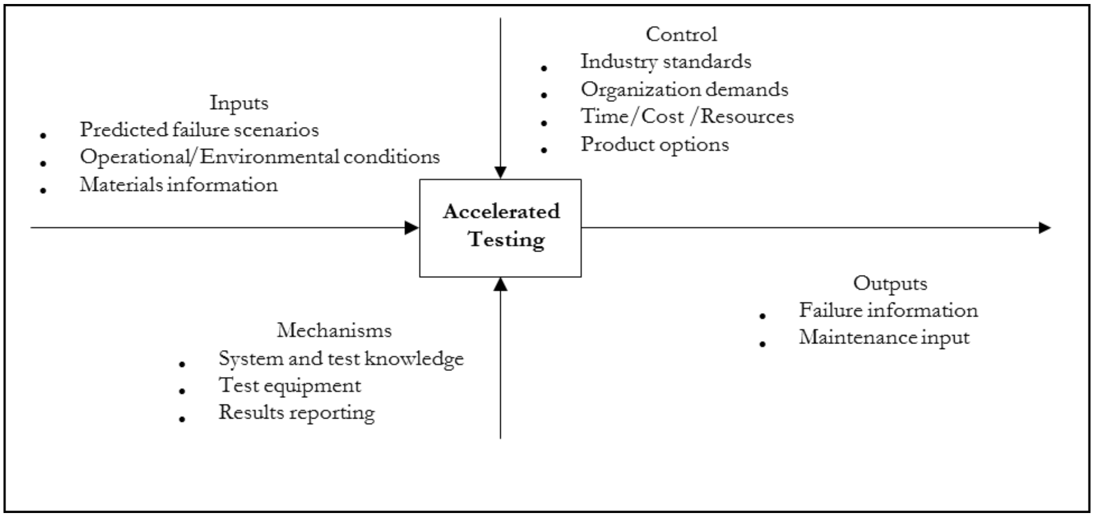


Figure 21: SADT Applied to ALT Reliability Method

Inputs

Accelerated life tests cannot be performed without knowledge about the materials in the system, the operational and environmental conditions and the possible system failures. Based on this information, it can be possible to deduce which tests are the most appropriate. (Ødegaard, 2003)

Mechanisms

As this method is physical, it is very important to have the appropriate resources. For the test operators, it is necessary with knowledge about the materials used in the product and its mechanical construction. Otherwise the test may be performed incorrectly, or the results misinterpreted. The analysts will also need this knowledge, in order to subtract the correct results. (Ødegaard, 2003)

Control

The main constraints and controls for this type of analysis are time, money, legislations and the product type. Time issues affect the tests available, especially when they demand much time for preparation and execution. Depending on the tests chosen and the materials used in the product, it may be very expensive to perform tests. If the materials are expensive to obtain, it is not desirable to use it for destruction alone. When products only are produced once or in very few numbers, the accelerated life testing can be difficult to employ. Among the standards suitable for the control of this method are IEC 62059 (2008) and IEC 60068 (1995).

Outputs

The outputs from the accelerated life tests may be used to confirm previously predicted reliability estimates. They can also help improve the manufacturing process and the design. If the tests are performed after the design is frozen, alterations will be difficult. A possible use of the outputs could be for maintenance and check-ups on specific modules and sub-systems which seems more probable to fail. If it is desirable to test before the design is frozen, it is possible to do testing on items which already exists. When the results are analyzed and given as failure data for a longer life, they can be stored for later development projects. (Ødegaard, 2003)

ALT is not suitable for use in DFR, and therefore does not meet all of the needs for CPV system reliability. It is clearly appropriate for use in Utilization Reliability. It is a method for analyzing reliability, but only upon failure investigation provides support for improving relativity. Therefore, it permits some of the need for CPV system reliability and might be part of a hybrid or synthesis reliability methods for CPV systems.

2.3.9 Failure Reporting Analysis and Corrective Action System (FRACAS) Reliability Method

FRACAS is a closed-loop method where the supplier and customer work together to study the product reliability. The main purpose is to have all failures in both hardware and software systems reported, analyzed and understood. All information concerning a failure will be recorded, identifying the failed items, symptoms, operating times and time of failure. The verification of the failure and the successful corrective actions are important to prevent the failure from recurring.

Inputs

For reliability purposes, FRACAS is best used together with other analyses. The intention of this method is to use it as a tool while the product or system is in use.

Other methods suited for earlier phases should be used as inputs. An example of how a combination of FRACAS and another method can be favorable is the coupling of FRACAS with FMEA/FMECA. FMEA/FMECA can give input to FRACAS by descriptions of failure modes which are encountered. A failure reported through FRACAS can be brought back to complete the FMEA/FMECA.

Mechanisms

FRACAS is dependent on accurate input data, well prioritized goals, and time and resources (Hallquist & Schick, 2004). A reporting system should be agreed on between the manufacturer and the client, and used as a mechanism for the reporting. The people reporting and analyzing the failures needs thorough knowledge of the system and the nature of the failures affecting it.

Control

In FRACAS, the extent of the failure is a control parameter. A failure leading to a destructive consequence takes time and money to investigate. If the destructions are extreme, it might not even be possible to find any answers. Another control issue is the agreement between the manufacturer and the client. This will regulate how the reporting is done and what information the parties are sharing. (Ødegaard, 2003)

Outputs
Outputs of the FRACAS method are of use to later development projects. All lessons learned will lead to less repetition of failures and history might therefore not repeat itself. (Ødegaard, 2003)

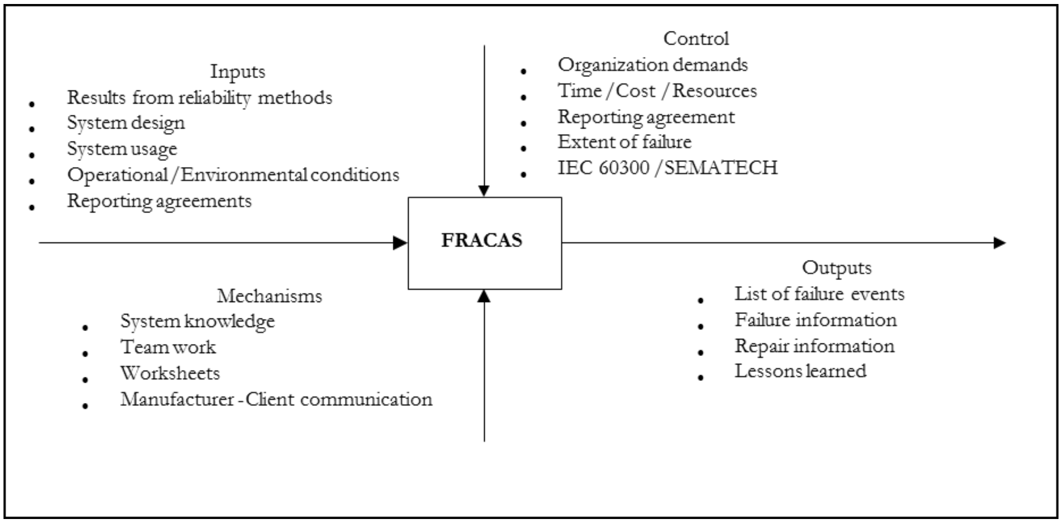


Figure 22: SADT Applied to FRACAS Reliability Method

In summary, there are nine commonly used methods for analyzing reliability, some of which provide no significant help to the problem of analyzing CPV system reliably, and some of which solve part of the problem. As summarized in Table 5 .

Table 5: Summary for the Reliability Methods

Reliability Method	Depends on	Provides	Sufficient for Design For Reliability in CPV System	Sufficient for Utilization Reliability in CPV Systems
PHA	• Team work, basic system information • Similar existing system information	• List of Hazards • Hazard information.	Potentially	No
HAZOP	• Team work, system design, • Process information, Similar existing system information • Operational	• List of Hazards, Hazard information, • System alteration ideas	Potentially	No

Reliability Method	Depends on	Provides	Sufficient for Design For Reliability in CPV System	Sufficient for Utilization Reliability in CPV Systems
SWIFT	• Team work, brain storming, basic system description	• List of hazards, Hazard information • No quantitative results	Potentially	Potentially
Reliability Growth	• Test, previous system information, prototype, materials information.	• Stress handling, materials alteration • Design alteration suggestions	No	Yes
FMEA	• System design drawings • Functional breakdowns • And a list of the possible hazards	• Inputs to another method • List of critical failure modes • Clear overview of the system reliability	Potentially	Potentially
FTA	• Hazard events • System functional design, failure event connection, failure probabilities and rates	• Improve the design • Evaluate the possible preventive measures against failures • Input to RBD • MTTF estimation	Potentially	Potentially
RBD	• FTA • System design	• Minimal cut sets • Inputs to method • System reliability, component importance	Potentially	Potentially

Reliability Method	Depends on	Provides	Sufficient for Design For Reliability in CPV System	Sufficient for Utilization Reliability in CPV Systems
ALT	• Materials information, • Operation and environmental conditions • Possible system failures	• Failure information • Maintenance input	No	Potentially
FRACA	• System usage • Results from another method • System design • Operation/ environmental conditions	• List of failure events • Failure information • Repair information • Less repetition of failures	No	Potentially

Table 6 explain which of the CPV system reliability needs are meet by which reliability method. Note that no method meets all the needs.

Table 6: Common Reliability Methods Compared to CPV System Reliability Needs

	Analyzing reliability	Improving Reliability
Design For Reliability	Needed for CPV PHA HAZOP SWIFT FMECA FTA (partial) RBD (partial) FRACAS (partial)	Needed for CPV PHA HAZOP Reliability Growth FTA (partial)
Utilization Reliability	Needed for CPV SWIFT Reliability Growth FMECA RBD ALT	Needed for CPV FTA (partial) ALT FRACAS (partial)

CHAPTER 3: METHODOLOGY FOR THE RELIABILITY

3.1 Introduction

As discussed, analyzing the reliability of the CPV system is an important and challenging problem, but a review of the literature found no existing method suitable for the CPV system which satisfied the dual lifecycle needs of DFR and Utilization Reliability, and in each case the need to both analyze and use that analysis to improve the reliability of the CPV system. Therefore, the aim of the present research is to propose and evaluate such a method.

The review of the literature did note that several existing reliability methods could make contributions to this problem, but none in and of itself was sufficient. The shortcomings of the existing methods could be summarized as unavailability of information required by a given method at points in the system lifecycle when the method's contribution to understanding reliability is needed. Careful consideration of these shortcomings reveals that some reliability analysis methods produce information need by other reliability analysis methods. This suggests that a reliability method based on a synthesis of existing reliability methods could provide the basis for addressing analysis of the CPV system reliability.

The present research therefore proposes a new reliability analysis method based on a synthesis of existing reliability analysis methods integrated into two complementary approaches applied at different stages in the life of the system, or the *Dual Approaches Reliability Methodology* (**DARM**). DARM defines each approach as a series of steps, each being specific reliability engineering activities, and may in fact be selected of the method from the foregoing discussion.

The DARM methodology integrates complementary of two approaches:

a) *Reliability Design Approach* (RDA), and
b) *Reliability Test and Mitigation Approach* (RTMA).

The first approach is applicable to and concerned about the system in the design or development stage (i.e. DFR); while the second approach focused and related to the system in deployment stage (i.e. Utilization Reliability) which comes after the finishing of the design stage. These two approaches are not completely separate, but there is a coherent integration between them as illustrated in Figure 23.

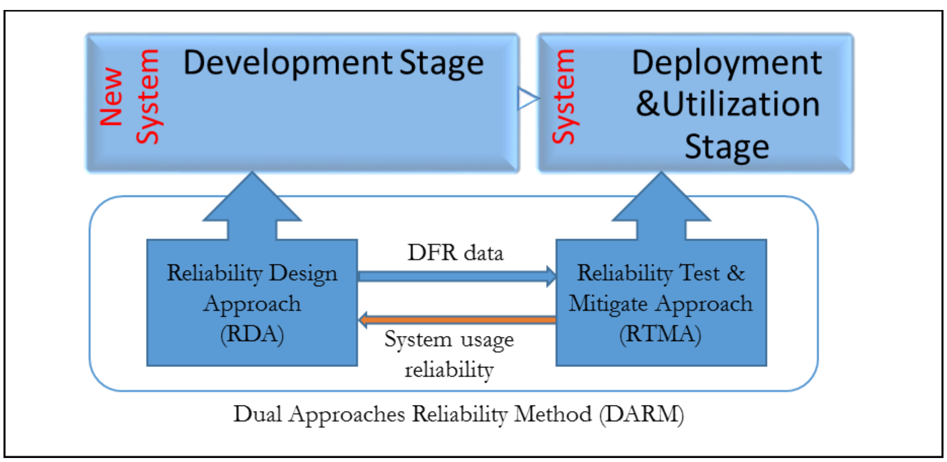


Figure 23: DARM Applied On System

This chapter describes the explanation and applicable steps used in each approach in detail.

3.2 Dual Approaches Reliability Methodology (DARM)

DARM is a reliability methodology to analyze and enhance the reliability of the system in the system development and system utilization stages. DARM harmonizes the reliability methods considered in chapter 2 to satisfy the reliability study needs of the CPV system.

The DARM analysis used in early design phases of the CPV system for DFR in order to enhance the reliability of the system in the design stage. In later phases of a project design, the DARM analysis used mainly as a verification and improving activity to show compliance with requirements and to enhance the overall analysis of the system's reliability. Using DARM analysis as a Utilization Reliability method by the system operators and maintenance give valuable information with regards to recommended sparing and repair philosophies, as well as advice in connection with the optimal redundancy introduced into a design.

In this methodology the reliability data analysis transfers from step to step in approach 1 (RDA) and approach 2 (RTMA), and in reverse direction from approach 2 back to approach 1 a as shown in Figure 24.

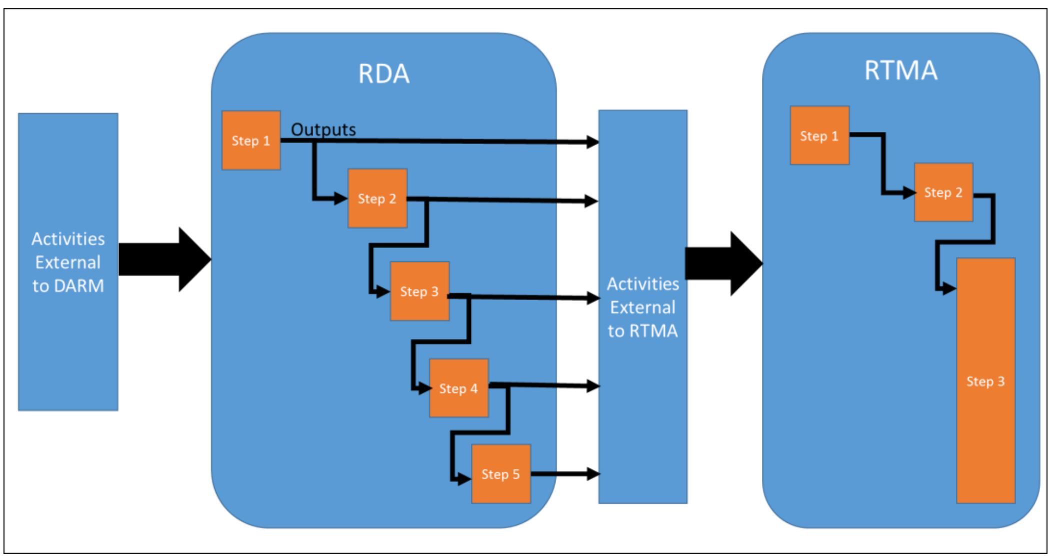


Figure 24: DARM Configuration

This strong integration simultaneously with:

a) Itself (RDA-RTAM),
b) Other systems engineering activities related to this system, and
c) Future versions of this and related system, updating the system to new version.

The old version reliability utilization outcomes can be a great contribution to correct and enhance the reliability performance for the new version.

The information came from system's Utilization Reliability analysis is very useful for the manufacturers of the system's components, that's how they can get true parameters of the reliability of such component working in a certain conditions and surrounding circumstances. The Government-Industry Data Exchange Program (GIDEP), a Department of Defense program established to promote and facilitate the sharing of technical information between government agencies and industry partners to increase systems safety, reliability, and readiness and to reduce systems development, production, and ownership costs. (GIDEP.ORG/Factsheets)

Using and applying this methodology in reliability of systems will be a good contribution to the database of GIDEP program based on real time applications.
In the following sections of this chapter, the study will explain each approach to identify the inputs, mechanism, and the outputs of each step, then explain the procedures of each method and the reliability analysis parameters transfer between these methods up to the final outcomes of each approach. This research used term (step) to identify the method(s) used in each approach inside DARM.

3.3 Reliability Design Approach (RDA)

RDA is DARM's DFR reliability approach used to analyze and improve the reliability of the system in the design stage of the system life.

The RDA analyzes and improves the reliability in the system design according to the reliability parameters of the components and subsystems of the system under design. The RDA can be started from the first conceptual design stage by marking the targeted reliability requirements of the system from the system requirements as the goal for the whole methodology, then apply the following steps.

1) The first step in RDA is to conducts a FMECA as introduced earlier and defined in the FMECA method in previous chapter.
2) The next step is to apply the FTA reliability method on the system under design.
3) This step is to build the RBD and use this diagram analysis to do the required redundancy for the system components to improve the reliability according to the cost constraints.
4) Calculate MTTF and failure rate ($\lambda(t)$) which is the reliability critical parameters of the CPV system and its components.
5) Using the results of the system reliability parameters to validate the total estimated reliability and check that the system will meet the designed reliability.

The reliability results from each step of the RDA will feed the reliability analysis of the second approach, or RTAM, which addresses Utilization Reliability.

Now we will raise the level of abstraction from the steps in RDA to an approach-wide view of RDA. RDA consists of its steps, therefore, this high abstraction view can be seen as simply the summation of the steps. This prepares the reliability engineer applying RDA for conduct of the entire approach, as opposed to attempting a step and discovering at that point a required input or control or mechanism for which the reliably engineer is compose unprepared to address.

RDA Inputs

To apply the five steps in the RDA approach on the CPV system using the ReliaSoft® Synthesis 11 software tool, the following are inputs:

a) System design information and drawings,
b) List of possible hazards, failure modes, and failure frequency for the components of the system,
c) System functional design and functional relationship, and
d) Environmental and operational conditions of the system.

RDA Control

The control used for the RDA are:

a) IEC62108 Redline CPV standards for 2016,
b) IEC60812 FMEA standards for 2006,
c) IEC61078 reliability block diagram standards for 2008, and
d) Time and cost resources of the CPV system.

RDA Mechanisms

Performing the RDA needs knowledge about the system, the software tools that used in this study to perform the RDA is the "Xfmea" tool from "Synthesis 11" platform to perform step 1, and the "BlockSim/ Reno" tool from "Synthesis 11" platform to perform step 2, 3, 4, 5.

RDA Outputs

The outputs from the RDA are:

a) Design FMECA reports and worksheets,
b) Design Review Based on Failure Mode (DRBFM), and
c) System reliability and system reliability function F(t).

Now that the reliability engineer is prepared for RDA as a complete approach, the following detailed each step within RDA in turn.

As mentioned earlier that the RDA is applied by running five steps, to apply these steps; RDA used defined sources for the inputs of each step, and the outputs from each step used to feed the inputs of other steps in RDA, RTMA or to the systems reliability analysis to use it for DFR. The inputs and outputs explained in the following paragraphs and tables.

The first step in the RDA of DARM is to conduct a FMECA.

Table 7 itemizes the inputs for FMECA and their sources. The controls and mechanisms for the FMECA are unchanged from the FMECA reliability methodology discussed in chapter 2. Likewise, outputs from FMECA are as defined in the discussion of the FMEA reliability method, however; DARM has specific uses for each output as noted in Table 8.

Table 7: RDA FMECA Inputs

RDA FMECA Inputs	Source
System design information/ drawings	-System Designer, System Manufacturer, System Operator. -Similar Systems by Analysis
Hazards, failure modes & frequency for components	-Similar Systems by Analysis -Components data sheets -GIDEP (GIDP, 2017) website for data exchange program -Military handbook for reliability prediction of electronic equipment, the MIL-HDBK-2017 (DoD, 1990)
System design and block diagram	-System Designer -Use Bill of Materials to build the System Block diagram
Environmental &operational conditions	-System Designer -System requirements

Table 8: RDA FMECA Outputs

RDA FMECA Outputs	Uses
Failure modes and effect	-System Reliability Engineer
Risk Priority Number (RPN)	-Inputs for Subsequent DARM Methods specifically RDA's FTA
Failure event connections	-Input to Subsequent DARM Methods specifically: -RDA's FTA -RTMA's FMECA
Failure probabilities and rate	-RDA FTA combined with RPN for the components to find Failure probabilities and rate for components input
Functional Block Diagram	-Reliability Needs -DFR System Reliability Analysis -DFR System Reliability Design Improvement -UR System Reliability Analysis -UR System Reliability Design Improvement -Input to Subsequent Methods specifically: o RDA FTA o RDA RBD & Redundancy Study o RTAM ALT
Process Flow Diagram (PFD)	-System Reliability Engineer
FMEA reports and worksheets	-System Reliability Engineer
Design Review Based on Failure Mode (DRBFM)	-System Reliability Engineer

The second step in the RDA of DARM is to conduct a FTA. Table 9, itemizes the inputs for FTA and their sources. DARM has specific uses for each output as noted in Table 10.

Table 9: RDA FTA Inputs

RDA FTA Inputs	Source
Functional block diagram	-Output from RDA FMECA
Failure event connections	-Output from RDA FMECA
Failure probabilities and rate for components	-Output from RDA FMECA combined with RPN outputs for the components to find Failure probabilities and rate for components

Table 10: RDA FTA Outputs

RDA FTA Outputs	Use
Failure probabilities and rate	-Input to RDA step 5 (Reliability Function R(t) Computation) -System Reliability Analysis
Enhanced Failure event connections	-System Reliability Analysis
FTA Diagram	-Input to RDA RBD & Redundancy Study. -System Reliability Analysis

The third step in the DARM's RDA is to conduct a RBD and redundancy Table 11 itemizes the inputs for RBD & Redundancy Study and their sources. DARM has specific uses for each output as noted in Table 12.

Table 11: RDA RBD & Redundancy Inputs

RDA RBD & Redundancy Study Inputs	Source
System design and block diagram	-System Designer, System Manufacturer, System Operator -Similar Systems by Analysis
Functional block diagram	-Output from RDA FMECA
FTA diagram	-Output from RDA FTA

Table 12: RDA RBD & Redundancy Outputs

RDA RBD & Redundancy Study Outputs	Use
Cut set	-Input to RTMA ALT -System Reliability Analysis
System reliability	-Input to RDA MTTF& λ -System Reliability Analysis
Components importance	-Input to RTMA ALT -Input to RTMA Mitigate Failure -System Reliability Analysis
Reliability Block diagram	-System Reliability Analysis
Improved cut set	-Input to RTMA ALT -System Reliability Analysis

The fourth step in the RDA of DARM is to conduct a MTTF and System Failure Rate Resolution Table 13 itemizes the inputs for RDA's MTTF and Failure Rate, and their sources. The outputs of the RDA MTTF & (λ) and where they used are listed in Table 14.

Table 13: RDA MTTF & (λ) Inputs

RDA MTTF and System Failure Rate Resolution Inputs	Source
System reliability	-Output from RDA RBD
Component importance	-System Designer

Table 14: RDA MTTF & (λ) Outputs

RDA MTTF and System Failure Rate Resolution Outputs	Use
System reliability	-Input to RTMA Mitigate Failures -System Reliability Analysis
Failure rate function	-Input to RDA Reliability Function R(t) Computation -System Reliability Analysis

The fifth step in the RDA of DARM is to conduct a Reliability Function R(t) Computation of the whole system. Table 15 itemizes the inputs for Reliability Function step and the input sources.

Table 15: RDA Reliability Function R(t) Computation Inputs

RDA Reliability Function R(t) Computation Inputs	Source
Failure probabilities and rate	-Output from RDA FTA
System reliability	-Output from RDA MTTF and System Failure Rate Resolution
Failure rate function	-Output from RDA MTTF and System Failure Rate Resolution

The final outputs of the RDA will be the outputs of the RDA Reliability Function R(t) Computation which is use for DFR by system reliability analysis, and combined with other steps' outputs mentioned in the output table of each step will feed the inputs of the next approach the RTMA. Table 16 shows the RDA Reliability Function R(t) Computation outputs.

Table 16: RDA Reliability Function R(t) Computation outputs

RDA Reliability Function R(t) Computation Outputs	Uses
System reliability function	- System Reliability Analysis
System reliability	-System Reliability Analysis -Input to RTMA Mitigate Failures

The Table 17 summarizes the inputs and outputs of the RDA five steps.

Table 17: RDA Inputs and Outputs Summary

Step	Main Function (s)	Inputs	Outputs
1	FMECA	-System design info./ drawings -Hazards, failure modes & frequency for components -System design and block diagram -Environmental &operational conditions	1) Failure modes and effects 2) RPN 3) Failure event connections 4) Failure probabilities and rate 5) Functional block diagram 6) Process Flow Diagram (PFD) 7) FMEA reports and worksheets 8) Design Review Based on Failure Mode (DRBFM)
2	FTA	-Step 1 5th Output (Functional block diagram) -Step 1 3th Output (Failure event connections) -Step 1 4th Output (Failure probabilities and rate for components)	1) Failure probabilities and rate 2) Enhanced Failure event connections 3) FTA diagram
3	RBD & Redundancy Study	-System design and block diagram -Functional block diagram -Step 2 3rd Output (FTA diagram)	1) Cut sets 2) System reliability 3) Components importance 4) Reliability Bloc Diagram 5) Improved cut set
4	MTTF and System Failure Rate Resolution	-Step 3 2nd (Output System reliability) -Step 3 3rd (Output Components importance)	1) System reliability 2) Failure rate function
5	Reliability Function R(t) Computation	-Step 4 1nd Output Failure probabilities and rate -Step 4 2nd Output (System reliability) -Failure rate function	1) System reliability function. 2) System reliability

The diagram in Figure 25 explain the DARM RDA approach using the SADT with the five steps that applied in this approach. This diagram explain the inputs, control, and the outputs of each step. Knowing that the mechanism for the RDA for the all five steps was applied by using the Reliasoft® Synthesis 11 software tools as mentioned earlier in this chapter in the RDA mechanism.

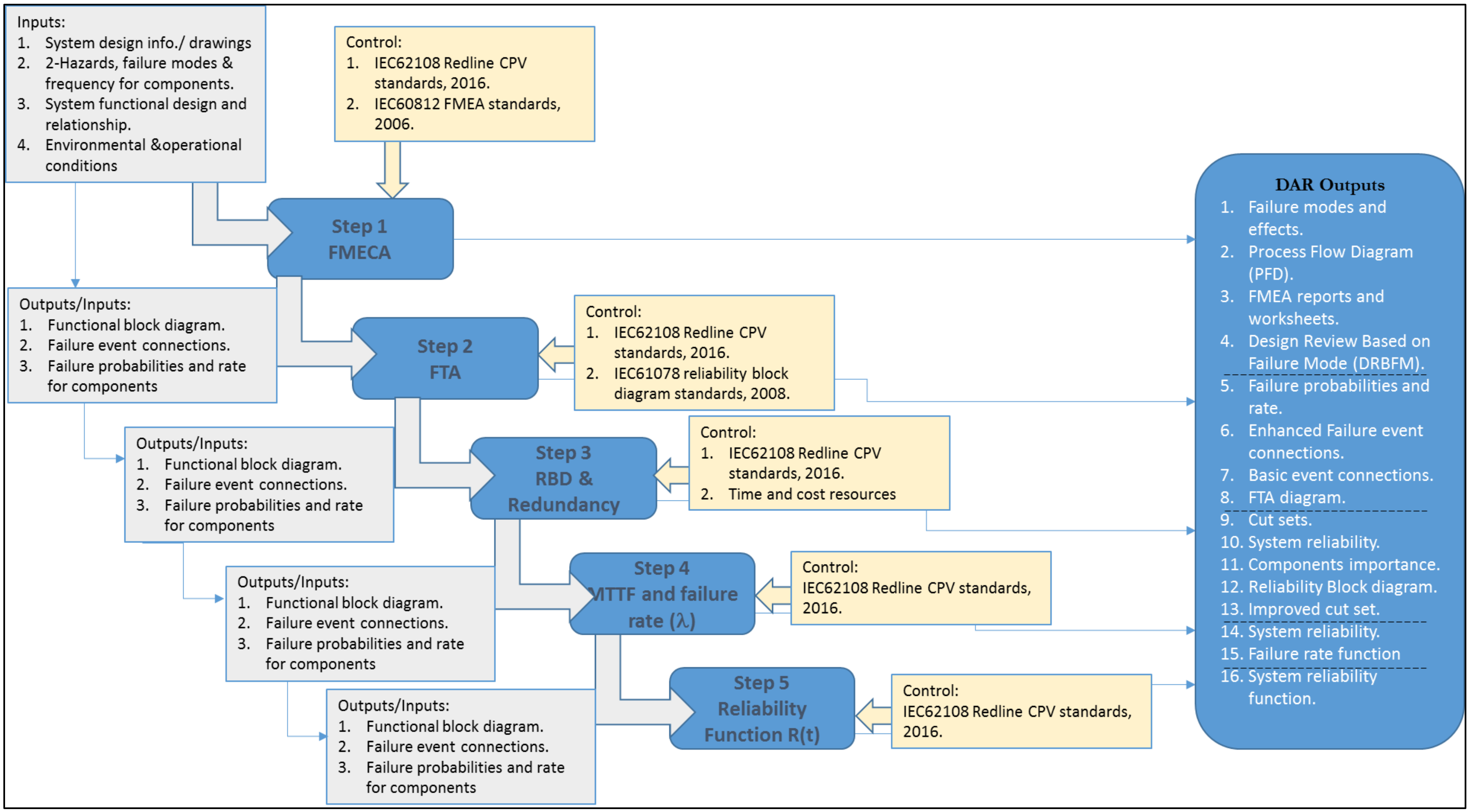


Figure 25: DARM'S RDA Flow Chart

3.4 Reliability Test and Mitigation Approach (RTMA)

RTMA is DARM's solution for utilization reliability, which to analyzes and improves the reliability during operations.

The RTMA consists of the following steps.

1) Repeat the FMECA to update the initial FMECA analysis parameters calculated in step 1 of the first approach (RDA). This update will improve the initial FMECA analysis and give more accurate results for the FMECA revised outputs.
2) The second step is to do the ALT for the system and /or critical components of the system (Minimal cut set) that analyzed in step 3 of the first approach (RDA). The output results of the ALT will update the reliability function parameters and failure rate of the system and its components.
3) Mitigate the failure of the system and its components using the outputs from the first two steps as inputs to this step to generate the failure prevention plan.

<u>RTMA Inputs</u>
To apply the three steps of the RDA approach on the CPV system using "Synthesis 11" tool, the following are inputs:

a) DFMEA,
b) System reliability resulted from RDA,
c) System functional design and functional relationship, and
d) Environmental and operational conditions of the system.

<u>RTMA Control</u>
The control used for the RTMA are:

a) IEC62108 Redline CPV standards for 2016,
b) IEC60812 FMEA standards for 2006,
c) IEC62506 ALT standards for 2013, and
d) Time and cost resources of the CPV system.

<u>RTMA Mechanisms</u>
Performing the RTMA needs knowledge about the system, the software tools to perform the RTMA is the "Xfmea" tool from "Synthesis 11" platform to perform step1and step3, and the "Weibull/ ALTA" tool from "Synthesis 11" platform to perform step 2, 3.

<u>RTMA Outputs</u>
The RTMA outputs resulted from applying the three steps of this approach, where the outputs of each step resulted general outputs of the approach and inputs to the next step. The general outputs of this approach listed:

a) DFMEA, FMEA reports and worksheets,
b) Design Review Based on Failure Mode (DRBFM),
c) System reliability and system reliability function F(t), and
d) Failures prevention plan.

As mentioned above that the RTMA is applied by running three steps, to apply these steps; RTMA used defined sources for the inputs of each step, and the outputs from each step used to feed the inputs of other steps in RTMA, the systems reliability analysis, system maintenance inputs, and prevention maintenance to use it for Utilization Reliability (UR). The inputs and outputs explained in the following paragraphs and tables.

The first step in the RTMA of DARM is to conduct a DFMECA. Table 18 itemizes the inputs for FMECA and their sources. The controls and mechanisms for the FMECA are unchanged from the FMECA reliability methodology in chapter 2. Likewise, outputs from FMECA are as defined in chapter 2 FMEA reliability method, however; DARM has specific uses for each output as noted in Table 19.

Table 18: RTMA FMECA Inputs

RTMA FMECA Inputs	Source
System design information / drawings	-System Designer, System Manufacturer, System Operator -Similar Systems by Analysis
Hazards, failure modes & frequency for components	-Output from RDA FMEA
System design and block diagram	-System Designer -Use Bill of Materials to build the System Block diagram
Environmental &operational conditions	-System Designer. -System requirements

Table 19: RTMA FMECA Outputs

RTMA FMECA Outputs	Uses
Developed Failure modes and effects	-UR System Reliability Analysis. -Maintenance plan
Developed RPN	-UR System Reliability Analysis.
Enhanced Failure event connections	-Input to RTMA ALT
Developed Failure probabilities and rate	-Inputs to RTMA ALTA
Functional block diagram	-Input to RTMA ALT
Process Flow Diagram (PFD)	-UR System Reliability Analysis
Developed FMEA reports and worksheets	-UR System Reliability Analysis -Maintenance plan

The second step in the RTMA of DARM is to conduct an ALT. Table 20 itemizes the inputs for ALT and their sources. DARM has specific uses for each output as noted in Table 21.

Table 20: RTMA ALT inputs

RTMA ALT Inputs	Source
Predict failure Scenarios	-System Designer, System Manufacturer, System Operator -Similar Systems by Analysis
Operational and Environmental conditions	-System Designer
Material information	-Components data sheets. -GIDEP (GIDP, 2017) website for data exchange program -Military handbook for reliability prediction of electronic equipment, the MIL-HDBK-2017 (DoD, 1990)

Table 21: RTMA ALT Outputs

RTMA ALT Outputs	Uses
Failure rate of the system.	- RTMA Mitigate Failures - UR System Reliability Analysis. - Maintenance plan.
Failure rates for the minimal cut set.	-RTMA Mitigate Failures - UR System Reliability Analysis. - Maintenance plan.
Mean remaining life for the system and components	UR System Reliability Analysis. Maintenance plan.

The third and last step in the RTMA of DARM is to conduct a Mitigate Failures.

Table 22 itemizes the inputs for Mitigate Failures and their sources. However; DARM has specific uses for each output as noted in Table 23.

Table 22: RTMA Inputs

RTMA Mitigate Failures Inputs	Source
Failure rate of the system	Output from RTMA ALT
Failure rates for the minimal cut set	Output from RTMA ALT
RTMA FMEA	Outputs of RTMA FMEA
System reliability	Outputs from RDA Reliability Function R(t) Computation

Table 23: RTMA Outputs

RTMA Mitigate Failures Outputs	Uses
Failures prevention plan	UR System Reliability Analysis

	Maintenance plan

RTMA approach uses reliability analysis of the system to improve the reliability of the system during system life cycle. The Table 24 summaries the three steps inputs and outputs of the RTMA approach. The diagram in Figure 26 explain the DARM RTMA approach using the SADT with the three steps that applied in this approach

Table 24: RTMA Steps Inputs and Outputs

Step No.	Main Function	Inputs	Outputs
1	FMECA	- System design information /drawings - Hazards, failure modes & frequency for components - System design and block diagram - Environmental &operational conditions	- Developed Failure modes and effects - Developed RPN - Enhanced Failure event connections - Developed Failure probabilities and rate - Functional block diagram - Process Flow Diagram (PFD) - Developed FMEA reports & worksheets
2	ALT	- Predict failure Scenarios - Operational and Environmental conditions - Material information	- Failure rate of the system - Failure rates for the minimal cut set - Mean remaining life for the system and components
3	Mitigate Failures	- Failure rate of the system - Failure rates for the minimal cut set - RTMA FMEA - System reliability	-Failures prevention plan

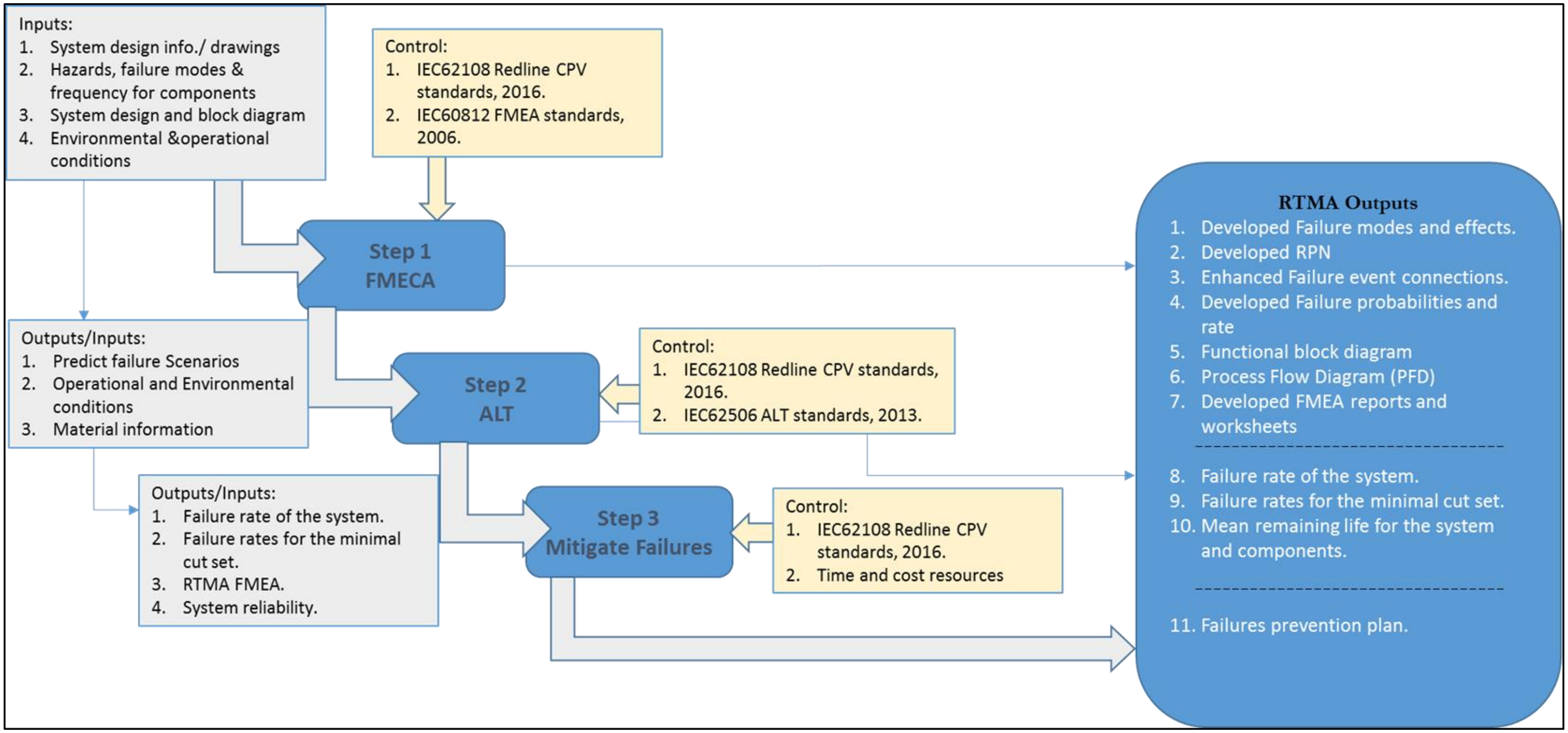


Figure 26: DARM'S RTMA Flow Chart

CHAPTER 4: RESULTS

The previous chapter proposed DARM as a method for analyzing the reliability of the CPV system by defining the specific steps involved. This chapter reports the results from actually applying DARM to REhnu's CPV system. ReliaSoft® Synthesis 11 software tool (HBM Prenscia Inc., 2017) used in this study to apply the two approaches of DARM methodology.

4.1 RDA Approach

As proposed in the method, first the inputs of the entire approach are considered; then the detailed results of each step within the approach are explained. The research applied on RDA the controls and mechanism in DARM's RDA described in previous chapter. The follow itemizes the RDA inputs developed in the course of this study.

System design information and drawings. The present research proceeded as per DARM defined previously to collect the systems design information and drawing by making site visits to REhnu labs and CPV system site, made meetings with CPV project manager to provide all the inputs. The resulting systems design information and drawings includes: a) requirements, b) subsystems, and their interfaces. The requirements of new CPV system are listed in Table 25. Notice that the system requirements have only one general requirement for system reliability listed as number seven (7) in the Table 25.

Table 25: CPV System Requirements

No	REhnu functional requirements for the CPV system /Generation 2
1	The system shall Generate 3 kW ±10% of electricity at 1000 w/m2 solar flux for 8 hours period per day
2	Use a 3.1 m square dish reflector and a receiver (power conversion unit) with thirty-six 15 mm PV thin film square cells, operate at a geometric concentration of 1200x
3	Design active cooling system to maintain the cell temperature running only about 20°C above ambient. The parasitic loss must be small, so the active cooling system consumes no more than 2.5% of the generated electricity
4	Increase DC system efficiency from 23% to 28%.
5	Dish reflector with better optical surface quality and improved reflectivity
6	Improved PV cell conversion efficiency, to 37–38% at 25°C
7	Increase reliability of the systems to work more hours in sun (≥500h) without any failure
8	Develop the Ball lens to boost sunlight transmission at blue wavelengths

In addition to the requirements, Table 26 lists the CPV subsystems interfaces for the REhnu second generation CPV system, Figure 27 illustrates these subsystems in the installed system.

Table 26: CPV System Subsystem Interfaces

CPV System Item	Description
CPV receiver module	Main solar power conversion unit
Mount Tracker structure	Steal structure tracker aim the sun rays
Paraboloidal reflector Mirror	Reflects and focuses the sunlight to the CPV receiver
Active Heat Exchanger system	Dissipate the extra heat of the CPV receiver
Tracker Motors	Move the mount tracker in AZ and EL directions
BOS Drive System	Balance of System: Inverter, batteries, UPS, sensors, and controllers

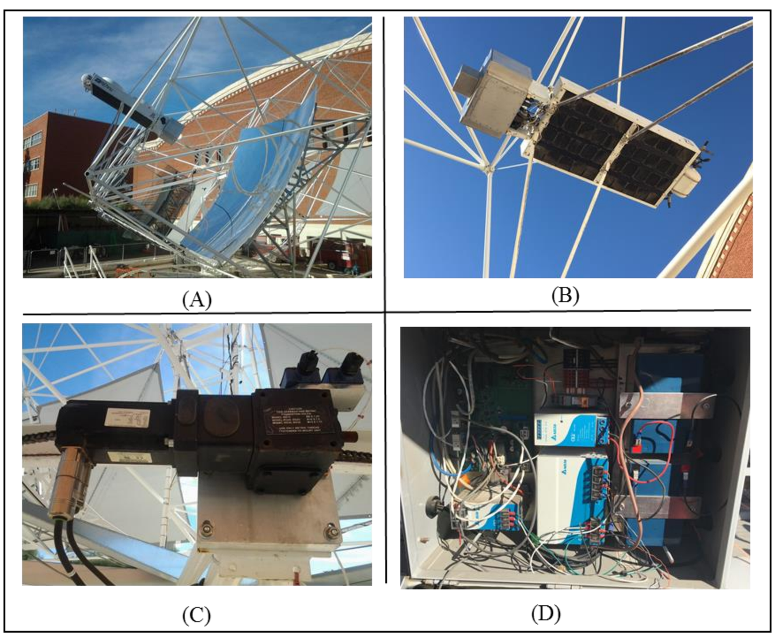


Figure 27: CPV Subsystems. A) Receiver, Tracker, and Reflector, B) Heat Exchanger, C) Motor, D) BOS

List of possible hazard, failure modes, and failure frequency for the components of the system.
Per the DARM RAD proposed, the research proceeded to collect information from the system designer, components manufacturer, components ALT and data sheets about the failure rate, failure modes, causes of failure, and effects of failure for the components of the system.

System functional design and functional relationship.
To study the system functional design and functional relationship, the research used the bill of materials of the CPV system from REhnu to build the system structural diagram shown in Figure 28, where the block in this figure represents a physical component of an item in the bill of materials, while the lines represent level of hierarchical connection of the product in each subsystem according to the bill of materials. This diagram shows the physical connections of the system components, but doesn't show the functional connection of the components which is required to implement the FMECA.

In order to use the information of this diagram in FMECA; this research collected more information from the REhnu about the functional relationship between the components of the system to build the system functional diagram shown in Figure 29 which is explains the functional hierarchical of the components in the CPV system, where a block in this diagram represents a function, and a line connection is the level of relationship between these functions.

Environmental and operational conditions of the system.
The CPV system requirements showed that this system working conditions to be in Arizona condition environment range of humidity is between 20% to 70%, temperature range from 25°C to 55°C.

This research implemented the DARM's FMECA step in the Xfmea software tool using the functional hierarchical diagram.

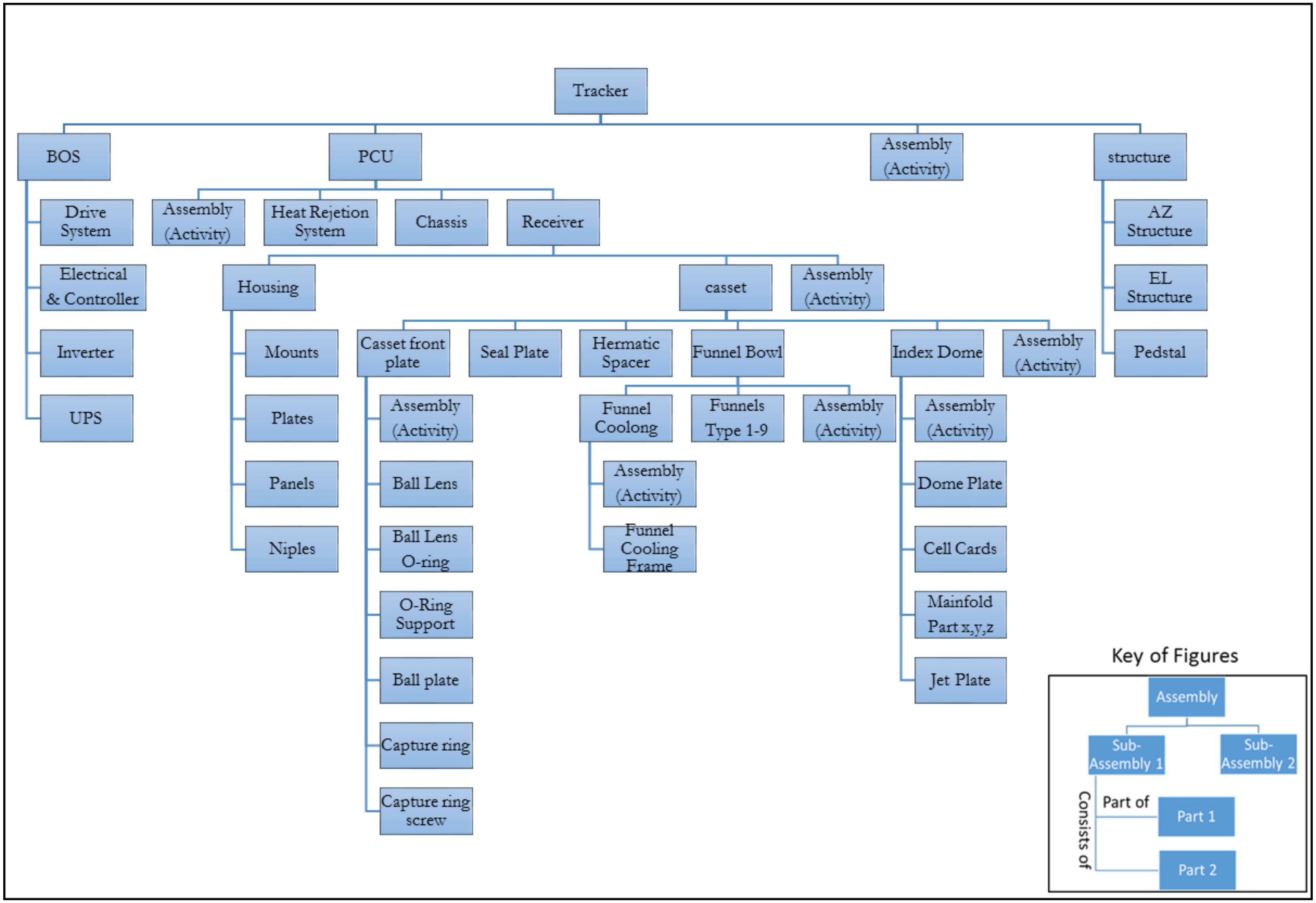


Figure 28: REhnu Second Generation CPV System Bill of Materials Diagram

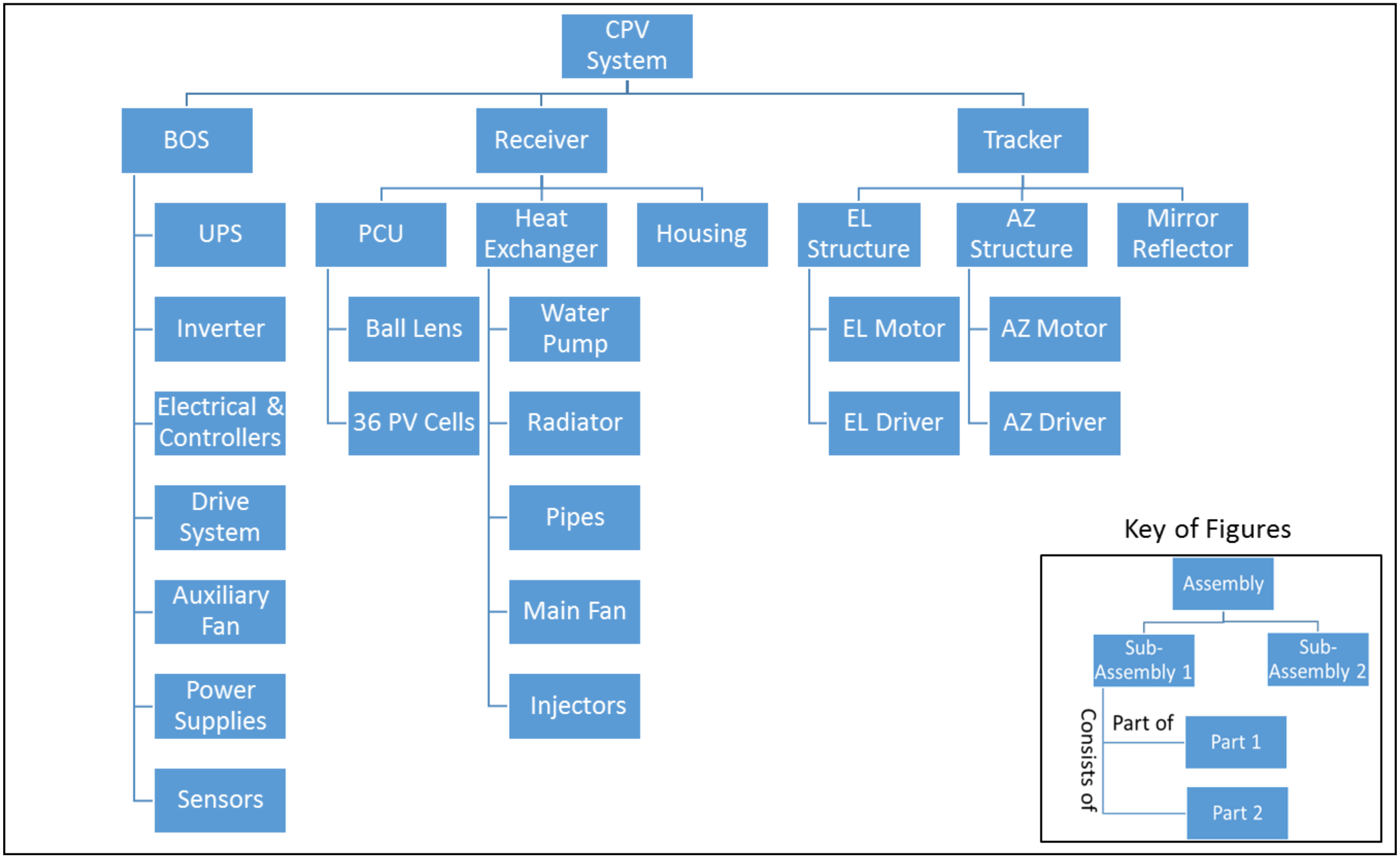


Figure 29: CPV System Functional Hierarchical Diagram

RDA Step 1 FMECA

In this step the study followed the DARM RDA FMECA and used the Xfmea software to get the results showing in Appendix A. shows the CPV system plugged in ReliaSoft® Xfmea (HBM Prenscia Inc., 2017).

RDA Step 2 FTA

The RDA method requested to apply the FTA in the step 2, the FTA implemented using the BlockSim / RENO software tool by ReliaSoft®. The resulted graph and results posted in Appendix B.

RDA Step 3 RBD & Redundancy Study

The present research followed DARM's RBD & Redundancy Study consideration using BlockSim /RENO software, this tool used for both FTA and RBD. The resulted RBD block diagram for the CPV system is captures in Appendix C.

The result from RDA's FMECA produced in Step 1 showed that the greatest RPN for the components of the CPV system was for the heat exchange subsystem. Therefore, the CPV system designer wanted to do the redundancy for the heat exchange system. The CPV system designer set a cost constraint for this reliability improvement to be about $1,000.

The following is the resulting calculation for the heat exchange subsystem for the CPV system using BlockSim /RENO (HBM Prenscia Inc., 2017).

The RBD resulting from doing what step 3 of DARM RBD and redundancy consideration the of the CPV heat exchange subsystem explained in Figure 30, where in this diagram the block represented the reliability of the associated component and the line is the type of connection in term of reliability between these components (parallel system, or series system).

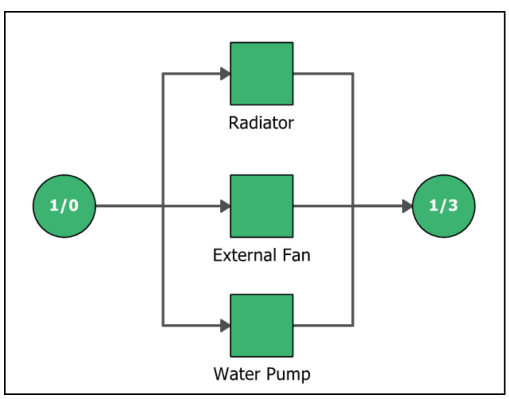


Figure 30: RBD of CPV Heat Exchange Subsystem

The research applied DARM's RBD & Redundancy Study to calculate the reliability of each component in the heat exchange subsystem. By using the outputs from DARM's FTA as explained in Figure 31 for the heat exchange subsystem. Table 27 listed the results reliability of these components, where A, B, and D are the components of the heat exchange subsystem and (TOP) is the heat exchange subsystem in the REhnu CPV system.

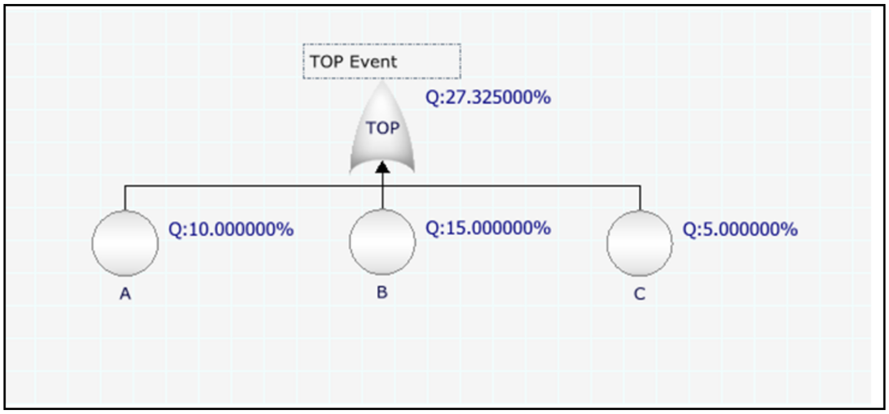


Figure 31: CPV FTA for Heat Exchange Subsystem Reliability

Table 27: Heat Exchange Subsystem Reliability

Component	Symbol	Reliability
Radiator	A	0.9
Fan	B	0.85
Pump	C	0.95

The source of the reliability rates for radiator, fan, and pump in this case study received from the data sheet and reliability information submitted by the CPV system designer, the provided reliability rates for these components based on similar components working in other systems with the similar conditions and environment.

The case study in this research used constant failure rate (CFR) for (ʎ) because the research studied the reliability in the Design For Reliability phase of the entire CPV System, and the main concern in this case is about the useful life of the entire system by eliminating the Burn-in and Wear-out failures for the components of the system.

<u>RDA Step 4 MTTF and Failure Rate</u>

The RDA implemented the DARM's MTTF and Failure Rate Resolution to calculate and the reliability of the heat exchange subsystem and the reliability for the CPV system as whole, using the cost constraints given by the system designer in RDA RBD & Redundancy Study, the following calculation resulted:

Pr (Top) = Pr (A) + Pr (B) + Pr (C)

Pr (TOP) = Q0 = $1-\prod_{i=1}^{3}(1-Q_i)$

= 1- [(0.9) (0.85) (0.95)] = 0.27325 ≅ 27.325 %

$R = 1 - F \quad , R = 1 - 0.27325 = 72.7\%$

Giving t=1 years for constant hazard rate (λ):-

$$MTTFbaseline = -\left(\frac{t}{\ln[R(t)]}\right) \; MTTF = 3.13 \; years$$

According to the above result that explained that the MTTF for this heat exchange subsystem is relatively low rate (3.13 years), DARM's RDA recommended the CPV designer to improve the reliability of the heat exchange subsystem by doing one of the following:

a) Sensing a mono pole and select alternative components with higher reliability rate,
b) Re-design the heat exchange subsystem for the CPV system to improve the MTTF and reliability for the whole REhnu's CPV system,
c) Doing redundancy study for the heat exchange subsystem by refer back to RDA Step 3 RBD & Redundancy Study.

<u>RDA Step 5 Reliability Function R(t) Computation</u>

The final step in the DARM RDA method directed to calculate and determine the total reliability of the system and defined the reliability function. The resulted output included in Appendix D which graph the resulted Reliability Function R(t) Computation of the system at the early phase (High-Level Design) of the CPV system. At this point, the study exposed that the reliability of the system is equal to 0.80 at 500 working hours, and this is consider low rate for such system, the study recommended REhnu to improve this reliability by finding other alternatives for the high failure rate components of the system like the steel structure in the tracker system and thermal system.

4.2 RTMA Approach

This research started in the early life of the CPV system in the design stage, and invented DARM method to be applicable for the whole system life which is given as 20 years. As discussed in chapter 3, the DARM directed to apply the RTMA approach in the after development phase of the system life (i.e. system utilization) to analyze and improve the Utilization Reliability, so according to the RTMA the first step in this approach should apply at the end of the CPV system design which was not available at the end of this research time.

At the above concept, this research couldn't test the results of applying the RTMA approach on the second generation of the REhnu CPV system because it was so early to apply this approach on the CPV system at the time of this research.

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Findings

The reliability methodology presented in this thesis is based on assumption that reliability activities throughout the product life cycle will give increased reliability. It is further assumed that activities can overlap each other and together give a good overview of the product reliability. The intention is for the methodology to be a tool for the development of reliability programs.

This study examined reliability of the CPV system which is an important type of system in the field of renewable and sustainable energy. Increasing the reliability of the CPV systems could potentially significantly decrease the cost of electricity produced by these systems. The present research determined studying reliability is not only essential for the product or system itself, but in most cases, has great impacts on the life and environments. (Kuo, 2011)

The examination lead to five criteria which define the need for understanding CPV system reliability. The first criterion was to consider the system as a whole rather than individual components of the system; the other four criteria are DFR, Utilization Reliability, Analyzing Reliability, and Developing Reliability. (Aggarwal, 1993)

Noting that the needs of this study focused on system, not component, reliability, the study and the methodology developed accepted component reliability data provided by the component developers. There are of course uncertainties in the values accepted. In general, the parameters in this model obtained from field data, or by the data from systems with similar functionality, due to the resulting uncertainties, the exact values of the parameters are hard to get. So, the reliability computed from the model based on the use of point estimates of input parameters is not trustable. Uncertainty analysis is necessary for the modeling work.

The present research therefore proposed a new reliability analysis method (DARM) based on a synthesis of existing reliability analysis methods integrated into two complementary approaches applied at different stages in the life of the system. DARM defines each approach as a series of steps, each being specific reliability engineering activities, and may in fact be selected of the method from the foregoing discussion.

The DARM methodology integrates complementary of two approaches (RDA), and (RTMA). The first approach is applicable to and concerned about the system in the design or development stage (i.e. DFR); while the second approach focused and related to the system in deployment stage (i.e. Utilization Reliability).

The research performed DARM's RDA for a specific system, namely the REhnu second generation CPV system, and applied the invented methodology on that system using ReliaSoft® Synthesis 11 software tool (HBM Prenscia Inc., 2017) software tool.

By applying DARM's RDA on the REhnu's 2nd generation CPV system, this research conducted these successful achievements.

1) Able to generate inputs when called for by RDA.
2) Able to execute steps in RDA in the order and time proposed.

3) The resulting reliably findings for REhnu's 2^{nd} generation CPV system (outputs from RDA steps) were sufficient study, these results helped the REhnu to:
   a. satisfy the DOE contractual requirements,
   b. satisfy REhnu need to know about their systems,
   c. Lead to specific changes in the system design which increased reliability, and
   d. Provide the REhnu with reliability analysis for their future products.

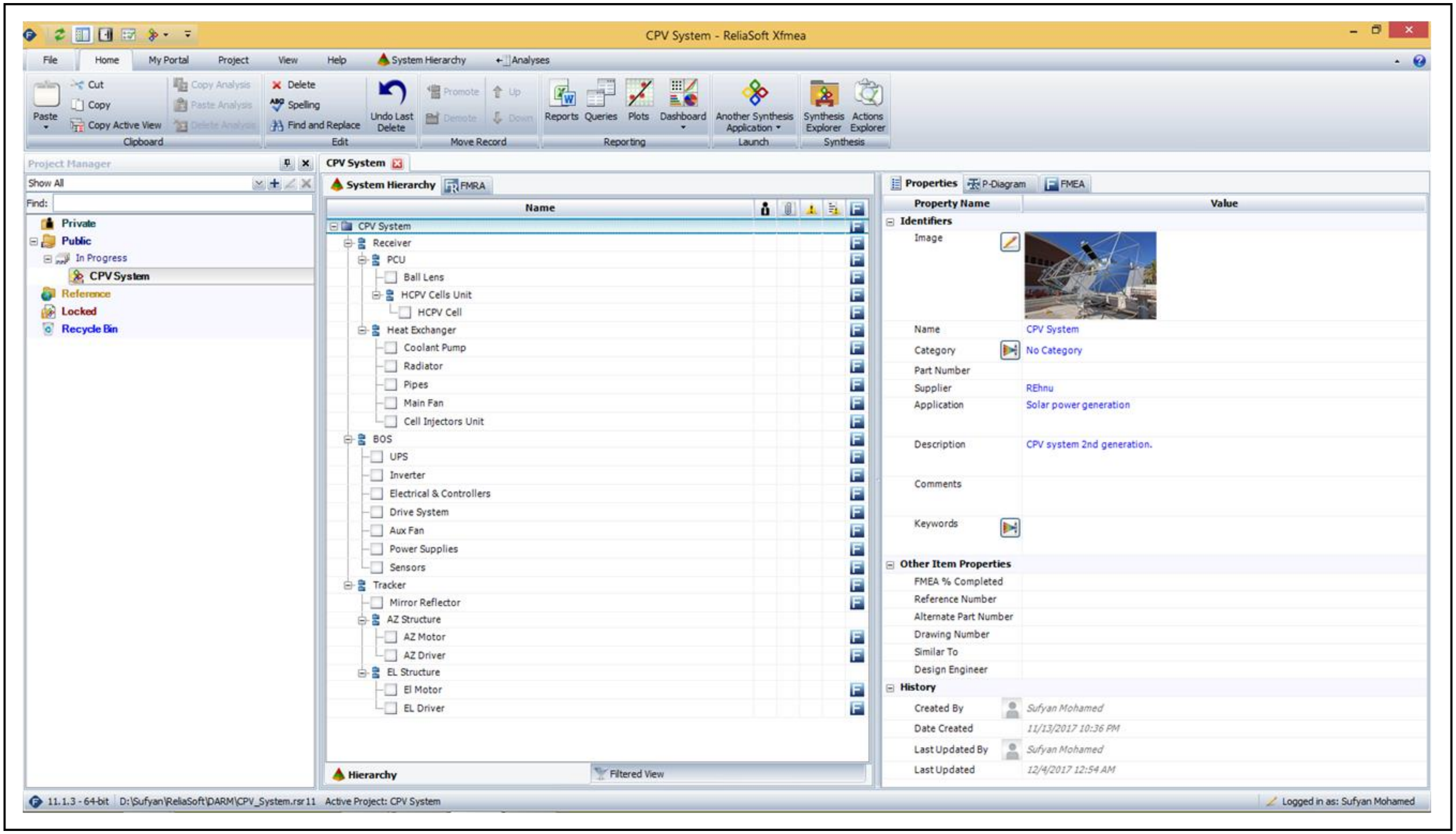
5.2 Future Work

This study recommends with the following for the future works in the field of reliability study.

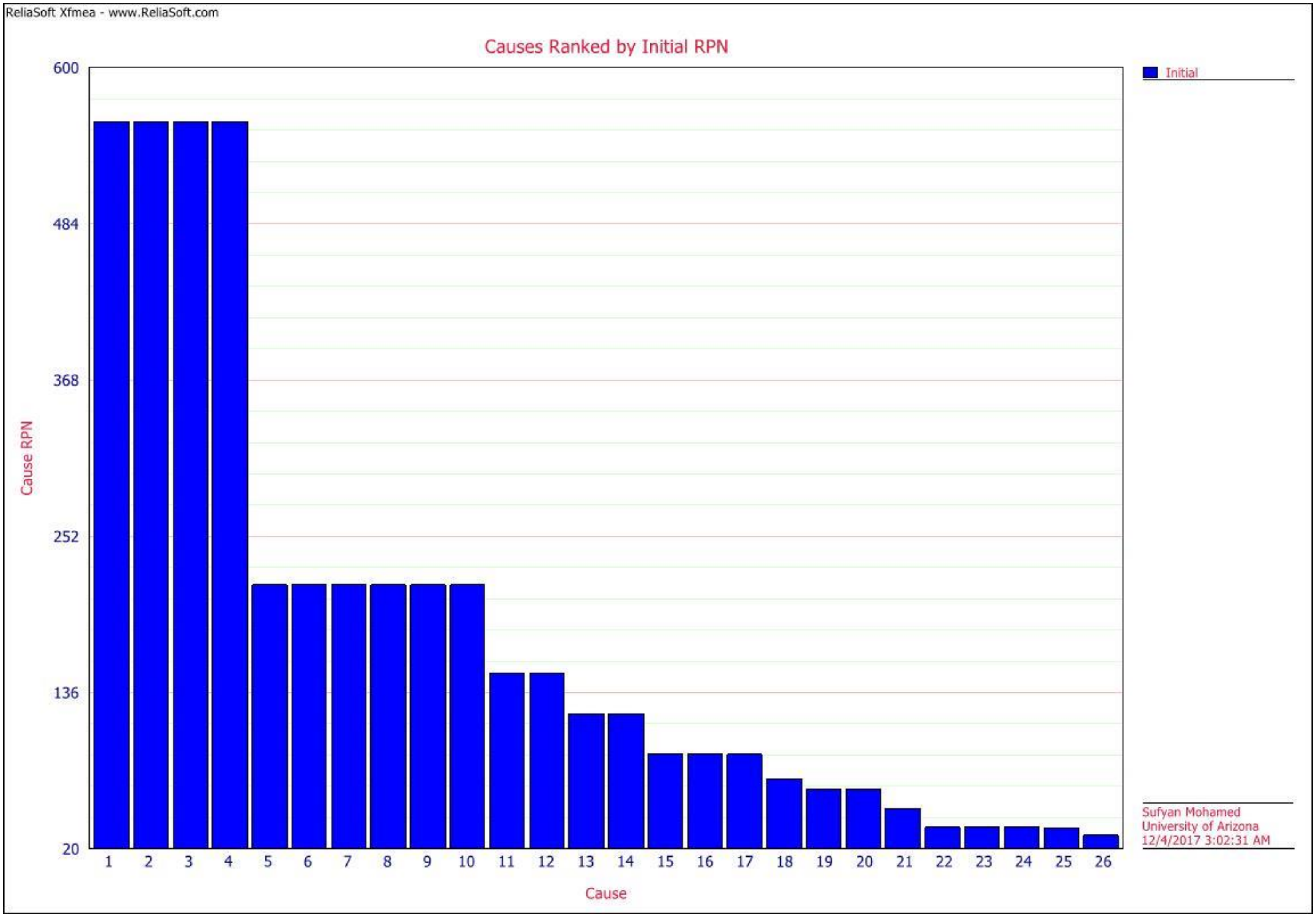
1) Exercise RTMA probably not on REhnu's 2^{nd} generation CPV system; instead on a suitable system (that is, one in the right lifecycle phase).
2) Repeat RDA & RTAM on differing systems by considering the concepts like human in loop, and consumer to determine scope of applicative for DARM.
3) Expand this new methodology analysis to cover the study of the availability of the system by implementing the study of the system's maintainability will be a great contribution to this methodology that make it widely applicable by both; the system designers/manufacturers and system's utilizers. Where: System Availability = System Reliability + System Maintainability (Repairs).
4) Building new metrics for coherent system reliability rather than concerning only the total reliability of the system R(t) will improve the reliability analysis of the system.
5) Plug in this methodology to database of the GIDEP website (Government-Industry Data Exchange Program) through a website port will enhance the efficiency and reduce the time required to obtain the reliability parameters for the components of the system and also will enrich the GIDEP database with the reliability outputs of the system through this methodology.
6) This methodology is focused on DFR, but it can be test for the Design for Six Sigma (DFSS) or ISO risk management.
7) Uncertainty and Sensitivity Analysis is necessary to implement in the study of this methodology in the future work to get the exact values of the components reliability parameters.

APPENDICES

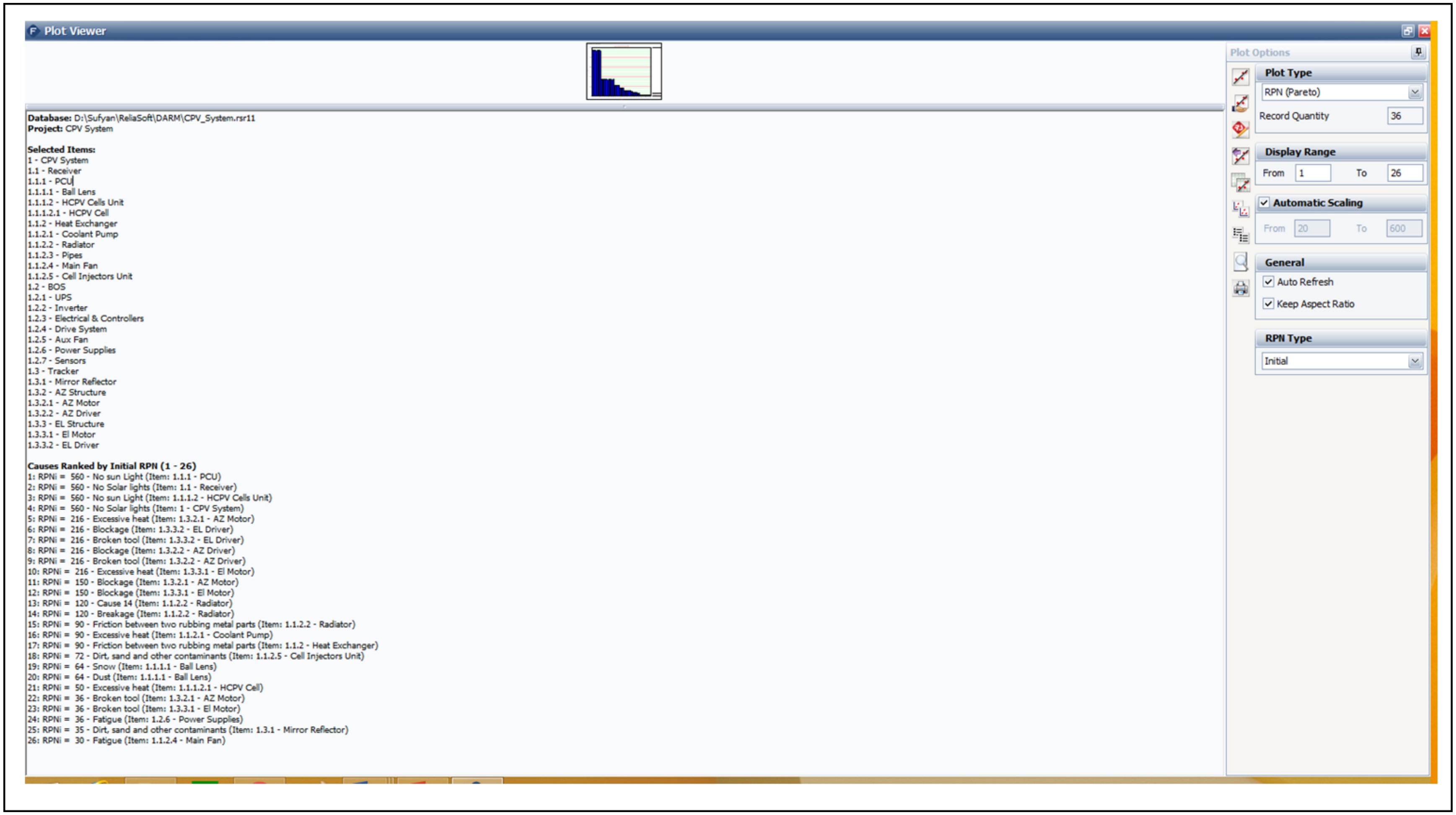
Appendix A: DARM RDA XFMEA Results



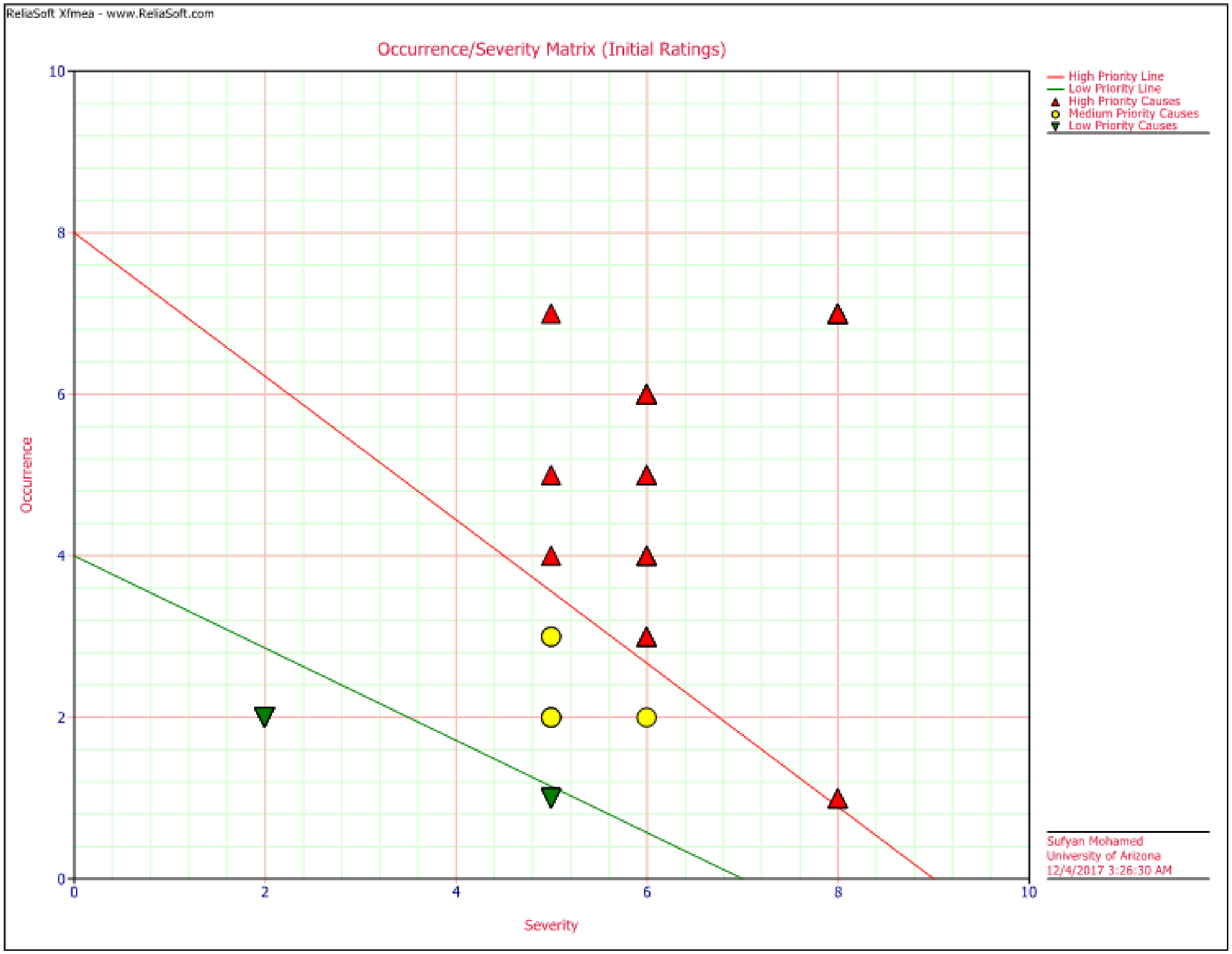
Screenshot on Applying FMECA on CPV System Using ReliaSoft® Xfmea



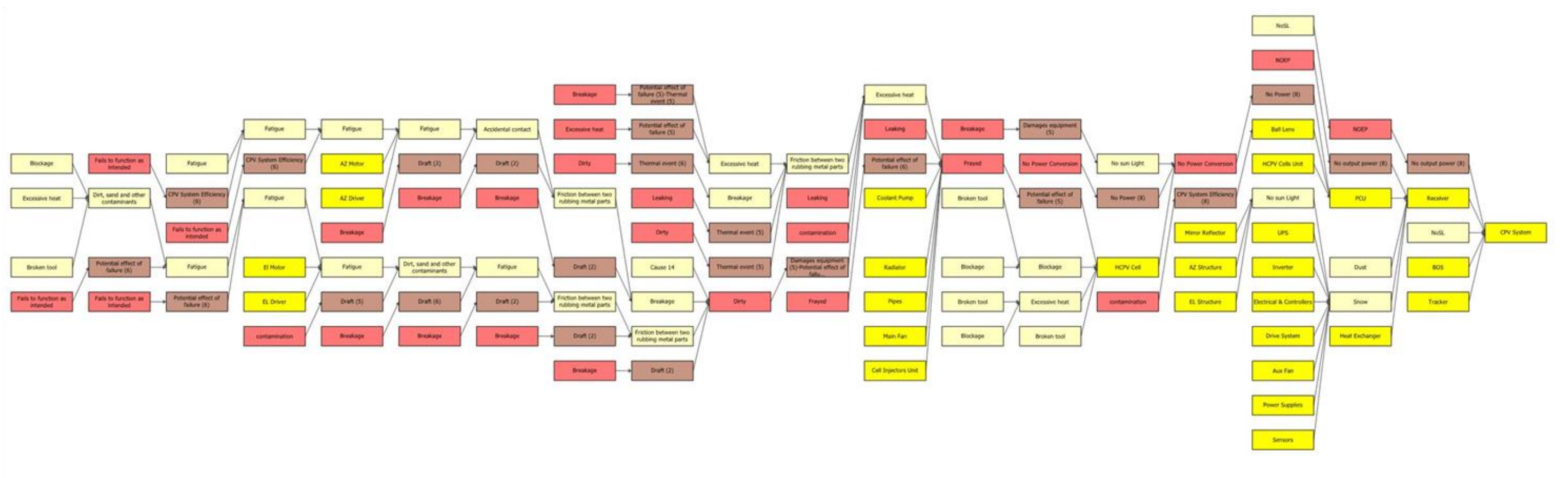
CPV system RPN diagram using FMEA



CPV system RPN Diagram with Components List Using FMEA

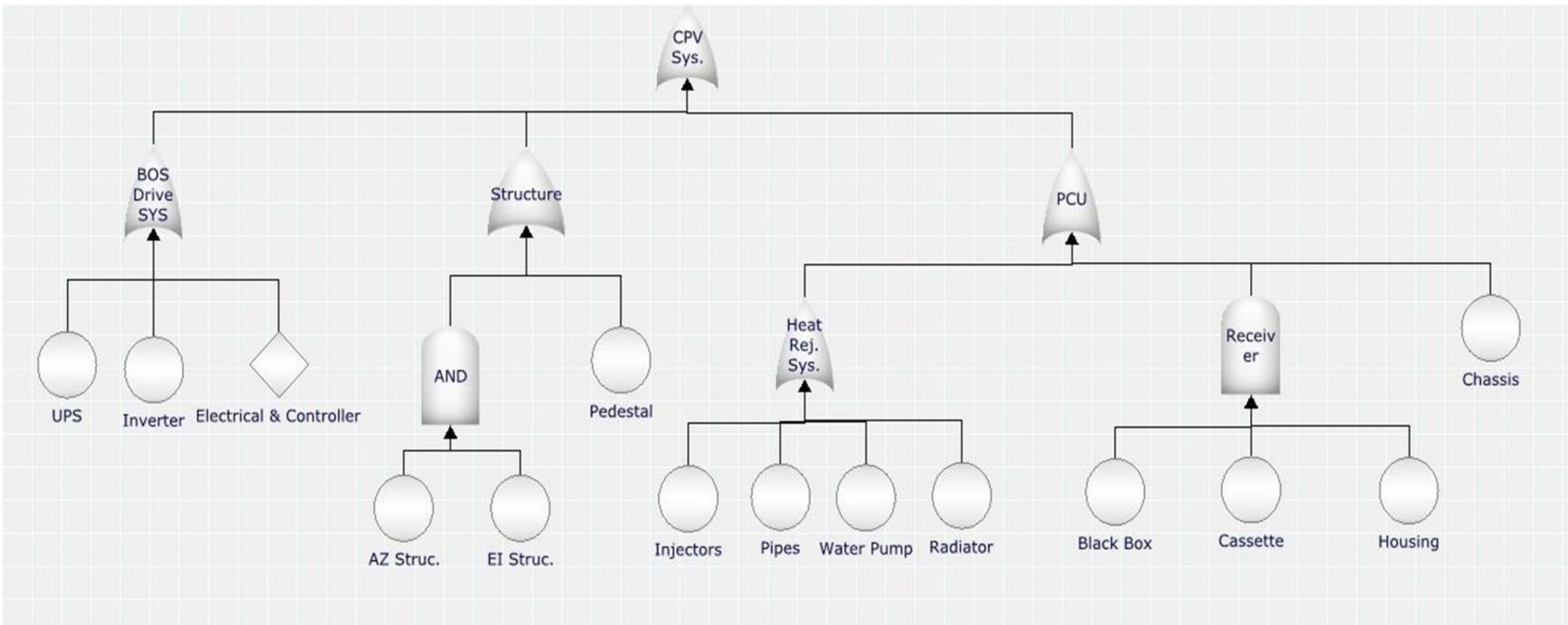


CPV Occurrence /Severity Matrix



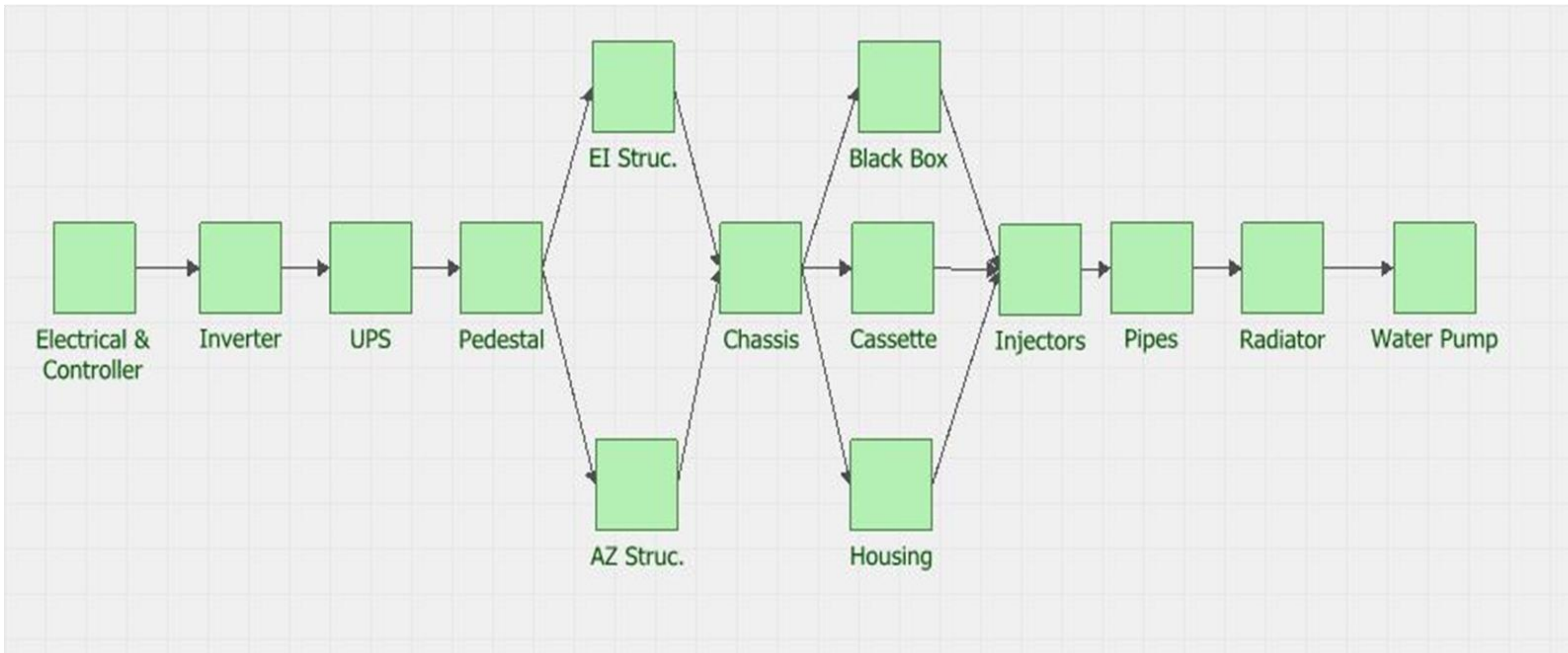
CPV Cause & Effect Functional Block Diagram Using Xfmea

Appendix B: DARM RDA FTA Results



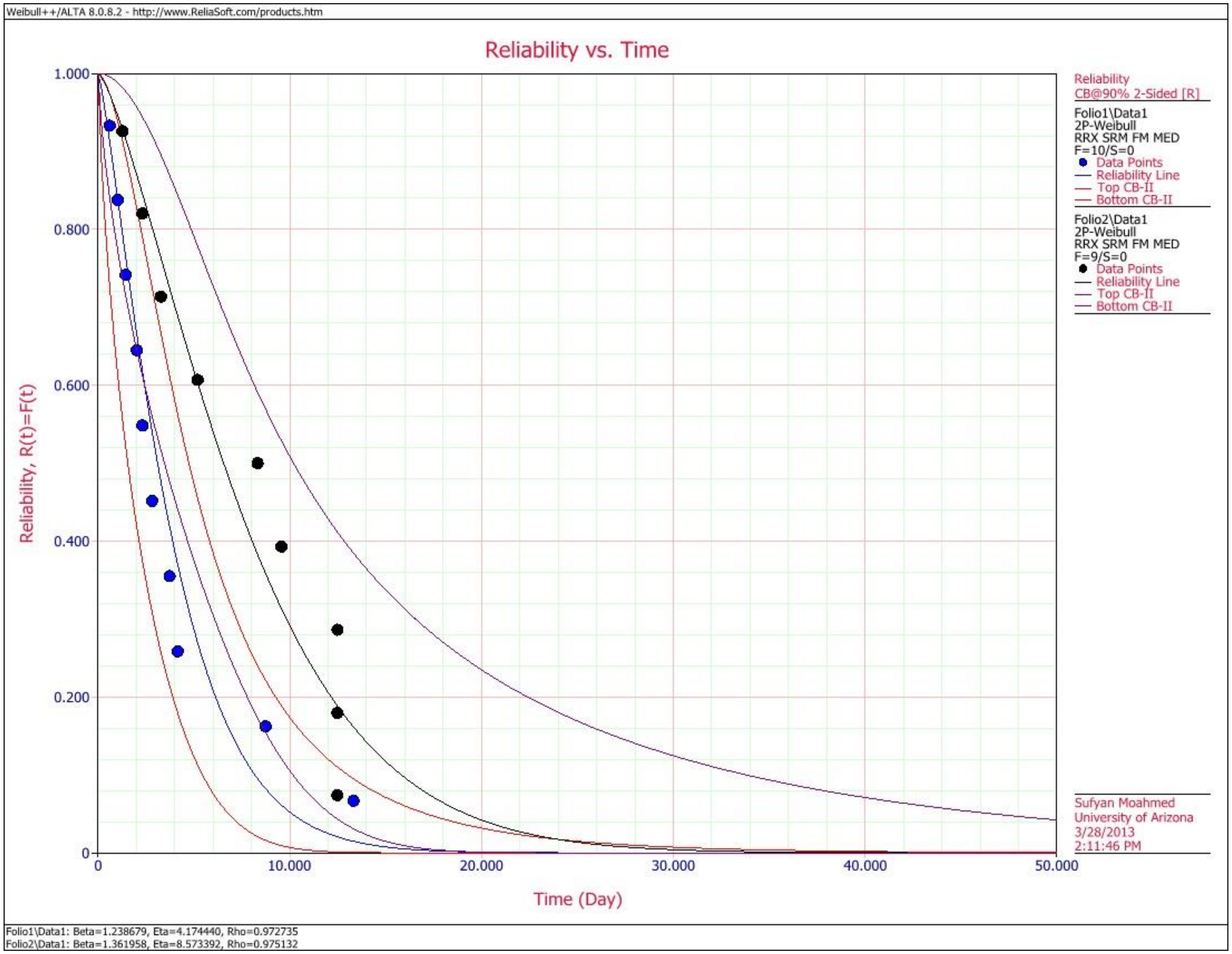
DARM's RDA FTA Analysis for the REhnu CPV System Using BlockSim /RENO

Appendix C: DARM RDA RBD Results



DARM's RDA RBD Analysis for the REhnu CPV System Using BlockSim /RENO

Appendix D: DARM RDA Reliability Function for CPV System



Reliability Function of the CPV System Using BlockSim

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