A Simulation Based Approach for Reliability Evaluation and Optimization of Time-Dependent Systems: A Case Study of Production Systems (Barin Plast Company)

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by

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Industrial and Systems Engineering.

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Declaration of Authorship

I, Morteza AHMADIVALA, declare that this thesis titled, 'A Simulation Based Approach for Reliability Evaluation and Optimization of Time-Dependent Systems: A Case Study of Production Systems (Barin Plast Company) ' and the work presented in it are my own. I confirm that:

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Morteza Ahmadivala

Abstract

Reliability is an important factor to assure the productivity, and efficiency of a system in many industrial establishments. One should look for a higher level of reliability, for his company, to increase the properly working time of the system by reducing the chance of failure occurrence in the system and so on increasing availability of the system which means more efficiency and profit.

The purpose of this study is to evaluate and improve the reliability level of Barin Plast Company (which is allocated in Iran, Tehran) based on available methods of reliability assessment and optimization. The product of this company is edge bandings which are mostly used in wood industries.

Generally, there are two approaches to evaluate the reliability in different systems which are analytical and simulation methods. In this study, problem restrictions don't let us to implement the assumptions of analytical approaches, therefore there would be a big difference between the results of this method and real conditions of company. So, Monte Carlo simulation has been chosen to evaluate the reliability level of this company. The simulation model has been prepared by Arena software that is a strong tool in this area.

After assessing the system's reliability, the main goal is to improve the reliability of company by adding redundant components to the system or replacing current machinery with better ones. There are some methods for redundancy allocation and finding the optimal solution for system's reliability. In this study a heuristic model has been prepared, for reliability evaluation of the system with redundant components, and the results are compared by solving the optimization problem.

The required data to prepare the machinery failure probability distributions are provided by company in which they show the failure scenario of machinery for a period of 5 years. The desired conditions of company's reliability is 85 percent for period of 30 days.

Reliability, Monte Carlo Simulation, Optimization, Redundancy Allocation

Tezin Türkçe Başlığı

Morteza AHMADIVALA

Öz

Tahran-İran'da faaliyet gösteren Barin Plast Şirketi'nin güvenilirlik düzeyinin analiz edilmesi ve geliştirilmesidir. Bu işletmenin ürünü, genelde ahşap sanayiinde kullanılan kenar bantlama makinesidir.

Farklı sistemlerin güvenilirliklerinin değerlendirilmesinde genellikle analitik yaklaşımlar ve simülasyon metotları olmak üzere iki yaklaşım kullanılır. Bu çalışma kapsamında incelenen problem, analitik yaklaşımların uygulanmasına izin vermemekte, bu nedenle bu metotların sonuçları ile işletmenin gerçek vaziyeti arasında büyük farklılıkların olması beklenmektedir.

Bu sebepten dolayı, bu işletmenin güvenilirlik düzeyinin değerlendirilmesi için Monte Carlo simülasyonunun kullanılmasına karar verilmiştir. Simülasyon modeli, kendi alanında güçlü bir ürün olan Arena yazılımı ile hazırlanmıştır. Sistemin güvenilirliğinin değerlendirilmesinden sonra, yedek bileşenlerin sisteme eklenmesi ya da mevcut makinelerin daha güvenilir olanlarla değiştirilmesi yoluyla işletmenin güvenilirliğinin artırılması amaçlanmaktadır.

Yedek bileşenlerin yerleştirilmesi ve sistem güvenilirliğinin optimum noktasının bulunması için bir takım metotlar vardır. Bu çalışmada yedek bileşenlerle donatılmış sistemin güvenilirlik değerlendirmesi için sezgisel bir model hazırlanmış ve optimizasyon problemi çözülerek elde edilen sonuçlar karşılaştırılmıştır.

Makine arızalanmalarına ait olasılık dağılımlarının hazırlanması için ihtiyaç duyulan ve beş yıllık bir periyodu kapsayan arıza senaryolarını gösteren veri işletmeden temin edilmiştir. İşletme için arzulanan güvenilirlik seviyesi 30 günlük bir periyot için %85'tir.

Güvenilirlik, Monte Carlo Simülasyonu, Optimizasyon, Yedek Bileşenlerin Yerleştirilmesi

I would like to dedicate this thesis to my Parents whom they have always been supportive toward my educations and personal life .

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Chapter 1

Motivation and Introduction

1.1 Motivation and hypothesis

Among different industries, having a reliable system, guarantees the appropriate system's availability, of which the result will be reaching the expected profit in the expected time of system's operation. However, in some industries, such as the military, the medical industry, energy, air transportation etc. having a high level of reliability plays a very important role. But reliability is an important key factor for any system, because failure occurrence causes interruptions in system's operation, which leads to deviation from the initiated aim and expectation from the system. In ordinary industrial systems such as production factories, in order to reach the maximum profit, the system should have maximum availability, which means that for a specified time interval, the system can be available and in operation for a higher time and the profit of the factory will be maximum. For such reasons, it is important for a factory or a production line to seek a higher level of reliability. In this study, I chose a factory, which produces polymer edge bands, which has a series of machinery to produce the final product and my goal is to achieve a better condition for its reliability and availability. The reliability of this system depends on the reliability of each component and its alignment in the system. As a result, the hypothesis of this research is, systems should be designed with better and more advanced safety features, to make the factory more affordable and reliable during its lifetime. To address the reliability of this production line we should know some statistics about each component, and the way that they are connected to one another. Hence, in order to conduct this study, one should follow some steps and find answers to some important questions. These questions are addressed in the following sections.

In general, there are few steps in reliability evaluation of practical models. The first step is to determine the system alignment and configuration of the components in the system.

One needs this because one has to know about the dependencies and interrelations of the machinery throughout the system. The second step is to find the failure probability distribution function of each component, and for this one can use the statistical data, which has been collected for a period of time. This includes the information about the time and failure frequency of each machine. So, based on this information and some useful technique such as the goodness of fit one can estimate the failure probability distribution function of the components. The next step will be about the reliability evaluation of the system by specifying the methodology. As it will be mentioned further in the introduction, there are few approaches such as analytical and simulation approaches that one can choose to assess the system's reliability. In this study, I use the Monte Carlo simulation to estimate the reliability of the system. After evaluating the system's reliability one needs to improve it based on the available techniques such as adding redundancies, stand-by, or improving the current components, which is the last step of this study.

Testing my hypothesis by some key questions can provide a good way and procedure of conducting the research. The key questions are:

- What are the past and present policies regarding to safety and reliability for production lines?
- What are the past and present processes and practices used in the safety and reliability of production lines?
- What are the motive factors to improve the reliability and safety, and how to do it?

The first two questions will include the first two steps of our research in which we have to find out about the ways and methods that have been used for reliability and safety of power plants, so the steps can be

1. Search for available data to extract a proper literature of the past efforts for production line reliability assessment.
2. Look for the best-fit theoretical method to model and simulate our system.
   And the answer of the last key question is the main part of this project which can include following steps
3. Developing a method which can satisfy the maximum of our aims for evaluating the reliability of the system.

4. Modeling and simulating a system as a case of study to validate the developed method or theory.

Therefore the expected outcome of this study can be developing a methodology to assess the reliability of production lines, especially for this case of study, and reconsidering safety standards and rules, which can provide better protection for unexpected catastrophes.

1.2 Introduction to reliability

The Reliability index is a very important criteria for assessing the quality of many system's services such as energy supply systems (power plants, dams), transportation systems, communication systems, military equipment, space crafts and airplanes, manufacturing systems, medical equipment, and many other systems.

Many of us may have an understanding of reliability and of what reliability is by some experiences of everyday life. For instance, some may complain about the number of failures that occur in their car during the week or month, and discuss how reliable or unreliable their car is or any other instruments. Similarly such failures can happen in many different areas as well as in simple products that we use in our homes or as personal tools. For example, factories, power plants, airplanes, hospitals, travel agencies, and many other fields of works are the sectors where their association with reliability has great importance. Just imagine if a power plant, which generates the electrical energy for a city or different factories, fails for a period of time. As a result there would be a big loss for the power plant owner as well as ordinary and commercial users. Having a reliable system insures the steady rate of working or profit from the system for a specified time interval. On the other hand, by improving the system's reliability, one can reduce the probability of failure occurrence, which means one can trust the system to meet the customer needs and bring enough profit.

Reliability will improve by removing the causes of failure in the system, so the magnitude of reliability depends on the number of unexpected failures that may occur in the system. Some of the causes that may reduce the reliability of the system by increasing the number of failures are:

- Variation
- Wrong specification
- Wear out of the machinery

- Misuse of the machinery
- Using the component in a different environment

As well, there might be many of other reasons for having unexpected failures in the system. As it was mentioned above, it seems to be clear that reducing the frequency of the failures by eliminating their reasons and Identifying the weak links in the system, and suggesting a cost-effective method to improve the weakness of the system regarding its reliability and availability are key factors to improve the reliability of a system. Here reliability engineering plays an important role to eliminate failures by:

- Applying appropriate knowledge to prevent the frequency of the failures
- Identifying the cause of the failures that occur in the system to fix them
- Identifying appropriate ways to overcome the occurrence of the failures
- Analyzing and estimating the previous and current conditions of the system's reliability by available methods [26].

Almost in all systems, the occurrence of the failures is a probabilistic phenomenon, so the measurement of reliability, which is directly related to the failure frequency is a measure of uncertainty, hence reliability estimation should be done by statistics and probability theory. For these duties reliability engineers need some techniques and methods to properly detect the failures in the system, and also suitable techniques to evaluate the system's reliability. Having a reliable system is crucial in many industrial sectors, because the high level of reliability has important implications, among which are:

- Increasing the safety of the system
- Competitiveness
- Preparing good profit margins
- Decreasing the cost of repair and maintenance
- Decreasing the delays further up supply chain
- Improving the company reputation

1.3 Important Definitions in Reliability Engineering

Reliability, Availability, and Maintainability are three key definitions for reliability studies, in which one looks for finding a way to evaluate and improve the factors in systems. Hence, the definition of these factors is given in this part. As well, there are other terms in reliability studies such as repairable and non-repairable systems, which one regularly comes across in different literatures. Last, one should decide about the system if it is repairable or non-repairable in the initial steps of the considerations.

1.3.1 System

A system is a collection of components, subsystems and/or assemblies arranged to a specific design in order to achieve desired functions with acceptable performance and reliability. The types of components, their quantities, their qualities and the manner in which they are arranged within the system have a direct effect on the system's reliability. To accomplish this, and in addition to the reliability of the components, the relationship between these components is also considered and decisions as to the choice of components can be made to improve or optimize the overall system reliability, maintainability and/or availability. This reliability relationship is usually expressed using logic diagrams, such as Reliability Block Diagrams and/or Fault Trees [24].

1.3.2 Reliability

Reliability is concerned with the probability of the proper functioning of a system under predefined conditions and for a specified period of time. It defines the probability of the lack of failures under specified conditions. There are common measures for defining the reliability of repairable and non-repairable systems, which are mean time between failures (MTBF) and mean time to failure (MTTF). So normally, reliability is more precisely defined by the probability of success for a period of time under determined conditions. For instance, the reliability of a cell phone or computer can be assigned 95 percent of working properly or success for a period of 1 year under defined conditions.

Mathematically speaking, reliability has been defined as the probability that a machine operates properly for a period of time. If one says *f(t)* is the failure probability density function of a component, and *F(t)* is the cumulative probability distribution function of it, then:

$$F(t) = Pr(T < t) = \int_0^t f(x)dx \tag{1.1}$$

And by the definition we can write the reliability as

$$R(t) = Pr(T > t) = \int_t^\infty f(x)dx = 1 - \int_0^t f(x)dx = 1 - F(t) \tag{1.2}$$

T is measured from time zero and is the lifetime of a component. By finding the expectation of T we easily can find the mean time to failure of the component. [22]

1.3.3 Availability

Availability is defined by the percentage of the time, in which the system is working properly. This means that by finding the down time of a system one can evaluate the availability of the system, so it is a function of down times. Because the availability of a system is concerned with all of the components working, it would be better if one evaluates the availability for the whole system rather than some components. Availability is actually a fraction of time, for example it is 900 of 1000 of working hours of a system, then its value is between 0 and 1 [24].

1.3.4 Maintainability

Maintainability measurement typically shows the ability of a component in the system and how easily it can be repaired or restored in the system, which is working under a specified condition. It should be noted that there is a difference between maintainability and maintenance. Maintenance is a set of operations and practices that try to fix or prevent the failure of happening. On the other hand maintainability is a design parameter, which shows how convenient it is to restore the system and the repair is conducted by some skillful personnel, which use assigned procedures and resources for each level of maintenance. Therefore, the maintainability shows how preventive actions and maintenance are quick and effective in the case of cost and time. Mean time to repair (MTTR) prepares a scale for measuring the maintainability [24].

1.4 Reliability Evaluation Approaches and Techniques

1.4.1 Reliability evaluation approaches

Basically there are two different approaches to analyze the reliability of a system, which are associated with different tools and concepts: the analytical approach, and the Monte Carlo simulation approach. In the analytical approach one models the system into a mathematical model, which is solvable by available analytical methods. For a simple example, if one has a system with two serial or parallel components and each component follows the exponential distribution with parameters of λ_1 and λ_2 in case of failure occurrence, it is easy to find the distribution function of the entire system, and respectively evaluate the reliability of the system. for instance if we have a serial system with two components with parameters of λ_1 and λ_2, and reliability of each component is R_1 and R_2, it can easily be understood that the system's reliability will be $R_1 * R_2$. And for a parallel system with two components reliability is equal to $(1 - (1 - R_1) * (1 - R_2))$. Mathematically speaking, for serial system we have:

$$R(t) = R_1(t)R_2(t) = e^{-(\lambda_1+\lambda_2)t} \tag{1.3}$$

and for parallel system, reliability is calculated as follow

$$R(t) = 1 - (1 - R_1(t))(1 - R_2(t)) = 1 - (1 - e^{-\lambda_1 t})(1 - e^{-\lambda_2 t}) \tag{1.4}$$

On the other hand, if it is not easy to find the probability distribution function of a system by the analytical approach because of the complexity of the system or other conditions that cannot be modeled by the analytical approach, it is possible to find the system's reliability by using the Monte Carlo simulation technique. In this approach, by having the actual statistical data of the system or distributions of components, one simulates the whole system process. By this method and putting the simulated model under real experimental conditions, and by having an adequate number of the experiments, it is possible to find or estimate the whole system's behavior or probability distribution function by statistical techniques such as the goodness of fit [24, 26].

The important thing about choosing the approach for reliability analysis is the nature of the system. First, one should examine the system to see if it is possible to find the system's distribution function via analytical techniques or not. Naturally, the analytical approach has priority in comparison to simulation, because it can gives us the exact solution of the problem. In the case where the system is very complicated and obtaining the reliability function is very difficult, the Monte Carlo simulation is applicable and is a very useful tool. Normally, via the simulation technique, one models the system mathematically and by running the model under real simulated conditions, one can find the statistical data for the system entirely. Finally, by using the achieved data from the simulation one can judge properly the reliability status of the system.

It should be mentioned that for obtaining the probability distribution function of any machinery or component in a system, normally the life test data of the component or the data from accelerated life testing would be used. These distributions describe the time between the failures of the components. Therefore, this statistical analysis should be done on all components of the system to find their distributions individually, because the system's operation is associated with component's contributions and the components build the system, and for finding the system's behavior or failure distribution one needs to know enough about different parts or components of the entire system. In the other words, in the system's reliability, the concern is about the behavior of the whole system, which is constructed from sub-systems, and by finding the properties of each sub-system, one can understand the behavior of the system.

1.4.2 Reliability evaluation techniques

Besides the approaches that are available for evaluating the reliability of the system, approaches include different methods and techniques that are well suited for reliability assessment. However, the construction of each technique addresses special problems regarding reliability considerations. It should be mentioned that here, the only discussion is about the quantitative methods for analyzing the reliability of a system, however, there are some qualitative methods for understanding the reliability and availability of the system. Here, I offer a brief introduction for different models, which are used to evaluate the system's reliability.

- **Reliability block diagram model**

Reliability block diagram is a tool to model large and complex systems for reliability and availability analysis. Diagrams help show the logical interactions and relationships of the components among the whole network of the system. There are two pairs of terminal nodes in block diagrams, which are input and output nodes. The input node follows sets of parallel and series blocks, which represent the arrangement of the system's components. There should always be a connection between the input and output nodes for the system to operate properly. The failure of the system occurs if and only there is no connection between these two nodes, and for the reliability analysis of the system the probability of having at least one connection should be found. Reliability block diagram has a success-based approach; this way one can calculate the probability of the system success. Figure 1.1 illustrates reliability block diagram for serial and parallel systems [26].

- **Reliability graph model**

Reliability graph modeling is another tool for modeling the system regarding analyzing the reliability of the system. Reliability graph is a set of nodes and edges, in which edges

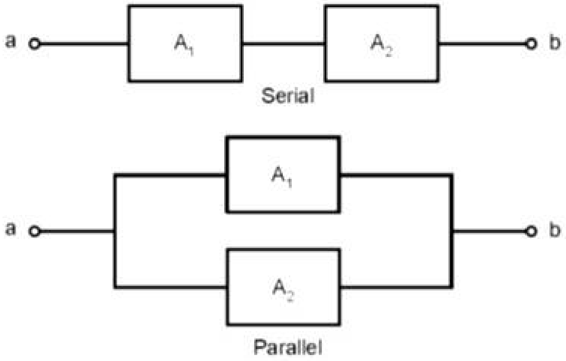


FIGURE 1.1: Reliability block diagram

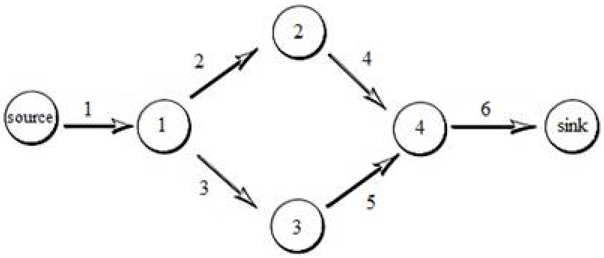


FIGURE 1.2: reliability graph model.

or arcs represent the components of the system, the nodes are inspection places, and they show the interconnection between the components or edges. Each reliability graph has a beginning node, which is the source node, and this node represents the input part of the system. There is no component of incoming edges in this node. On the other hand, there is a sink node, where there is no outgoing edge from this node. To have a successful system there should always be a path from the edges between the sources and sink node. The reliability graph is equivalent to a block diagram with no parallel-series components; however, in block diagrams, components are shown with boxes, and in reliability graphs they are shown with edges. An example of reliability graph model is presented is Figure 1.2 [26].

- **Fault tree model**

Fault tree model is a technique, which measures the probability of the system's failure. In this technique the systems is modeled as a tree like structure, which shows a series of consequences between components. So the fault tree model is a graphic view of the system (Figure 1.3), which is the combination of events that cause the system's failure. Each level of the model is connected to another one based on logic gates, and the usage of the gates surely depends on the interrelationships within the components. There is an assumption behind the fault tree modeling, and because of this one assumes that the failure occurrence of the basic events (failures) of each component are independent. The failure occurrence is shown by logic values. For example, 1 is the logic value for having failure and 0 is logic value for success. These logic values are decided by suitable gates as "and" and "or" gates which are chosen based on the system's configuration. The final value, which comes out from the fault tree model is the failure probability of the system. This method is generally used for reliability evaluation and safety analysis [26].

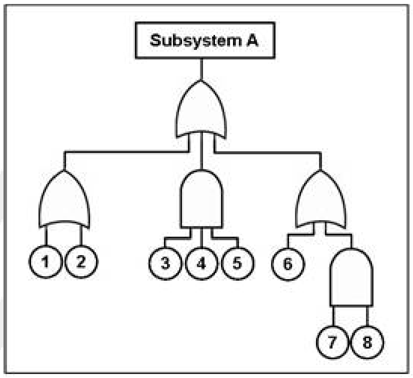


FIGURE 1.3: Fault tree model

- **State space models**

In the previous techniques such as block diagrams, reliability graphs, and fault tree analysis, which are so efficient to find solution for the reliability problem, but there are some assumptions behind them such as independency of the components. This means that the failure and repair of a component of the systems has no effect on any other part of the system, and this means that one has a pure reliability/availability model, and the solution for the reliability problem is incomplete, or the results have less value. Therefore, if one wants to consider these influences in the system, he should use other techniques, which can address the dependency between components. One of the tools that can help evaluate the reliability of these systems is state space modeling by Markov chain or Markov modeling. In Markov modeling one divides the performance of the system into different states, and in each state there is a specified level of production or performance, clearly with probability. The system can go from one state to another with the determined probability and it can go back to the previous or to another state with different probabilities. The value for each probability of going from one state to another can be achieved by the statistical data that is collected over a period of time. Therefore, by means of the Markov chain and by finding the probability of the system in the states where it has a performance or production more than zero, it is possible to find the reliability level of the system. There are few assumptions for Markov modeling as well as other models. In Markov modeling one assumes that the failure occurrence follows the Poisson distribution and the time between failures follows exponential distribution [22, 26].

1.5 Introducing the company- Barin Plast Company

Barin Plast Company started to work in 2010. The production of this company is PVC edge banding in different types and colors. This product is a narrow and thin strip of PVC materials, which can be used for different applications such as covering the exposed sides of other materials such as plywood, particleboard, or MDF. The application of this product is to increase the durability of the materials that has been covered by edge banding and to increase the pleasant appearance of the product to seem solid and more valuable with a better appearance.

At the beginning, this company was working and producing edge bandings during one shift of 12 hours per day, and after one year they changed it into two shifts of 12 hours full- time. Now, three groups of staff work during two shifts of 12 hours, working time. One of the groups continues to work from 8 A.M until 8 P.M, the second one works from 8:00 P.M until 8:00 A.M, . Groups change every two days. The engineering department of the company includes four different engineers, the production engineer, quality control engineer, R and D engineer, and the production-planning engineer. Different departments of the company such as financial, management, and administrative departments work in the company during only one shift per day, which is eight hours.

Production plans of the company are presented by the production-planning engineer, based on market and customer needs, and the results are given to the production engineer. The production engineer implements the production plan, which has been given to him into the production lines to produce the required products with the requested quality. The role of the quality control engineer is to test the quality of the producing product at each level of production, based on the accepted quality parameters and tools. Finally, the R and D engineer follows and investigates the problems related to material replacement, quality improvement, and cost changes of the product.

The production line of the company includes four groups, which are strip production group, printing group, slitting group, and grinding group. Besides these groups there are installation and warehouses that have their own responsibilities. The strip production group has been composed of the mixing unit, extrusion unit, calendaring unit, premiering unit, and rolling unit. There are five workers, which are responsible for this group, and one of them is the line operation supervisor and one cooperates with him. One is responsible for the premiering unit and the other two operators work on the mixing unit. The supervisor or the line operator is in contact with the production engineer and with the help of his cooperator he handles the production plans. He should supervise the mixing unit, extrusion unit, calendaring unit and rolling unit precisely. All units are under his supervision directly. Mixing unit operators should prepare the required material with specified weight, which has been formulated by the production engineer, and then he puts them in the turbo mixer. The mixing operation is done automatically. For each type and color of the product, there is a special formulation, which has been achieved experimentally. After this stage the mixed materials are transferred into the extruder, and melted and extruded under the specified conditions of temperature and speed of melting and extruding (extruder works like meat grinder). After the extrusion unit the material is transferred into the calendaring unit for cooling and taking a determined shape and emboss (thickness, width), which is based on the current production policy of the company; the thickness of the products are 1 and 2 millimeters. Determining the temperature, speed, and rotating speed of the rollers of the extrusion unit is the responsibility of the production engineer and should be taken into action by the production line operator. The produced sheet in the extrusion unit is transferred to the premiering unit and a special material called premier is then applied under the sheets, which is important for the treatment between the edge bands and wood glue. Then the premiered sheets are rolled to be transferred to the printing unit.

The printing unit includes a machine that does the varnishing on the rolled sheets. There are three personnel in this unit among which one is responsible for preparing the required paint and is the unit supervisor, and the rest are the unit's operators. The unit supervisor should prepare the paint based on the specified formula for each type of product and other operators do the painting and varnishing duties. After painting the sheets, they are rolled once again to be transferred to the slitting unit.

The slitting unit includes three different sub-units, which are the slitting, packaging, and pulverizing units. There are four operators in this unit, which conduct different duties. Two of them are responsible for slitting and pulverizing, and the other two workers do the packaging. In the slitting unit, prepared and painted sheets are cut into strips with different widths by a machine, which has blades that enable the distance between them adjustable, so the strips with different widths can be produced. The strips with thickness of one millimeter will be rolled in 200 meters length and the strips with the thickness of two millimeters will be rolled in 100 meters rolls. Usually, there occurs waste after cutting the sheets into slits, and then the wastes are transferred into the pulverizing machine. Finally, the rolled strips are boxed to be transferred to the warehouse where they wait to be sold.

There are two operators in the grinding unit, and their responsibilities are to collect the waste from different units of the factory and grind them to be used in the production cycle again with a determined formulation.

In following some pictures of machinery alignment, and different machines in the system are presented.

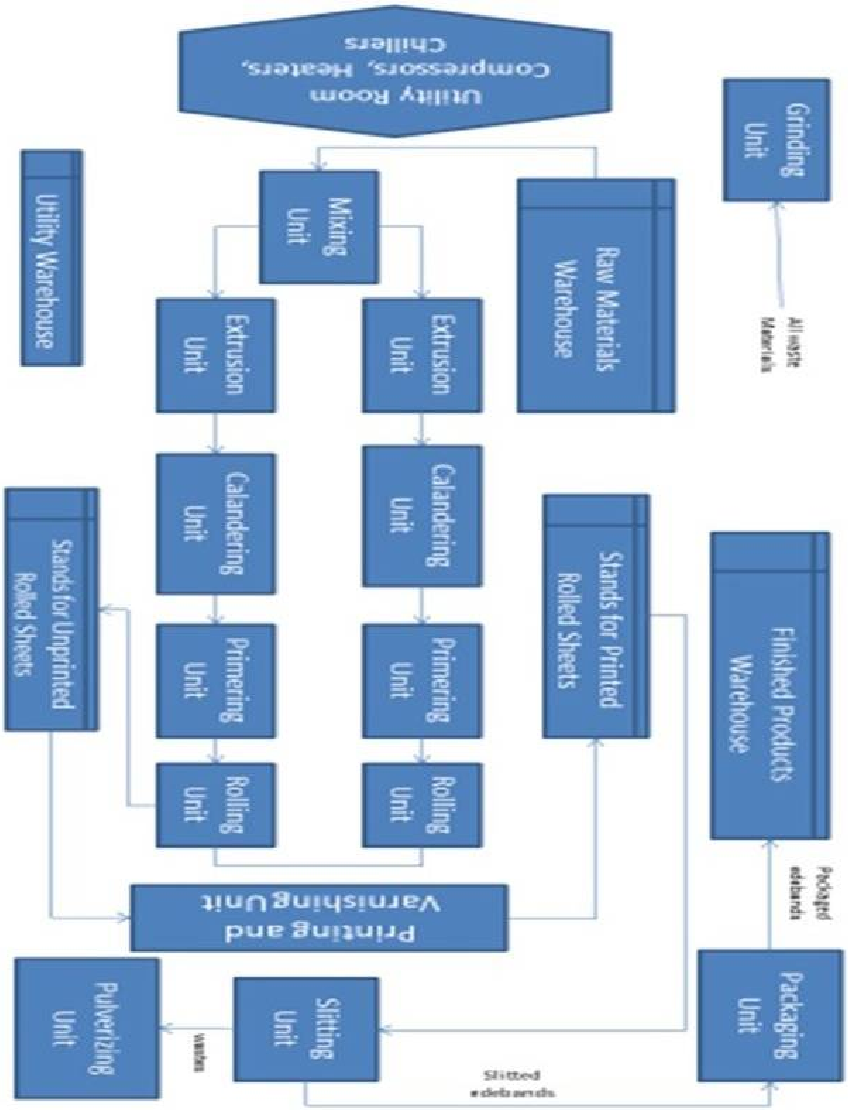


Figure 1.4: Company configuration

The purpose of this study is to evaluate the reliability of the Barin Plast production line system. Barin Plast Company prepared the initial information about the components alignment and failure statistics of each component for a period of five years. This information is needed to be able to understand about the failure probability of each component and the system. Therefore the main purpose of this study is to provide a heuristic model for reliability evaluation of the company when redundant components are added to the system for reliability improvement. In this method, first, the initial reliability level of the system will be evaluated (which based on the company requirement is not an appropriate level) by simulation, then hot standby and cold standby redundancies will be applied for this system and reliability level for this conditions will be evaluated and the optimal solution will be chosen among these options.

In the second chapter, the previous works on this area are studied. There are some articles which study the reliability evaluation for production lines and other applications. In some of them reliability based optimization has been considered, and several of the articles have studied the redundancy allocation problem for reliability improvement. A number of these articles have been chosen to prepare the literature review of this thesis.

Chapter three concerns with the methodology which will be used for reliability evaluation of the company. This method uses Monte Carlo simulation and goodness of fit tests for reliability assessment.

Forth chapter is related to initial reliability evaluation of the system by the methodology which is introduced in the third chapter. Arena simulation model is presented in this chapter which allows us to achieve the appropriate data about the initial reliability conditions of the system.

Finally in the fifth chapter, reliability optimization will be considered. in this part I will apply a heuristic model to find the best solution for redundancy allocation for hot standby redundancy options. In this model, firs the weaknesses of the system are identified, and then by allocation some levels of redundancy I try to improve system's reliability based on the company's requirements.

Chapter 2

Literature Review

2.1 Literature Review

There are many studies and works on the reliability allocation of different systems in different areas of the industry. Some of them have assessed the system reliability based on the analytical techniques, and some used the simulation technique for reliability evaluation of their system, which is as well the approach of this study in order to evaluate and improve the system mentioned in this study. There are few studies that optimize the reliability of the system based on constraints such as the cost and weight of the components. Each study helps the better understanding of how to evaluate and improve the system concerned in the case of reliability assessment, which can increase the profitability of the company by increasing availability and reducing mean time of failures. In this part, I will review some of the past efforts briefly regarding reliability allocation for different systems; as well, I will present different approaches.

H.Ge and H. Asgarpoor have used the Monte Carlo simulation approach to evaluate the reliability and cost estimation for different systems. Based on the available historical data of the system, and the application of simulation techniques, they were able to find the reliability indices, and probability distribution functions of each component, which are important to assess the reliability of the whole system. In order to discretize the time periods of the simulation, to have more efficiency, and to be faster, they have used a parallel programming methodology. With this they were able to use parallel processors to run the simulation and they achieved the results faster than a normal simulation running. They have checked their methodology for different case studies with analytical solutions to validate their methodology and to show that this method is faster than those of previous studies on reliability evaluation by the simulation approach [7].

R. Bakkiyaraj and N. Kumarappan have tried to evaluate the reliability of the "composite electric power systems" by using the Monte Carlo simulation. They applied a none-sequential Monte Carlo simulation to assess the reliability of the components of the system and the reliability indices of the system entirely. Afterwards, they tried to optimize the problem or the system by means of particle swarm optimization. As usual, by simulation they found the probability distribution of each component and they assessed the whole system. For the optimization problem, their objective function was to minimize the system interruption cost and component investment cost. Finally with the particle swarm technique they solved the optimization problem [4].

In another study on the Monte Carlo simulation application in the area of reliability engineering M. Moazzami et al. applied a sequential Monte Carlo simulation to evaluate the reliability of different power plants. In this study, they developed a new technique based on the simulation to estimate the reliability indices of a power plant under the effect of generator breaker and bus- section. Then, they applied this method to evaluate the reliability of the Karoon III power plant as a real life case study. The reliability indices that they tried to estimate were loss of load expectation, expected energy not supplied, and expected load curtailment [21].

There are few studies that have been done on reliability based optimization and redundancy allocation. In these studies, the main goal was to optimize the system's reliability by the appropriate allocating of redundancies for different components based on minimum cost and weight, which would be added to the system. Because the purpose of this study is to research reliability assessment and the optimization of the system, I will refer to few works that studied optimization problems to find the optimal solution for the reliable system.

L. Zia and D.W. Coit published a paper, which offers a heuristic solution for optimal redundancy allocation of a series-parallel system. Based on the general objective function in these kinds of systems, which are non-linear, by increasing the number of components, solving the problem will be very time consuming, and in some cases impossible. They offer a new methodology to approximate the optimum level of redundancy. The optimization problem for a series-parallel system is a non-linear integer-programing problem, which has been tried to be solved by different methods such as mathematical and meta-heuristic algorithms in previous studies. In their study, they offer a new method to solve the problem with a column generating approach, which converts the problem into a linear master problem and some non-linear sub problems and by iterating the solution for sub problems they find the optimal solution for the master problem. As any other study in this area, the restrictions for the optimization problem are added cost and weight to the system. Therefore, the offered answer by this approach gives the maximum level of reliability by considering the minimum value of cost and weight [37].

Another study on reliability-based optimization was done by A. Billionnet. The goal of this study was to find the number of machines and their types in each subsystem, which leads to maximum level of reliability by minimum cost and weight. The objective function in this study was a non-linear problem. As well he tried to solve the problem with the integer programing method. The final solution was an approximate to optimal solution, which gives an upper bound for the optimal solution and the answer was close to the optimal solution. For this reason, he prepared a mathematical model, which could be used in integer programing software to solve it. The results showed great precision compared to previous studies [5].

There are other techniques to allocate the redundancy for achieving the optimal level of reliability such as neural networks and genetic algorithm, and tabu search. In these methods unlike the previous approaches such as the column generation and integer linear programing, the final solution is an approximation to the optimal answer. Tabu search and genetic algorithm are meta-heuristic approaches, which can estimate the optimal level of the reliability for the system. Following studies show the application of these methods for redundancy allocation in series-parallel systems to find the optimal value of reliability for the system.

D.w. Coit and A.E. Smith suggested a technique for redundancy allocation for series-parallel systems by using a combination of neural network and genetic algorithm. In their methodology, the role of genetic algorithm is to find the components with minimum costs, which would add an appropriate value to the system's reliability, and the neural network would be used to find the optimal answer among the suggested allocations by genetic algorithm. As it is clear, this technique is not the exact solution for the optimization problem of redundancy allocation, therefore, the final solution is the estimation for the exact solution with an appropriate confidence interval [6].

Tabu search is another technique, which can be used to find the optimal level of redundancy for series-parallel systems. S. Kulturel-Konak et al. applied this technique for reliability allocation of a series-parallel system. Tabu search is a meta-heuristic approach for finding the optimal solution for the system. The advantage of this method over other mathematical techniques such as integer programing is that it can be used for more complex systems, and has better efficiency than the genetic algorithm for redundancy allocation. They compared the results of the tabu search to other methods at the end of the paper, which shows it has a very good level of precision and efficiency [10].

J. Lin and L. Chang considered the reliability evaluation of production lines, and they modeled the system by stochastic-flow network. In their study they called it the manufacturing network. First, they conformed the manufacturing system to a stochastic network and then based on the system network; they tried to decompose the system into some network paths in which they could pass the minimum demand of customers (there should be a certain amount of output). These paths are minimal, and they connect the source to the sink without any cycles, as well they pass the adequate capacity. For transforming from the production line to the manufacturing network, they used an Activity on Arcs (AOA) network diagram. In this diagram each arrow represented a machine and each node represented an inspection unit. There are some assumptions in this study such as: inspection stations are perfectly reliable, the capacity of each machine is a random variable based on the defined distribution, capacity of machines are independent, and each defective products will be rework at most once. So based on the product that can be perfect or defective there will be 2 scenarios for each production line in which in the second one needs rework. As a case of study they have done the calculations of this technique on a tile production line, which has two production lines. It should be mentioned that in this study the criteria for the reliability analysis is not the failure rate or down time of the machinery; the criteria for reliability evaluation is the probability of having non-defective products and meeting the customer's demands [15].

J. Lin et al. have another study as well on the reliability for a system, which has a waste reduction parallel line. They used the same network modeling and graphical based modeling as their previous paper and they came to the same assumptions. The only difference is that they considered the reworking actions and they tried to find the probability of meeting the demand probability based on this assessment. They considered a foot wear factory as case study [16].

H. Gea and S. Asgarpoor developed a methodology for reliability assessment with the sequential Monte Carlo simulation technique for different systems and equipment. In this study, they tried to compare the reliability evaluation of systems by using analytical methods such as the Markov process (which is normally useful for systems with limited states) and the simulation technique. In addition, they presented a parallel computing methodology by different computers and prepared the simulation to be processed by parallel processors, which led to less processing and calculation time rather than normal simulation. By simulating different cases they showed that the simulation method has wider application rather than analytical approaches [7].

A. Azaron et al. developed a new technique to evaluate the reliability index of time dependent systems, which work by standby components. They have used the shortest path algorithm to find the reliability level of the system, because the shortest path density function in the directed stochastic network or E-Network shows the minimal cuts in the system, represents the failure function of the system very well. In this approach they constructed the E-Network and after finding the minimal cuts, they found the shortest path distribution function, which is equivalent to the failure function of the system with standby redundancy. There are some assumptions for this study which are: first some elements of the system will not work from the beginning, so based on this we have standby redundancy that in case of failure the system will switch to the next path and standby components will start to work. This study shows that a system with redundancy is more reliable rather than the same system without it, so adding some standby components leads us to have a better reliability conditions [2].

In another paper A. Azaron et al. worked on the reliability function of non-repairable, multi-component systems with standby redundancy. In these systems, the system was made by different units in which each unit has different components and components are independent with generalized Erlang distribution. The unit's configuration can be in any general arrangement. This study represents a new technique to assess the reliability of an l-dissimilar-unit non-repairable cold-standby redundant system. As in the previous approach, they used E-Network, which is a directed stochastic network of the system and it is constructed from minimal cuts of the reliability graph of the system. In this study as well as the previous one the lifetime of each component of the system is a random variable and the length of each arc in the E-Network represents a component on minimal cut, and its lifetime follows generalized Erlang distribution with a constant failure rate. Also, in this paper the results of reliability evaluation for a multi-component system without redundancy have been shown and this evaluation was calculated by continuous Markov chain. As a result, it can be can seen that the reliability level of a system with redundancy is higher than a system without standby components [1].

There is one other article written by A. Azaron et al. in which they tried to solve a multi-objective optimization problem by using the genetic algorithm. In this optimization problem, which is presented for k dissimilar-unit multi-component non-repairable cold-standby redundant system, the objectives are to maximize the system's reliability, minimize the variance of the system's lifetime, maximize mean time to failures, and minimize the cost; it has been supposed that the cost will increase with lifetime increasing. In this study, first, to find the system's reliability they used their previous approach for reliability evaluation of non-repairable, multi-component systems with standby redundancy, which uses the E-Network and shortest path algorithm for systems with standby redundancy. In the next step they developed a multi-objective discrete model to choose the most suitable components to replace by a standby component. To solve this multi-objective model where it is almost impossible to use available techniques, they developed a "genetic algorithm with double strings, using continuous relaxation based on reference solution updating" [3].

J. Lin et al. worked on reliability evaluation of a touch panel manufacturing system. In this study they developed a technique to assess the reliability of this production system with failure rates for each work station in which reworking on the products is allowed. They defined the reliability of the system to pass the costumer's demand. This means that if the system can produce enough products that costumers need, the system would be a reliable system. For this consideration they constructed a capacitated manufacturing network, which is an Activity on Arcs (AOA) network [17].

There are few initial assumptions in this study, seen as follows: inspection stations will not destroy the products, workstations can have different capacity values that their probability is different, workstations will not affect the capacity of another workstations, and non-repairable product will be scrapped. On the other hand, to construct the network for the manufacturing lines, they assumed: each node is totally reliable, the capacity of arrows is a random variable which for each capacity they have different probabilities, the capacity of workstations are independent, and each defective product will be reworked at most one time.

After constructing the network and finding the minimal capacity vectors for the system, for a constant input flow of raw materials, they considered different scenarios, to find the different outputs of the system with their probabilities. Finally, the minimum value passes the demand and its probability defines the system's reliability.

In another study, P. Pourkarim Guilani et al. developed a new method to assess the reliability of a three-state non-repairable system, of which the approach was based on Markov process. In this study first they described two methods of reliability evaluation, which are universal generation function and recursive method. They normally would have used it to evaluate the system's reliability. In this paper, in addition to presenting a new method they also compared their method with previous methods to prove that it needs less time of computation to solve the equations and to find the system's reliability. The states that they defined for the systems are actually the performance conditions of the components that can work with full performance, work with 50 percent performance, and not work or fail. Then there should be transition rates for going from each state to another, and after, they can generate the Markov process easily. Actually in this study they offered an easier method to obtain the equations by Markov process and to solve them. In their proposed model they followed steps to find the reliability. In step 1 they determined the number of components, next they obtained the state space, and then, they obtained a matrix model based on the state space. In the fourth step they obtained differential equations of all states and in the final step they solved the equations and evaluated the reliability of the system [8].

In terms of the Markov process application in reliability engineering, A. Lisnianski et al. developed a multi-state Markov model to analyze the reliability of a power generating (coal power generating unit) unit in short term. As it was indicated this modeling technique is for short-term reliability analysis, which normally is different from long term reliability analysis. This analysis can help in short term the security analysis and operating decisions. In this study, they presented a method to obtain the transition rates between different power generating levels, which define the states in Markov process. The estimation of transition rates is based on the data that has been achieved from the field observation in the power plant and it is applicable to other generating systems where their output generating capacity is uniformly distributed. In their paper, they offered a method to construct the states for the power-generating unit. Because power generating is a continuous time stochastic process and a continuous state process, it is very difficult to model in a continuous way. The best approach to model such a system is to use discrete state continuous time process. After constructing the process for the system they presented a methodology to find the transition matrix based on the observation and statistical records. Finally, they considered a case study to show the way of assessing the reliability of a power generating system based on the introduced method [18].

G. Yingkui et al. prepared a systematic review for reliability analysis of multi-state systems. They introduced different approaches towards assessing the reliability of multi-state systems such as: extension of binary models to multi-state cases, stochastic process approach, the universal generating function, Monte-Carlo simulation, and recursive algorithm. Then they introduced the works that have been done on reliability-based optimization for multi-state systems. Finally, they reviewed the previous studies about the maintenance of multi-state systems [34].

On the reliability analysis of manufacturing systems and production lines, G. Liberopoulos and P. Tsarouhas studied the reliability of a pizza production line. They used the statistical data for the production line, which they have collected for four years and a month from an actual automated pizza production line. The statistical data shows the failure report of different machinery along the production line. Then they fitted the best probability distribution function to their data to find the failure distribution function of the system. In this case they tried to fit a distribution for mean time to failure (MTTF), mean time to repair (MTTR), and the time of lost production (TLP). They have used a least-squares fit for each candidate distribution, estimated its parameters and performed a goodness-of-fit test using the software package SPSS. This work is very helpful for other studies on the reliability analysis of production lines. As it was mentioned earlier, they have used real statistical data for all machinery in the production line, then after processing the data they tried to recognize the most sequential failure modes of the system. To identify the important modes they used some criteria, which are for example: smallest mean time to failure, largest coefficient of variation of time to failure, and etc. Afterwards they found the failure distribution of the system, and they could find the system's reliability based on the achieved distribution easily [13].

Few researchers such as H. Touama and M. Basha have studies on the reliability of different machinery in the production line of the textile industry. In one study, they considered the reliability for each component individually so they did not consider the reliability of the system entirely. Their purpose was to find the components that have the least reliability in the system, so they could make a decision about these components easily. First, they suggested the exponential distribution for lifetime of components and then they proved that this estimation is fair enough for their study. Then they suggested a theoretical method to estimate the parameter for exponential distribution for each machine. After the theoretical part, they implemented the presented techniques to analyze the reliability of the components based on the statistical information that they achieved for six month for 50 percent of the machinery, which include Winder 10 machines, Sewing 8 machines and Twisting 6 machines. They chose these components because they were used in the same period of time, and they could reach a valid conclusion about them. For estimating the parameter of exponential distribution they used the goodness of fit technique, and the result shows that the exponential distribution is a good fit for the lifetime distribution of machinery. Finally, they calculated the reliability of each machine and made a comparison between them based on their reliability status. In addition, by the means of one way ANOVA, they compared the reliability of each machine and the final result shows: "There is no statistically a significance differences between the estimative values of the reliability functions R (t) of the machines of textile section which are to be studied " [28].

Another study on reliability analysis of manufacturing systems is the reliability analysis of a cheese factory production line, which was done by P. Tsarouhas et al. In this study their concern was the reliability, availability and maintainability of the system. For this purpose, they collected the statistical data of machinery failures in the production line for a period of 17 months. After analyzing the statistical data, they found the failure rate of the machinery and then by assuming that the distribution function of the system is log normal they found the reliability function of the system. During this period of time they calculated the reliability reduction and their explanation for this loss was that it was because of the lack of spare units, inadequate skillful staff for maintenance operation, and shortage in good management system. So they offered to overcome these drawbacks to improve the reliability and availability conditions of the system [30].

In another study toward reliability analysis of production lines, P. Tsarouhas et al. studied a strudel production line. In this study they used a factory as a case study and they tried to evaluate the reliability of the production line of the factory. So, regarding their purpose, they collected the statistical data of the failure information of the factory for a period of 16 months. Then they used the goodness of fit technique to find the best fit for the distribution function of the failure rate of the machinery and production line, and the results show that the best fit for the failure distribution of the machinery is Weibull distribution. Then they found the parameters of this distribution for different machines to be able to assess the reliability of the machinery and the line. They conducted this study to be able to evaluate the system's reliability, and to predict the reliability in case of any change or improvement in the maintenance policy. In this factory they had a system with a serial alignment in which all machinery was implemented in series in the system. The reliability of the system is multiplication of all component's reliabilities [29].

Y. Liu et al. applied the Markov approach for reliability analysis to assess reliability of laser diodes under space radiation conditions. They defined some states for diodes until complete fail. Their assumption is based on the Markov chain where failures occur based on Poisson process and the mean time between failures follows exponential distribution. By defining the states, they found the transition rates among different states and by using the simulation they evaluated the reliability of the diodes to find the CDF, PDF, and hazard function. Their simulation for reliability is for a time period of 100000 hours [19].

In the field of distributed computing systems, J. L. Wang developed a new model for reliability analysis of distributed networks. They evaluated the reliability of these kinds of systems by using the state space approach, which uses the Markov chain method. In this study, the discrete time Markov chain with finite states was used, and they studied the system repair with finite time for the reliability analysis to analyze the effects of repair on systems reliability. For this study they had a set of assumptions of which few are: each component is considered to have just two states or up and down, failures of components are statistically independent and failure of each link does not have any effects on another components, repair rates of each components are independent as well and they are exponentially distributed, at time zero all components are working properly, and at any time unit there is only one component that can fail or repair. For other parts of the system, which they did not research in this study, they assumed they were perfectly reliable [32].

Regarding the manufacturing systems which are built with a set of machinery that work in parallel or serial lines, J. Lin and Y. Chang studied the performance of these systems based on the reliability indicator as an important criteria to evaluate the performance.

In their article a manufacturing system with parallel line of machinery was their main concern. Because the capacity of each component in production lines is stochastic they used the stochastic flow network model for modeling their manufacturing system. After preparing this stochastic flow network, the next step was finding the general manufacturing or reworking paths. This means they decomposed the network into general paths that can pass the minimum capacity of the system. These paths are minimal paths that connect the source to the sink without any cycles, and pass the adequate capacity. For transforming from the production line to the manufacturing network, they used an Activity on Arcs (AOA) network diagram [15].

Reliability in this system defines the probability of producing enough products in system lines in a way that meets the demand of the market. Each component has different states based on its stochastic property that can produce the products at different levels, which is considered its state. After preparing the network and general paths, the authors evaluated the system's reliability based on some assumptions such as: each node is perfectly reliable, each machine's capacity is a random variable based on the defined distribution, capacity of machines are independent, and each defective products will be rework at most once. In the parallel lines of concern in the manufacturing system are the same. This means they had the same components and the distribution of the same components was the same. Then they evaluated the probability that the line or the system could produce the specified amount of product for a specified period of time. To prove their methodology they used a case study, which is an IC card manufacturing system. "The IC card manufacturing is a high-volume production of only a certain type of product".

In another study, M. Kumral studied the reliability based optimization of mine production system. In these kinds of systems usually there are 5 kinds of subsystems (drilling, blasting, loading, hauling, and ventilation), in which the purpose of the study is to optimize the reliability of the system in order to increase the system's reliability based on some monetary and technical constraints. It is obvious that the improvement of the system's reliability depends on the reliability progress among subsystems. There are some assumptions towards achieving the goals of this study and they are as follows: subsystems are statistically independent; they have only two states of up and down; among the reliability evaluation, the failure of subsystems are considered; and finally as it is expected the overall cost of the system is the collective cost of all subsystems. In this study reliability comes through the optimization model. The optimization model is a single objective problem which they have used the genetic algorithm to solve the optimization problem [11].

S. Verlinden et al. presented a hybrid model for reliability analysis for safety of nuclear reactor systems. The hybrid model that they studied includes a reliability block diagrams at systems levels, and for describing the system dynamics (to describe the dynamics of the 2-out-of-3 redundant neutron flux measurement chains), continuous time Markov chain has been used. They combined the static modeling techniques such as reliability block diagrams with dynamic ones such as the Markov chain. Because static techniques are not capable of analyzing the redundancy, repair, or test activities. On the other hand, dynamic models are more powerful tools while addressing problems, but they lead to very large and difficult models. Also, in dynamic modeling techniques such as the Markov chain, the assumption of exponentially distribution for time to failures of the components is not a real representation for actual systems in real world problems. To overcome these shortcomings, in this study, they offered a hybrid model to evaluate the system's reliability. The case study for this model was the Belgian Reactor 2 (BR2), which is a high flux research reactor that is used for preparing nuclear materials for medical and industrial applications. After modeling the system by dynamic techniques, the number of states of the system is very high ($4*1012$). To simplify the model to be able to evaluate it, they made some assumptions, which keep the accuracy and reality of the model fairly high. First, they considered the failures that led to the emergency shutdown of the nuclear reactor, and they assumed that the shutdown state is an absorbing state. In addition , they had limited the testability and reparability to some special states [31].

In the area of wind turbines in which each turbine is combined of different components and should work for a long time without failure, reliability has great importance. They are normally designed to work for a period of 20 to 30 years of lifetime. W. Zhang et al. studied the reliability of new design of modular converters in wind turbines. One of the essential parts of the wind turbine is the power convertor, which converts the current or electricity from one type to another. Because the number of failures that occurred in this part of the turbine was higher than other parts, the authors became interested in analyzimg the reliability of the new design of the convertor, which was invented by Hojrat. They used six models of the new type of converter to analyze the reliability with respect to cost and space occupation. The Markov process was used as a modeling approach to model these six types of converters. There are some assumptions to apply this methodology on converters, seen as follows: all modules are independent and identical, they have constant failure rates, all modules are working with a same work load, modules can be replaced from one side to another side when it is needed, failure mode is while the on each side they have less than 5 modules which are operating, and since on each side there are enough operating modules, replacing is not allowed. Based on these assumptions they constructed the Markov model for the system and then evaluated the reliability of the system based on the numerical examples, which come from the field data of wind farms. The results show that if they added more modules for each side of the converter they would achieve a greater reliability level [36].

In multi-component systems, redundant components are a way to improve the reliability levels of a system. But the problem is that it should be taken into the consideration in multi-component systems with redundancy being the dependency of failure occurrence that happens for different components. J. Yua et al. considered this type of problem for multi-component systems. They evaluated redundant dependency among these types of systems and finally they found a function, which shows the reliability based on this dependency. There are two types of dependency considerations, which are deterministic and probabilistic categories; in this article they studied the probabilistic class which represent the statistical extents of dependences. In the system that was studied there are some (let say n) identical components where their failure occurrence distribution follows the exponential distribution. This case is not K out of N problem, and the system will fail when all components fail. Based on the assumptions for this problem (exponential distribution for mean time to failures), they can be modeled by the Markov process and by means of Markov modeling they will be able to evaluate the reliability function of the system with different levels of dependence redundancy [35].

In terms of cost considerations among reliability analysis, Y. Niu et al. developed an algorithm to take the cost into consideration while assessing the reliability of the system. The reliability index for multi-state systems that they have studied is two terminal reliability for level (d, c). This means that the reliability of this system is equal to the probability that d units of products can be transferred from the source node to the sink node in which the total cost for this process is less than or equal to c. The authors claimed that their method has two main advantages which are: first, this algorithm is unique while addressing the minimal path for cost and demand, and second, in comparison to previous methods and algorithms, the efficiency of this method to solve the similar problems is much higher and this method is more practical especially in terms of cost consideration. Regarding previous methods they had to find all minimal paths from source to the sink for reliability analysis, but in this study, the only minimal paths that are considered are the minimal paths with respect to the (d, c). They found these paths by implicit enumeration algorithm [23].

Naturally, for this algorithm the authors followed few assumptions. Few of the assumptions are as follows: the nodes are reliable, the capacity of each component (arrow) is a random variable, the states of each components are independent, and flows in the network follow the conservation law. To represent the network they used the activity on arrow method. After developing the algorithm they sowed its performance by a numerical example.

For evaluating the system's reliability, there are different methods, and one of these methods is the Markov chain process. By means of the Markov chain usage models and different methods for evaluating the reliability of systems can be presented as such: Bernoulli sampling models, Failure state models, and Arc-based Bayesian model. In Bernoulli sampling models the evaluation of reliability is based on the number of failures and successes, and there in no difference between long time tests and short time tests. In the Failure state models, the reliability assessment is based on the Markov chain, which is prepared from test information. By using Markov probabilities the reliability can be computed. And in the last method "A Bayesian model has been applied to individual arcs in the Markov chain to produce an arc-based Bayesian model". S.J Prowell and J.H Poore worked on the last approach, which is the Arc-based Bayesian model and they presented an analytical computation method for evaluating the systems reliability, which is faster and more accurate than other techniques [25].

In the area of power systems, especially for wind energy,J. Lin et al. studied the reliability of wind power systems. They considered different approaches and methods for reliability analysis of power systems in the planning and operation phase where their results showed there is a great difference among reliability assessment methods in different phases. In terms of reliability analysis in the planning stage they considered some methodologies such as: multi-stage capacity outage probability model, multi-state Markov model, and simulation models. These techniques offer different models to evaluate the reliability of the system. On the other hand, during the planning stage they investigated few algorithms for reliability assessment. Some of these algorithms are analytical algorithms and simulation algorithms. After analyzing the reliability evaluation techniques in the early stages of the wind power systems they considered some applications of reliability in this phase for the system. This shows a good level of reliability in early phases of the power system is helpful in many cases for example a reliable systems helps more regarding to expansion of power generating, transmission expansion, and maintenance. Finally, they investigated extra models of reliability assessment for the operation phase of the system such as Gaussian distribution model and ARMA model [14].

There are a few articles and research that combine the heat and power systems with respect to reliability analysis. Normally, for reliability evaluation these two systems are assessed separately. M. Haghifam and M. Manbachi conducted a study on reliability of combined systems, which include power and heating systems. They developed a model which addresses the indices of reliability, availability, and maintainability for such systems. which considers the interactions of subsystems among the entire system. Because the nature of failure occurrence in the system is stochastic they used some probabilistic techniques. By dividing the system work plan into different states they were able to use the continuous Markov chain to model the states of the system. Naturally, there were few assumptions for this study to be able to use the Markov process as a tool to evaluate the system reliability, such as exponential distributions for times between failures and Poisson process for failure happenings. A case study was conducted to show the results of this model numerically. The authors evaluated their model on a natural gas engine with two exhausts and an engine heat exchanger. They also considered the effect of different subsystem's reliability improvement on the whole system's reliability[9].

G.R Weckman et al. studied the reliability evaluation of repairable systems such as machinery in the aviation industry as jet engines. Reliability in jet engines is a crucial issue and these components should have a very high level of reliability. Most of the crashes in airplanes happen because of problems in the engine part. They work at a high temperature, and have a very high rotating speed. They should be kept in an appropriate level of reliability by conducting some repairs and maintenance operations. Their study is on modeling a novel approach to model the jet engine lifetime based on probabilistic processes such as Weibull and non-homogenous Poisson process; because the non-homogenous Poisson process is very suitable for modeling the effect of different conditions during the lifetime of the engine and Weibull distributions are so helpful to model the repairable system. In order to estimate the parameters of the distributions, the authors used the statistical data from two airlines for 25 different engines which were collected over 15 years. After finding the model parameters they used the simulation technique to find the nature of failures and suggest new repairing plans. The results show that the Weibull distribution provides a very compatible model for repairable systems [33].

Performance considerations and working status of hospital mechanical and electrical machinery is a very consequential issue. If a crucial failure happens for a hospital and the time for getting back to normal is not adequate, a disaster will occur. Hospital equipment should always be reliable or the mean time to failure of the systems should increase enough and the mean time to repair has to be small enough to prevent dangerous accidents. F. Salata et al. studied the reliability of hospital machinery, especially thermo-mechanical components. The goal of their study was to investigate the type of maintenance for unwanted and unplanned accidents. The reason was to minimize the mean time to repair of the components when they are faced with failure. So the main purpose of this article was to compute the mean time to repair and mean time to diagnosis of the entire system when all the parameters of the components are known. The assumptions for this study are: the authors assume that the failure distribution of the components follows the exponential distribution, they have taken some issues into the consideration such as diagnostic time, mean down time, and time service reactivation. For their model application they used a hospital as a case study [27].

J. Lu and X. Wu published an article, on the reliability evaluation of generalized phased-mission systems. Their study was on repairable conditions for such systems, because previous research on generalized phased-mission systems only considered unrepairable systems. The approach for developing a model to assess the repairable conditions for these systems is to use the continuous time Markov chain in which the system's behavior can be a combination of different components and sub-systems. They will have a set of states, which show the operations of the system and by the failure of some of the states the system will fail. Other states that do not have any contribution to the systems failure will be considered redundant states, which can be excluded from the calculation, and this helps easier modeling and ensures less computational time. As a prerequisite for applying the continuous Markov chain to a system, the failure occurrence of the components and time to failure for each component should follow failure distributions or one should assume that the failure occurrence of the components follows the Poisson distribution and the time between failures follows the exponential distribution. As evidence for their model the authors solved a case with their presented model to show that the results are appropriate for repairable PMS (phased-mission system). This model has some useful features such as, when the number of sub-systems or components in the system increases, the model will not increase, and another important issue is that this method can be used for "systems with complex combinatorial phase requirements". There are few limitations for this method because of primary assumptions to reach the model. For example following some especial distributions such as Poisson and Exponential by components, and another assumption that components need to stay after being repaired until next phase to be used [20].

There are some systems that are combined of sets of parallel components. These parallel components are usually identical for each set and if one assumes that the number of the parallel components is n in the set, to have success in the system, k of them should function properly. These systems are usually called K out of n systems. There are few studies on the reliability evaluation of k out of n systems. As it is clear the reliability analysis of such systems usually is more difficult than normal systems without redundancy. The reason for this difficulty can be due to the increasing the number of states, complicated state of system's probability distribution firstly to find and secondly to solve.

W. Li and J. Zuo considered the reliability evaluation of k out of n systems. In their study they discussed different methods of evaluating the reliability assessment methods for k out of n systems. First, they compared two methods for reliability analysis of such systems, which are weighted in a binary way. Then, they developed models of reliability evaluation for multi-state k out of n systems. By means of two strong approaches such as recursive algorithm and universal generating function, they were able to provide their model for these systems. Binary systems they studied for the first part of their article are systems that have only two states of success and failure. For the binary systems they compared the results of recursive and universal generating functions together. For this purpose they modeled the algorithms for each approach in MATLAB software. The results show the computational time for both methods for small number of components is almost the same, but while the number of components increases the computational time of universal generating function increases dramatically. The second part of the article is about the multi-state k out of n systems. In this system each component can have different levels of performance. So for each level of performance or state, the component can have different association with the system's performance. The main aim of this part was to find and compare the efficiency of recursive and universal generating algorithm for multi-state systems. After modeling the algorithms in MATLAB and running the program, the results were the same as the first part and this illustrates that if the number of components increase the computational time for universal generating function will increase much faster than the recursive method. The results that were achieved for both approaches have been tested on examples to show the speed of the computation and to make an appropriate comparison among them [12].

By studying the previous works on reliability evaluation methods for different systems and compare it with Barin Plast company, the reliability assessment procedure for this system is as follow. First, by achieving the primary data from the company, I will try to find out about the probability distribution functions of failures for each machinery in the system to decide about the evaluation technique. This job has been done by goodness of fitness tests. Studying the distribution functions shows that it would be very hard to evaluate system's reliability by analytical methods and the probability distribution function of failures for entire system cannot be found by this method. Therefore, I chose the simulation technique to model the system and get statistical data about the failure frequency of system which makes us able to learn about system's failure distribution function. After finding the initial reliability level of the system by simulation I need to improve this level by considering some cost limitations. Reliability improvement has been done by allocating different redundancies in the system. For finding the optimal value for different redundancy conditions, a heuristic technique has been offered in which redundancy allocation will be applied for the components that show more failure frequency in the system and by comparing it with the model which consider the redundancy allocation for all components, we make sure that our heuristic model works properly.

Chapter 3

Methodology

3.1 Introduction

As it was mentioned earlier, in the main introduction of this study, there are different approaches to the reliability analysis of a system such as analytical ones, and simulation. Their application somewhat differ in this area. When using the analytical approach, one looks for a solution to the reliability problem by analytical and mathematical methods, which leads to the exact solution of the problem. In the analytical approach we try to model the system into a mathematical model which is solvable by available analytical methods like state space method or applying Markov chains for analyzing the reliability and also some other techniques such as fault tree analysis and reliability graph models can be used to evaluate the system's reliability. However, there are limitations in applying this approach for different problems, because not all of the cases in the real world can be evaluated by analytical methods. In other words, the complexity of the system, correlations between components, having some components with different probability distribution functions, and so on prevent one to use the analytical method to solve the problem. For complex systems that are difficult to be assessed by analytical techniques, there is another approach to solve problems, which is the Monte Carlo simulation, as aforementioned. In following part, I will briefly introduce this methodology.

3.2 Monte Carlo Simulation

The Monte Carlo simulation is a strong tool for modeling the systems for reliability analysis. The Monte Carlo simulation is a simulation model based on the Monte Carlo methods and its application is in mathematical and physical models. The idea behind the Monte Carlo methods is to generate a random event by means of the computer model, which is prepared based on the predefined system's conditions. By iteration of the simulation many times and under specified conditions, one can achieve the requested system's behavior. Each iteration in simulation, which prepares some data based on the defined conditions, is a kind of real experiment that can be analyzed by statistical tools to understand the final results and also the confidence interval for the results. For example, consider a queue in a store by the cash register. In this case, simulation enables us to estimate the mean waiting time by modeling the system regarding to inter-arrival times of customers, probability distribution function of service time for each cashier, number of parallel stations which serve the customers, and the capacity of waiting line in front of each cashier. By using the simulation and generating random events, which can be the probability of waiting, one can achieve the mean time of waiting in the line by a confidence interval and deviation from the mean.

By using the Monte Carlo simulation it is possible to consider a different phenomenon (such as reliability of complex systems, systems with redundancies and standby component, k out of n success criteria, maintenance and repair consideration, and etc.) in the system, which is difficult or impossible to evaluate with the analytical approach. There are four basic steps in the Monte Carlo simulation procedure: "(1) Define a domain of possible events, (2) Generate events randomly, (3) Perform deterministic judgments of system states based on the events, (4) Count the occurrence number of a specific system state among total observations."

There are some advantages and disadvantages in using the Monte Carlo simulation and analytical approach. For instance, the analytical approach is the exact solution, however, simulation is more flexible and has less limitation for different distributions and complexity. The analytical models are not flexible and they are used only for a limited number of models.

In reliability evaluation by simulation, one should know the probability distribution of failure or perhaps the repair of each component. There are few methods such as goodness of fit that can help find distribution functions by statistical tests. In the next section I will explain this method briefly. Afterwards by means of computer programing or available software, which can perform simulations such as ARENA, one can prepare a model based on the system. An appropriate model should have almost all the predefined conditions such as correlations, sequences, and other different working conditions. Finally, by running the simulation for the prepared model many times, one can learn the nature of the system, and by the achieved results, one can judge how the system works by a level of confidence.

3.3 Goodness of fit

In real world problems, most of the time, one comes across field data and observations, and it is generally very difficult to decide on the nature of the data and what distribution it follows. However it is crucial for one to know the statistics to be able to apply them in different mathematical modeling. There should be a method that can help understand this information. Goodness of fit test is a powerful tool, which one can use for this reason.

Goodness of fit is a method to compare a set of predicted values with real observations. It describes how well they are fit to one another, and explains the variance between the real data and expected values. For example, if one expects that a set of data would follow the normal distribution, for testing this hypothesis, by using the goodness of fit tests, he can see how much the data is fit to normal distribution, and he can decide whether the expectation about the distribution is correct and accurate by comparing p-values, which was found by goodness of fit tests. There are some tests that helps fit data to different distributions such as the Chi Squared test, Kolmogorov-Smirnov test, Anderson-Darling test, Shapiro-Wilk test, and etc. Naturally, if the sample size of the observations is large enough, the fitted distributions are more accurate rather than when the sample size is small. In this study, I applied goodness of fit to understand the failure distributions of the system's components. Based on the field statistical data that I have, archived over a period of time from observations and samples, I can decide what distribution is the best fit for different components.

3.4 Methodology

As it was mentioned previously, in this study, I will evaluate and improve the reliability condition of an edge banding company, which uses different machinery, and has almost a complex alignment. The nature of failure occurrence in different components is difficult to consider by analytical methods, so I chose the simulation approach to assess the system. Before preparing the model for simulation, there is initial information about the failure history of the machinery in the company for a period of time, which is a key function in understanding the probability distribution to implement in the simulation. To accomplish this study there are three steps that need be conducted, as well to evaluate and improve the reliability of the system concerned.

In the first step, one should learn about the nature of failure occurrence for each component and as it was explained before, a very strong method to understand the probability distribution function of machinery is using the goodness of fit test, so for each machinery and based on the field data, I use the goodness of fit test to find the probability distribution function for them. The second step of study is to make a model, which follows the reasonable logic of the system and enables me to evaluate the reliability of the system. For this purpose, I prepared the model by Arena simulation software, which is a very strong tool in many areas of simulation. In this step, all the logic behind the system was implemented, and an appropriate model was provided, then by running the simulated model and getting the results I can easily judge the reliability condition of the system. In the final step, I need to improve the reliability level of the system. Generally there are some ways that can be used to improve the system's reliability such as, adding redundancies (using standby components), improving the components, and also some other ways such as changing the maintenance policy. But not all the remedies are the optimal solutions for the system, because, naturally, improving the reliability will add a cost for the system and in some cases perhaps the weight and the occupied space is important as well.

Improving the reliability can be an optimization problem to look for the maximum reliability, but based on the cost and perhaps weight constraints. In other words, what is sought here is a level of reliability for the system based on the budget. For this purpose, in the last step, optimal reliability level is important to find, by adding some redundancies or adding a standby component, and then it can be decided which one will be affordable for the company.

Chapter 4

Reliability Evaluation

4.1 Construction of the field statistical data

In this part, I prepare the initial requirement for the simulation model, which is to constructing the probability distribution functions for each component. This is not possible without having enough statistical data from failure occurrence and working conditions. So I needed detailed reports of the company for a period of time, which can show when failure occurred for each machine. With this data, I can then decide on the failure frequency and the time interval between failures. Also, enough information about the repair procedure is needed, in order to evaluate the reliability under repairable conditions. The company prepared the suitable sets of data for this reason, and a summary was given in Table 4.1. The failure statistics tables that the company provided include enough information to understand the time between failures, failure frequency, different times with respect to repair conditions and some other applicable data, which was prepared during a period of 5 years. As Table 4.1 illustrates, some of the components have much failure frequency for this period of time, which leads to less reliability, and others show a better contribution to the system's reliability condition. But to judge appropriately, and reasonably, one needs to simulate the system, and check the component's contributions in the system's reliability. In the next section of this study, I will use this statistical data and goodness of fit test to find the probability distribution functions of each machine, which is crucial in simulation.

As it is stated in Table 4.2, I am going to use shorter names for different machinery which make it easier for preparing the tables or another data sets. Therefore, for the rest of this report I am going to use the shorter names which are presented in the above table.

TABLE 4.1: Machinery statistics

No	Description	Failure	Shut down(hrs)	Start up(hrs)	Logistic	MTBF
1	Mixing	7	0	0	0.5	258
2	Extrusion 1	51	0.3	0.5	0.2	35
3	Calendering 1	9	0	0	0.3	202
4	Primering 1	10	0.5	0.2	0.5	180
5	Rolling 1	0	0.2	0.2	0.5	-
6	Extrusion 2	50	0.3	0.5	0.2	36
7	Calendering 2	9	0	0	0.3	203
8	Primering 2	10	0.5	0.2	0.5	182
9	Rolling 2	0	0	0	0	-
10	Printing	11	0.3	0.3	6	166
11	Slitting	20	0.3	0.3	0.5	91
12	Pulverizing	12	0.5	0	0.5	152
13	Packaging	24	0	0.5	0.5	76
14	Grinding	19	0	0	1	96
15	Utility	6	0	0	0.5	304

TABLE 4.2: Machinery Abbreviations

No	Machinery	Abbreviation
1	Utility Unit	Ut
2	Mixing Unit	Mx
3	Printing Unit	Prt
4	Slitting Unit	Slt
5	Packaging Unit	Pac
6	Extrusion Unit1	Ext1
7	Premiering Unit 1	Pre1
8	Calendaring Unit 1	Cal1
9	Extrusion Unit2	Ext2
10	Premiering Unit 2	Pre2
11	Calendaring Unit 2	Cal2

4.2 Goodness of fit results

After I achieved the statistical data for different machinery of the company, I need to find their probability distribution functions individually. One can have two types of distribution functions with this data, which is helpful for simulation. First, one can find the failure probability distribution function that shows the chance of failure for each machine, and one can find the reliability of each machine directly by this distribution. Another distribution fitting is to fit a distribution for the time between failures. If one finds this distribution one can easily find the mean time to failure of each component and also by simulation one can find the mean time to failure for the system. On the other hand, by applying the simulation by using the distributions that are fitted to time between failures, for a number of iterations, one can find the chance of the failure of the system for a specified period of time or in other words, one can judge the reliability of the system. With this explanation, for this study, I am willing to use the fitted distribution to the time between failures, but first I need to fit a suitable distribution to the data.

I need strong software to be able to fit different distributions to the data which will help find the best fit for the data. Hence, EASY FIT software, which is a powerful distribution fitter, will be used. Working with this software is not difficult; all is needed is to enter the prepared data of time between intervals, and then to choose the suitable tests and distributions. Finally, by running the software, one can get the best-fitted distributions for the data. The tests that are used to find the best fit for the data are Kolmogorov Smirnov, Anderson Darling, and Chi Squared tests. The software will provide a ranking for different distributions, which are the best fit for the data based on the p value calculated for it. The priority for choosing a distribution for each component is to have the highest ranks in almost all of the tests. Tables 4.3 and 4.4 show the results of the fitted distribution for the data for different machinery. Table 4.3 shows the first priority for distribution and Table 4.4 shows the second one. These tables depict P values, distributions, and parameters for each machine. For example, for the Extrusion machine, the best-fitted distribution is the Weibull distribution where its parameters are a= 2.5566, and b= 38.668, and the second priority is the Burr distribution with given parameters in Table 4.4.

There is more flexibility in the simulation approach in using different probability distribution functions and a more complex system rather than analytical methods. For this simulation model one can use the best fitted distributions, which are presented in Table 4.3, without any limitation.

As an example, for the mixing unit, by using the Easy Fit software one achieves the following results for the fitted distributions, which in the Table 4.5, one has the results of Kolmogorov-Smrinov, and Anderson-Darling tests with their values and the ranking for each distribution, which is fitted for the data. In the next Table 4.6 the parameters for each distribution is provided, and in the last table the results of hypothesis tests for each test are given for different significant levels; here one can see the results for the Weibull distribution for the mixing unit which is not rejected for each significance level based on different tests. The ranking of each distribution is based on the calculated P value, which shows the strength of the hypothesis that the data follows the desired distribution. As discussed before, the desired distribution is one that has the highest rankings for different tests and is not rejected for different level of significance. In Figure 4.1 one can see the histogram of the data and the fitted distribution diagram on the mixing unit data that shows a good fit for it.

TABLE 4.3: First ranked fitted distributions

no	Component	Distribution 1	parameters	P value
1	Mx	exponential	l=0.00388	0.74
2	Ext1	weibull	a=2.5566 b=38.668	0.681
3	Cal1	weibull	a=1.9162 b=208.25	0.85
4	Pre1	weibull	a=10.461 b=186.08	0.48
5	Rol1	-	-	-
6	Ext2	weibull	a=2.7234 b=39.115	0.85
7	Cal2	weibull	a=3.0929 b=293.51	0.86
8	Pre2	erlang	m=105 b=1.7176	0.55
9	Rol2	-	-	-
10	Prt	weibull	a=1.5669 b=162.22	0.86
11	Slt	erlang	m=66 b=1.3638	0.39
12	Pul	erlang	m=17 b=8.5946	0.72
13	Pac	weibull	a=3.9436 b=81.757	0.91
14	Gr	weibull	a=4.0717 b=99.564	0.68
15	Ut	erlang	m=15 b=18.039	0.63

TABLE 4.4: Second ranked fitted distributions

no	Component	Distribution 2	Parameters	P value
1	Mx	weibull	a=1.1661 b=242.66	0.61
2	Ext1	burr	k=1.3256 a=3.4706 b=36.031	0.512
3	Cal1	erlang	m=3 b=55.887	0.64
4	Pre1	erlang	m=124 b=1.442	0.27
5	Rol1	-	-	-
6	Ext2	burr	k=1.2958 a=3.7687 b=36.327	0.69
7	Cal2	erlang	m=8 b=33.615	0.81
8	Pre2	weibull	a=12.396 b=183.58	0.38
9	Rol2	-	-	-
10	Prt	exponential	l=0.00604	0.28
11	Slt	weibull	a=9.4676 b=93.719	0.3
12	Pul	weibull	a=5.1357 b=153.92	0.72
13	Pac	burr	k=2.9613E+5 a=4.4815 b=1379.7	0.9
14	Gr	burr	k=2.5667 a=4.8805 b=117.48	0.68
15	Ut	weibull	a=2.8293 b=295.69	0.47

4.3 Model Preparation

After working on the machinery statistical data and finding the appropriate probability distribution functions for time intervals between failures, in the next step, one should prepare a model for simulation, which is well suited with the system's conditions. First I will consider the system properly. This system has been constructed of parallel-series subsystems, which can be divided into three subsystems and each has been constructed of some components. I chose these three subsystems because if each of them fails, the

TABLE 4.5: Distribution ranking for mixing unit

#	Distribution	Kolmogorov		Anderson	
		Smirnov Statistic	Rank	Darling Statistic	Rank
1	Beta	0.16221	5	3.6524	10
2	Erlang	0.41224	13	1.9925	8
3	Exponential	0.26674	8	0.4422	2
4	Gamma	0.21936	3	0.36324	1
5	Triangular	0.36359	12	6.2172	14
6	Uniform	0.2394	5	0.60338	5
7	Weibull	0.23982	1	0.45556	3

TABLE 4.6: Different tests of Weibull distribution for mixing unit

Weibull					
Kolmogorov-Smirnov					
Sample Size	7				
Statistic	0.23982				
P-Value	0.7356				
Rank	6				
a	0.2	0.1	0.05	0.02	0.01
Critical Value	0.38148	0.43607	0.48342	0.53844	0.57581
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size	7				
Statistic	0.45556				
Rank	3				
a	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No

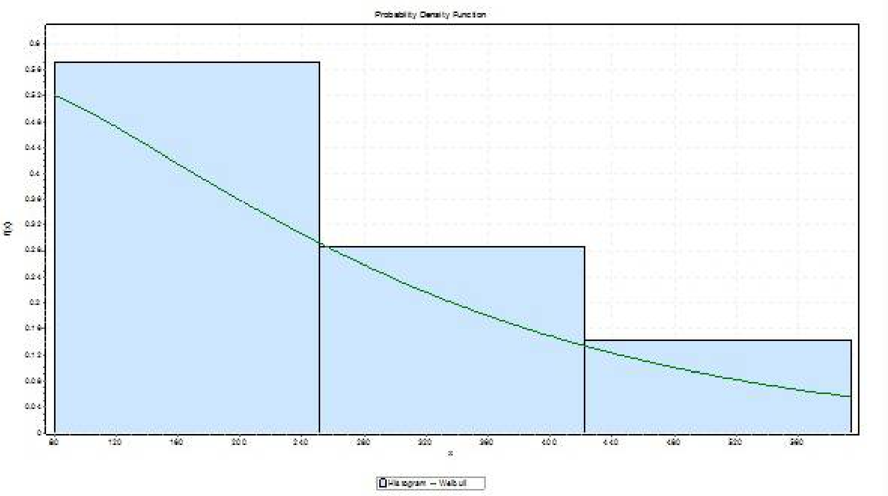


FIGURE 4.1: Data histogram and fitted Weibull distribution

whole system will fail accordingly. For example, if the third subsystem fails there is no way between source and sink on the system, so the system will see failure. As it has been illustrated in Figure 4.2, the first subsystem is a series system with two components in a row, which are utility unit and mixing unit, and the second subsystem has two identical parallel lines where each one has four components in series. The third subsystem has three series components in a row. The other two components in the third subsystem such as the pulverizing unit and grinding unit, do not have any contributions to the production line, because they are installed to process wasted material and prepare it for recycling.

One can say reliability of the system is formed by the reliability of the three subsystems, because the system's reliability can be defined by multiplication of the reliability of them. So if we say reliability of the system is R, and for subsystems, R_1, R_2, and R_3 respectively, we can define R as

$$R_s = R_1 * R_2 * R_3 \tag{4.1}$$

And for each subsystem we can find their reliability by using their component's reliability based on the simulation model that we will prepare for this purpose.

As previously stated, I will use the probability distribution of time intervals to failure of components in simulation, and to achieve the time interval between failures for the entire system, the same logic can be applied. For example, for one replication, while the system is working, the minimum time failure of each subsystem is time to failure for the system, because for the same reason, it can be said, if the first subsystem fails, there is no way for the system to continue performing. So one can apply this logic to the simulation model. Hence, by applying the distributions that were found for the components, one can find their time to failure for each iteration, and then the time to failure of subsystem can be determined, as well as the time to failure of the system. By increasing the number of replications of the simulation, one can increase the sample size of time to failure of the system. By applying statistical methods, one can easily define the mean time to failure of the system, which is an important factor in reliability evaluation, and the variance of the mean time to failure and the system reliability can be found.

4.4 Arena Model

There are different methods to prepare a model for simulation such as computer programming, which mostly are used for models that are not easy to model them by available software, and another way is using related software. The second way has been chosen

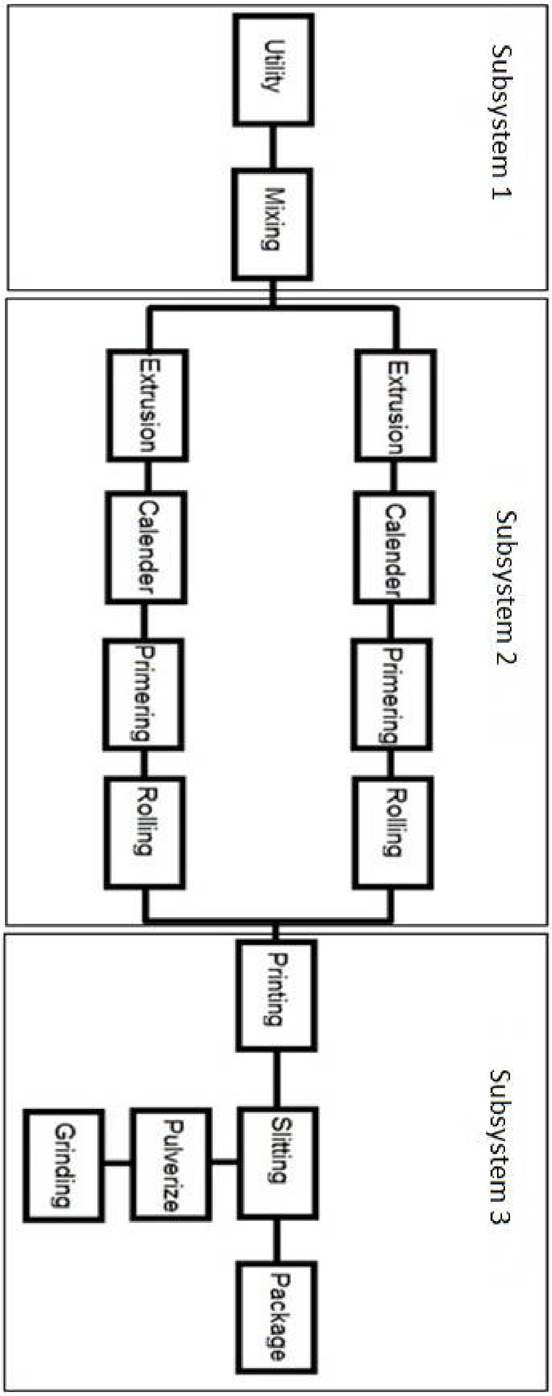


FIGURE 4.2: Schematic of system and its subsystems

for this study because the system could be modeled by this method; I will prepare the model by the Arena software, which is a very strong tool for the simulation of different sectors in the industry. It is convenient to prepare the model for simulation by Arena, because it is a visualized modeling and one can see the components and their relations in the model. The only important issue that should be taken into consideration is, the logic behind the model should pass all the requirements of the system. Arena software gives the ability to change the features, and make the model in many different ways, and by using this software, one can get various kinds of information and results, based on the definition in the prepared model that is easy to interpret.

4.4.1 The logic of Arena model

I divided the system into three subsystems in which each include different components, and the failure in each subsystem leads to the failure of the system, therefore the minimum time to failure of each subsystem is equal to the failure time of the system. An algorithm or model is needed, which can find the min time to the failure of subsystems. Here, the logic behind the model will be discussed further, in detail.

First the subsystem is constructed with two machines, which work in series, and the failure of each machine results in the failure of the first subsystem. The time to the failure of the first subsystem is equal to the min failure time of the two components that are working in this subsystem. In the second subsystem, there are two identical parallel lines and each line has been built by four components in series. For each line time of failure is equal to failure in at least one of the components that are operating in that line. So I chose the minimum time to failure of components for each line, but the important issue in this subsystem is, if one line fails, another one can continue to work and the system will continue to operate. There occurs failure in the second subsystem when both lines fail. Therefore, if one chooses the maximum time to failure between time to failure of both lines, he can make sure both lines have stopped working, and as a result, the second subsystem and afterwards, the system will fail entirely. The third subsystem works as the first one, and one can behave the same with the third subsystem as the first one. The only difference is the last subsystem includes three components and one should choose the minimum time to failure among them to make sure the subsystem will fail. There is other machinery in the third subsystem that does not have role in the failure of the subsystem, because it processes waste materials, and does not have any contribution to final products.

There are some assumptions behind the study, in which it is assumed that the components are independent of one another. This means the failure of a component and its working conditions does not have any effect on other machinery. I model the system by simulation, therefore there is no limitation for choosing a special distribution, and I use only the best fits to the data. Naturally, there are other effects on the reliability of the system such as the working skills of operators, environmental conditions, and etc. but I do not take them into consideration.

Based on the logic discussed earlier, as it is illustrated in Figure 4.3, which is the model from the Arena software, the min time to failure of each subsystem will be found by an appropriate decision module, and it selects this time by considering the failure times of each component in subsystem. Finding the time to the failure of the second subsystem is challenging, because there are lines where each one includes some components in series. There are three decision modules for this subsystem, in which two of them will find the failure time of each line and the third one determines the failure time of the subsystem. In the last subsystem, the same conditions exist as the first one and one can find its time in the same way. In the next part, the model will determine the failure time of the system by comparing the failure times that come from the subsystems.

After one replication, one can get the time to the failure of the system, for the first entities on which components are working. As known form the statistics, by increasing the number of replications, one can get close to the real working conditions of the system and it makes the judgment much easier regarding the system. Therefore, the number of replication for the model is increased as much as possible. Because the Arena software that is used for this study is a student version it cannot increase replications above a certain amount of entities. I will increase the replication as much as possible, which are approximately 200 replications for this model. After running the model, time to failure of system for each replication can be seen, and one can find the mean time to failure, the reliability of the system for a period of time, the availability of the system, and the variances.

4.5 Reliability evaluation results

After the model is prepared based on the system conditions, it is ready to run. The Arena software, as previously pointed out, is a student version, and cannot run over a certain number of replications. Therefore, I ran the model for 200 replications, which gives enough information to judge the reliability level of the system. The outcome of each replication is the time between the failures of the system, which includes 200 failures. Also, besides the failure times of the system, with the results of the simulation, one can understand the component that is the reason for failure.

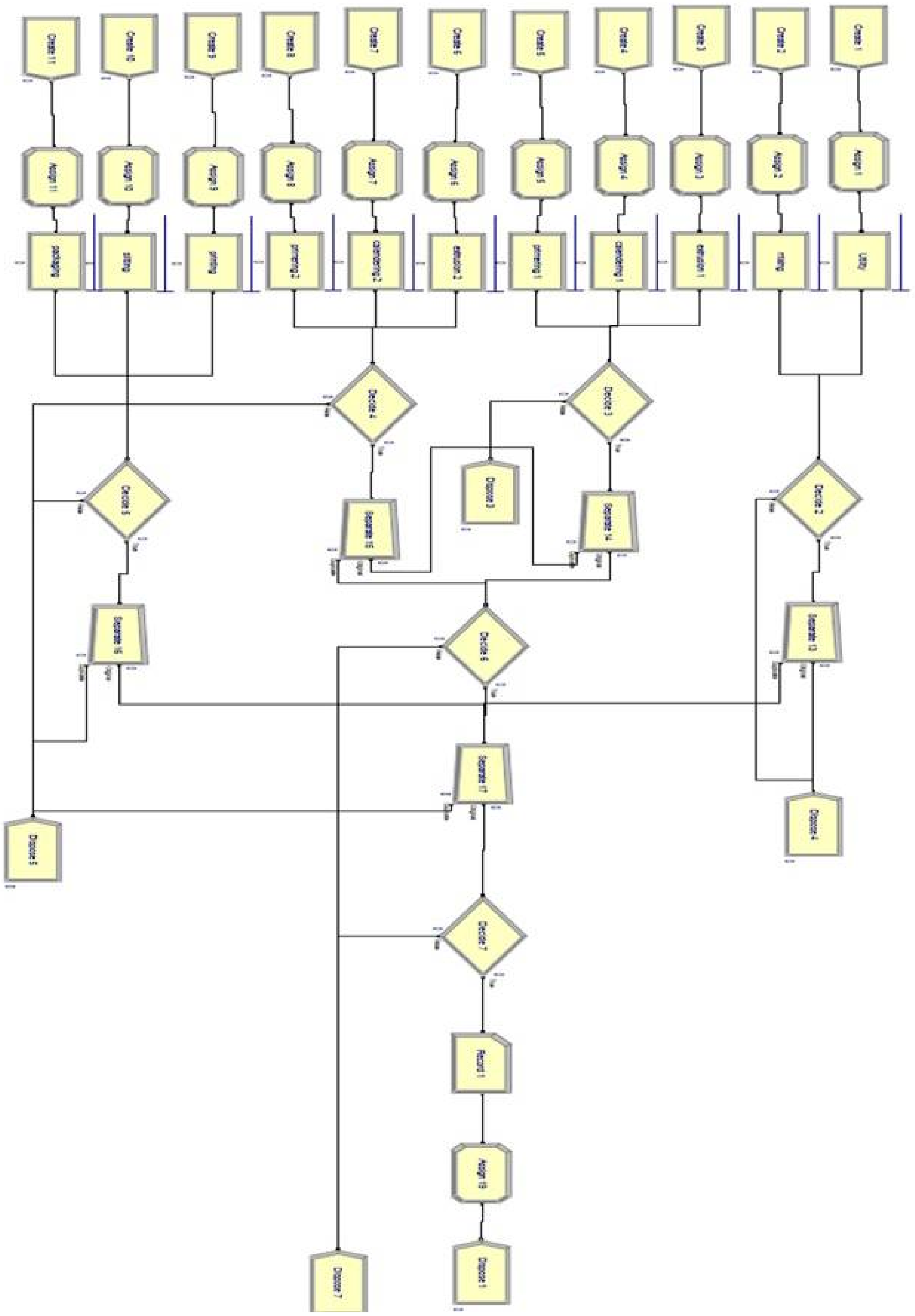
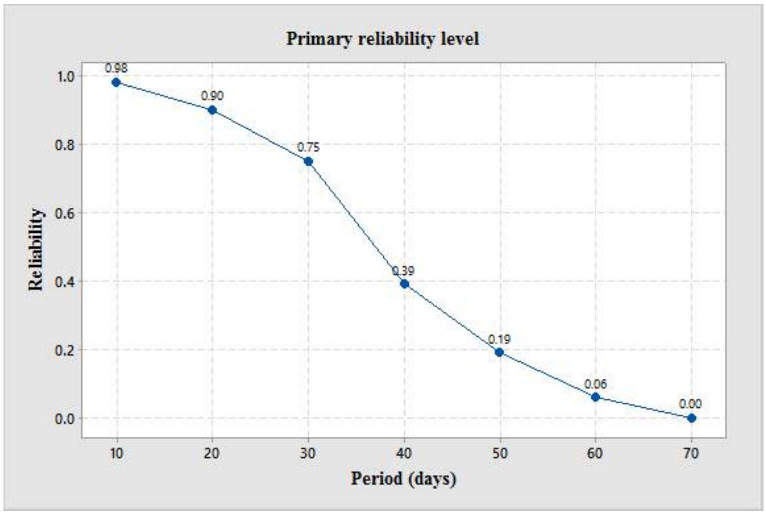


FIGURE 4.3: Arena model for primary reliability evaluation

[illegible]

[illegible]	[illegible]	[illegible]
10	[illegible]	98%
20	[illegible]	[illegible]
[illegible]	[illegible]	75%
[illegible]	122	[illegible]
50	[illegible]	[illegible]
60	[illegible]	[illegible]
[illegible]	400	0%



Therefore, the primary conditions of the system will not be considered as desired, because it has a lower level of reliability than the expected value for the system. Hence, the company is seeking suggestions and solutions, which can improve the reliability and availability level of the company. Naturally, there are methods to increase the reliability of the system, but they will add extra costs to the system. For example, one of the techniques to increase the reliability is to add redundant components to the system, but in order to do, so there should be constraints such as monetary, spatial, or weight constraints. Hence, it seems the reliability improvement problem is an optimization problem, which is going to maximize the reliability level of the system based on mentioned constraints. To find the optimal solution, a heuristic model will be used for this system in which the optimal value will be found by allocating redundancies for weak machinery in the system. I will discuss this further in next section.

4.6 Model Verification

After modeling the system with Arena software and getting the results, the model should be verified by some analytical techniques to show that the results of the model are enough accurate. The model itself as I used for company cannot be compared with analytical methods because the components in the system do not follow the distribution that can be used in analytical methods. Therefore I am going to use another way to verify my model.

The purpose of this section is to verify the logic of the simulation model, hence instead using machinery that are following different probability distributions, we can use other components which follow the exponential distribution and they are working with the same logic that I used in my model. Therefore, the system's reliability can be evaluated analytically and experimentally. By using these components, system's reliability can be calculated easily, by analytical method which is the exact solution for system's reliability. The analytical model for reliability calculation is as follow:

$$R(t) = R_{ut}(t)R_{mx}(t) * (1 - (1 - R_{Ext}(t)R_{Pre}(t)R_{cal}(t))^2) * R_{slt}(t)R_{prt}(t)R_{pac}(t) \tag{4.2}$$

$$R(t) = e^{-(\lambda_{ut}+\lambda_{mx}+\lambda_{slt}+\lambda_{prt}+\lambda_{pac})t} * (1 - (1 - e^{-(\lambda_{ext}+\lambda_{pre}+\lambda_{cal})t})^2) \tag{4.3}$$

In the above equation for system's reliability, by replacing t with the time of different periods, system's reliability for that period will be calculated analytically. The results of reliability calculations are given in Table 4.9.

Afterward, by running the model and achieving the results of each replications and evaluating the system's reliability, the comparison between the results of analytical method and simulation, will show the strength of my model. I will use the machinery with exponential parameters which are presented in Table 4.8 in my model.

TABLE 4.8: Exponential parameters of components in verification model

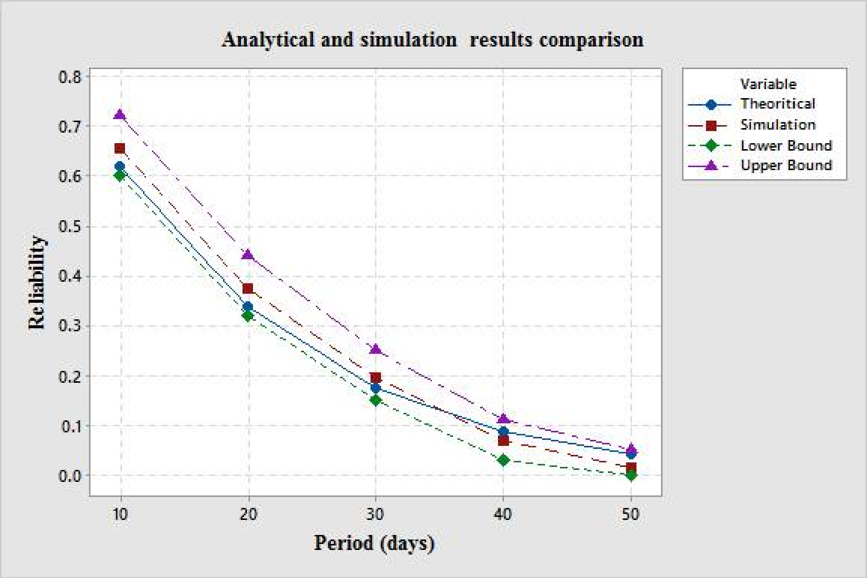
No	Component	Exponential Parameter
1	Mx	0.003
2	Ext1	0.03
3	Cal1	0.004
4	Pre1	0.005
5	Ext2	0.03
6	Cal2	0.004
7	Pre2	0.005
8	Prt	0.006
9	Slt	0.01
10	Pac	0.015
11	Ut	0.003

I did run the model with these components and also I calculated the exact value of system's reliability for different periods of 10, 20, 30, 40, and 50 days and 200 replications. The results have been presented in Table 4.9 and Figure 4.5.

TABLE 4.9: Reliability values for simulation model and analytical method

Period	Fail frequency	Lower Bound	Simulation	Upper Bound	Theoritical
10	69	0.6	0.655	0.72	0.619
20	125	0.32	0.375	0.44	0.337
30	161	0.15	0.195	0.25	0.173
40	186	0.03	0.07	0.11	0.086
50	197	0	0.015	0.05	0.042

As it is clear from the results, results of the model are fairly close to the analytical results. The theoretical values for reliability fall in between the upper bound and lower bound of confidence interval of simulation results (with 95 percent confidence) and if the numbers of replications is increased the simulation results will be cohere to the analytical solution.


Analytical and simulation results comparison
Reliability
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10
20
30
40
50
Period (days)
Variable
Theoritical
Simulation
Lower Bound
Upper Bound

Chapter 5

Reliability Optimization

5.1 Reliability Improvement Methods

In the previous chapter I evaluated the reliability of the system by simulation technique with Arena software. The results that I got form the assessment show the reliability of the system for a period of 30 days is equal to 75 percent, which is less than company requirements i.e. approximately 85 percent per month. In this part, improving the system's reliability based on the available techniques is necessary. All techniques for reliability improvement follow the same logic and it is to lessen the failure occurrence in the system. Some of methods that can be used to improve the system's reliability are:

- Redundant components which they have different types
  - Cold standby (passive redundancy)
  - Warm standby (active redundancy)
  - Hot standby (active redundancy)
- Replacing the components by components with higher reliability level
- Improving the maintenance policies, and,
- Other adjustments which helps the system have less failure frequency

Redundancy components usually are used for critical machinery in the system to improve the reliability or lessen the chance of failure occurring. Cold standby redundancies are redundant components that do not work since the main component is working properly, and when it fails, the standby system starts to work in the system. Hot standby redundancies are different; the stand by machine is working at the same time as the main component and they are at their highest performance level. There is another type of redundancy, which is called the warm standby component, and which is similar to hot standby redundancy. It is working simultaneously with the main component, but with a different level of performance. Sometimes, it would be beneficial to use redundant components with a less reliability level and at a lesser price. Otherwise, in some cases, the designer should allocate more than one level of redundancy for a component or components in critical systems to minimize the chance of failure in the system. To improve the reliability of the system, based on the criticality of the system one can choose different and appropriate types of techniques to improve the system's reliability.

As a result of the discussion, one can conclude that in any case, the first duty in reliability improvement is to find the appropriate method, with which one can decide, based on the failure frequencies or the role of different machinery, on decreasing the system's reliability. In many cases adding a redundant component is a good approach to increase reliability. In redundancy allocation technique, some redundant components are added to the system to improve the reliability by decreasing the failure frequency by replacing the failed component with the redundant machine, and of course there are some added cost and weight to the system by adding a redundancy for those components. In this study, for allocating the redundancy, the weak components are identified first and then redundancy allocation will be applied on those components. In some systems it is easy to recognize these components, but if the system is complicated, it would be very difficult to allocate the appropriate redundant unit, because besides improving the reliability, there are other factors that should be taken into consideration. For example, one does not want to improve the reliability by any price or sometimes there are space or weight limitations inside to considerations. Hence, the redundancy allocation problem is an optimization problem where sometimes the purpose is to maximize the reliability based on cost and weight constraints, or on the other hand, sometimes it is an optimization problem with minimizing the cost by reliability and weight limitations, and one can minimize the weight by the reliability and cost constraints. For this system, in the next step, I will check the reliability improvement of the system by applying hot standby and cold standby redundancy.

Redundancy allocation problem will be solved for hot redundancies by a heuristic model, and also the results of heuristic model will be compared with optimal values of the problem. For cold standby problem which is much harder than hot standby problem, I just consider on level of cold standby component only for the weakest component by simulation method.

5.1.1 Redundancy allocation and finding the optimal reliability values by using a heuristic model

Thus far, I have evaluated the primary reliability level of the company for a period of one month, and the results show there is need to improve the reliability level of the system. Adding redundant components is one of the main techniques which helps us to improve system's reliability, but it will leave us an optimization problem which should be solved to find the optimal value of reliability based on different redundancy levels that lead to some extra costs and spaces on the system. Normally, in a redundancy allocation problem, some level of redundancies are considered for components to find out the best level of redundancies for a desired system. The problem is that, reliability allocation and finding the optimal solution for the system with redundancy levels is not an easy task, because in many cases the optimization problem will be a multi-objective, none-linear integer model which is very difficult to solve. As it was studied in literature review chapter, for many of redundancy allocation problems, the presented model uses a heuristic method in which the solution is close to the optimal solution.

To overcome the difficulties of general redundancy allocation model, a heuristic model can be considered. Identifying the weak points of the system, which are the main causes for the lack of reliability, and then finding the optimal solution, gives us the idea of this heuristic method to find the solution for reliability optimization which is close to the optimal value. One can suggest the appropriate answer for the company by this heuristic model. Therefore, for system's reliability improvement and optimization, based on this model, the components which show more failure frequency in the system are identified by comparing the statistical data that has been achieved from the primary results, then redundancy allocation will be applied for weak components and the reliability value for improved system will be evaluated. As a result, in this method the problem is less complicated in which the optimal reliability value can be found easier.

After evaluating the primary reliability condition, the following steps will build the heuristic model that I am going to use in this study.

- Find the weak components based on their reliability index which have the max contribution to the unreliable conditions of the system
- Choose a reliability level which the components with reliability lower than that level will be chosen for redundancy allocation (for instance, machines with reliability lower than 95 percent will have redundant components)
- Define the level of redundancy based on cost or another constraints

- Allocate redundancies for components in serial part of the system and evaluate system's reliability level (if there is any weak components)
- Allocate redundancies for components in parallel part of the system and evaluate system's reliability level (if there is any weak components)
- Allocate redundancies for components in both parallel and serial part of system if possible and evaluate system's reliability
- Choose the best option among the possible solutions which pass the desired conditions

Here, I evaluate the reliability level of the system for different redundancy levels based on the heuristic model that was discussed above. In the first step of this heuristic model, the weak components should be recognized. For this reason I evaluated the reliability level of different components in the system to to be clear which of them have the most effect on the system's reliability. The results are presented in the following table.

TABLE 5.1: Components reliability for different periods of time

component	Period	Reliability	Period	Reliability
Ext1	20 days	0.77	30 days	0.61
Ext2	20 days	0.77	30 days	0.61
Slt	20 days	0.98	30 days	0.95
Pac	20 days	0.97	30 days	0.93
Other components	20 days	1	30 days	1

As it can be seen from Table 5.1, all the components have reliability of one except four components i.e. extrusions machinery, slitting machine, and the packaging unit.

In the second step of heuristic model, I choose the components with reliability level less or equal than 98 percent to be considered for having redundant options. Therefore, in this system, Extrusion, Slitting, and Packaging machinery will be given the redundant components to see if there will be any changes in reliability level of system or not.

Step three is related to defining the redundancy levels. In this step based on the cost constraint which is given by the company. In our case, the cost should not be exceeded from 50000 dollars. Based on this constraint and the price of each machine which is given in Table 5.2, redundancy level for each component in each combination of them can be defined. For instance, we can have one redundant option for extrusion machine and one for slitting component, or it is possible to have two redundant options for extrusion unit in which the price will be 40000 dollars.

Therefore the possible redundancy options will be as follow: for one level of redundancy, all the weak components can be considered with one level of redundancy. For two levels of redundancy, the only options are: extrusion 1 with two redundant components, extrusion 2 with two redundant components, extrusion machine 1 and 2 each with one redundancy, extrusion 1 machine with one redundancy and slitting with one, extrusion 2 with one redundancy and slitting with one.

In step three we have decided about level of redundant components for different machinery. In the parallel-series systems, the serial part is more sensitive and by failure of only one components system will go down. Therefore, in the heuristic model, firstly, I allocate the redundant options for the serial part and evaluate the system's reliability which construct the forth step in the heuristic model. There are two weak components (slitting and packaging)in the serial part that can have redundant component, and because of the price of the component they only can have one level of redundancy separately. As it clear from Table 5.3 for having a redundant component for slitting unit, the reliability will increase up to 0.77, and by having a redundant option for packaging, system's reliability will improve up to 0.80.

Allocating the redundant components into the parallel part which construct the fifth step of the heuristic model, is the next step of calculations. In the parallel part, extrusion 1 and 2 are the weak components. According to the prices of these components, the can have up to two levels of redundancy in different combinations. For example, one of them can have two level of redundancy, or both of them can have one redundant component, or other combinations. The results of reliability assessment for this part are given in Table 5.3. In this part, having two level of redundancy leads to the reliability level of 0.86 in which the added cost will be 40000 dollars.

In the other hand, if the cost constraint allows us, we can have redundant components both in parallel and serial part. In this system for example, because sum of the prices of slitting and extrusion units are 50000 dollars, we can consider having a redundant component for extrusion 1 or 2 and a redundant component for slitting unit in the same time. The results are shown in Table 5.3 and the system's reliability for this options will be 0.87 by cost of 50000 dollars.

In the final step, we should decide about choosing a suitable solution for the reliability improvement of the system. One can say that I want the max reliability within the cost constraint which in this case having redundant options number 6 and 7 in Table 5.3 will be the answer on which there will be a redundant component for extrusion 1 or 2 and one redundant component for slitting unit. In the other hand, one can say I want to pass the min level of desired reliability level by spending less money, therefore the redundant options will be number 5, 8, and 9 in Table 5.3.

Table 5.2: Machinery Prices

No	Component	Price (USD)
1	Extrusion	20000
2	Slitting	30000
3	Packaging	45000
4	Mixing	25000
5	Utility	27000
6	Calendaring	40000
7	Printing	35000
8	Premiering	20000

Table 5.3: Reliability levels and costs for different redundancy levels using heuristic model

Redundant options	ext1	ext2	slt	pac	Reliability	Cost (USD)
1	2	1	1	1	0.83	20000
2	1	2	1	1	0.83	20000
3	1	1	2	1	0.79	30000
4	1	1	1	2	0.80	45000
5	2	2	1	1	0.86	40000
6	2	1	2	1	0.87	50000
7	1	2	2	1	0.87	50000
8	3	1	1	1	0.86	40000
9	1	3	1	1	0.86	40000

To prove that this heuristic model leads to a feasible solution, I am going to solve the optimization problem for redundancy allocation of this system In the following section.

5.1.2 Optimal reliability level for active redundancies by solving the optimization problem (hot standby)

For redundancy allocation (active redundancy) and the optimization of systems such as my system, there are few works that have been done on the optimal solution for parallel-series systems. In general the problem, and solving the problem would be very difficult, because of the non-linearity nature of the problem and the number of iterations that should be done for this reason. As pointed out previously, there are few studies on how to solve the problem by some techniques such as column generation, tabu search, or genetic algorithm.

In Figure 5.1, the general configuration of a parallel-series system has been illustrated, which is constructed of s subsystems, and each subsystem has n_s components. Therefore the optimization problem would be as below:

Objective function

$$MaxR(x) = R_1(x_1)R_2(x_2)R_3(x_3)...R_s(x_s) = (\prod_{i=1}^{s}(1 - \prod_{j=1}^{n_i}(1 - R_{ij})^{x_{ij}})) \tag{5.1}$$

Subject to:

$$\sum_{i=1}^{s}\sum_{j=1}^{n_i} c_{ij}x_{ij} \leq C \tag{5.2}$$

$$x_{i,j} \geq 1 \; integer \; values \tag{5.3}$$

Where C is the cost constraints, where a value above it cannot be spent on this system to improve the reliability level of the system. s indicates the number of subsystems in the system and n_i shows the number of components in subsystem i. c_{ij} is the cost for component j in subsystem j. x_{ij} is a variable which shows the number of components that have been used in each subsystem based on the component type.

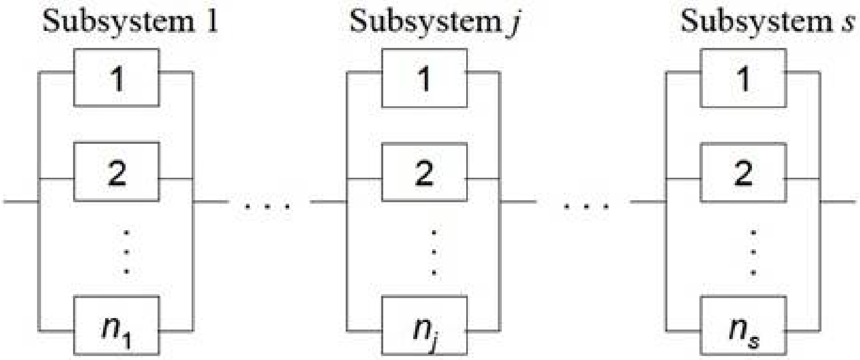


FIGURE 5.1: General configuration of parallel-series system

This equation shows the non-linearity of the problem clearly. Also the variable x_{ij} accepts integer values. It means that to solve this problem integer programming will be needed. The methods that are used to solve these kinds of problem normally are integer programming, genetic algorithm, column generation, tabu search technique, and some other techniques. Luckily, in this problem, because the system configuration is not very complicated and it is only needed to find the optimal solution for limited number of redundancy combinations of different machinery.

One should allocate the redundancy for reliability improvement based on the company conditions. The cost of improvement should not exceed 50000$, which allows one to have at most two levels of redundancy according to the average cost of components. Therefore, one must find the optimal solution for different combinations of redundancies in the system to get the maximum reliability level regrading to the company's restrictions. Also, the desired value of improved reliability should be more than 85 percent.

As it can be seen from the table 5.2, which shows the average prices for different machinery (which are currently working in the company), for one level of redundancy allocation there is no cost constraint because the price of each component is less than the cost limit. But for two levels of redundancy, there are limited number of combinations, because the cost will exceed the cost limitation for other combinations with two level of redundancy. For instance if I choose redundancies for slitting and utility machines, the cost would be 57000$ and it is beyond the cost limitation. Therefore, the purpose of this optimization is to find the redundancy combinations that pass the company constraints which are cost (less than 50000 dollars) and reliability (greater than 0.85) constraints.

It should be stated, based on the company conditions, there are no weight or space limitations, to install the new machinery to improve the reliability, and the only restriction there is, is cost constraints. Therefore, the objective function of this problem is to maximize the reliability of the system by the minimum cost according to the constraints.

If one wants to conform company's model to the general model for redundancy allocation, in conformed system, as it can be seen from the following equations, because we intend to minimize the cost and maximize the reliability, the model will become a multi-objective optimization problem. Also because of the nature of the reliability optimization problem including redundancies, the problem is a nonlinear integer model. Therefore the final model for this system is a multi-objective nonlinear integer model which for complicated systems is not solvable easily.

To model the system's reliability mathematically, As it was mentioned in chapter 4 I divide the system into three subsystems (Figure 4.2) which the system's reliability is the multiplication of the subsystem's reliability. Reliability of each subsystem is calculated as following equations.

$$R_(x) = R_1(x) * R_2(x) * R_3(x) \tag{5.4}$$

$$R_1(x) = (1 - (1 - R_{11})^{x_{11}}) * (1 - (1 - R_{12})^{x_{12}}) \tag{5.5}$$

R_{11} shows the reliability of utility machine and R_{12} is mixing unit's reliability. and x shoes the number of components in the system.

$$R_3(x) = (1 - (1 - R_{31})^{x_{31}}) * (1 - (1 - R_{32})^{x_{32}}) * (1 - (1 - R_{33})^{x_{33}}) \tag{5.6}$$

In this formula R_{31}, R_{32}, R_{33} show the reliability of slitting, printing, and packaging units respectively. and x shoes the number of components in the system.

And for the parallel part we have two parallel lines that they are identical and in each line there are three components such as extrusion, calendering and premiering units. In the following formula R_{213} shows the reliability of third component in the first line of second subsystem which is premiering, and so on for other R values in the formula we can judge the same. and x shoes the number of components in the system.

$$R_2(x) = 1 - (1 - R_{21}(x)) * (1 - R_{22}(x)) \tag{5.7}$$

which

$$R_{21}(x) = (1 - (1 - R_{211})^{x_{211}}) * (1 - (1 - R_{212})^{x_{212}})(1 - (1 - R_{213})^{x_{213}}) \tag{5.8}$$

$$R_{22}(x) = (1 - (1 - R_{221})^{x_{221}}) * (1 - (1 - R_{222})^{x_{222}})(1 - (1 - R_{223})^{x_{223}}) \tag{5.9}$$

and the cost can be defined by the following equation

$$C(x) = \sum_{i=1}\sum_{j=1}^{2} c_{ij}x_{ij} + \sum_{i=2}\sum_{j=1}^{2}\sum_{k=1}^{3} c_{ijk}x_{ijk} + \sum_{i=3}\sum_{j=1}^{3} c_{ij}x_{ij} \tag{5.10}$$

Therefore the objective function for this problem would be as follow

$$MaxR(x) \tag{5.11}$$

$$MinC(x) \tag{5.12}$$

Subject to:

$$R(x) \geq 0.85 \tag{5.13}$$

$$C(x) \leq 50000 \tag{5.14}$$

$$x_{i,j} \geq 1 \; and \; integer \tag{5.15}$$

In order to solve this problem, there are some methods which convert the main problem into a single objective optimization problem such as goal attainment, weighted sum or some other techniques which can be used in these kinds of problems. I am going to use weighted sum technique to find the optimal solutions for this problem.

In weighted sum method the set of objectives will be converted into a scalar problem by preparing a weighted sum of all objectives. Each objective gains a weight in which the decision maker decides about the value of weights. In general the weights are not related to the importance of an objective, but if they were scaled based on the priority of the objectives, it will result in a better solution. Hence if the objective functions in a multi-objective problem are as follows:

$$minimize\ F_i(x)\ i = 1\ to\ n \tag{5.16}$$

By applying the weighted sum method the problem will be converted into the following problem which has a single objective.

$$minimize\ f(x) = \sum_{i=1}^{n} w_i F_i\ and\ x \in \Omega \tag{5.17}$$

in which Ω defines the feasible design space. Therefore, by changing the weights for objective functions a set of optimal solutions will be achieved. In this method as well, it is better to normalize the weights such that:

$$\sum_{i=1}^{n} w_i = 1\ and\ w_i \geq 0 \tag{5.18}$$

There is a condition to apply the weighted sum method which says that the feasible design space and all objective functions should be convex. Function defined on a convex set is convex if and only if the Hessian matrix of the function is positive semi-finite or positive definite at all points in the set. Thus, if the Hessian matrix for each constraint and for each objective function is positive semi-definite or positive definite, then the weighted sum method can provide all Pareto optimal points. In this problem, objective functions and constraints have a positive second derivatives regarding to the decision variable x_ij, R_ij and c_ij therefore the Hessian matrix will be positive and definite, so the objective functions and design space will be convex which let us to apply weighted sum method on this problem. As a result the weighted sum method will be applied on our multi-objective problem (equations 5.5-5.11). So the multi-objective problem will be converted in a single objective optimization problem as below:

$$Minimize\ F(x) = w_1(1 - R(x)) + w_2 C(x)\ and\ x \in \Omega \tag{5.19}$$

In this problem, the cost values are normalized between 0 to 1 to be in the same range with reliability values to have a better understanding of them while the weights are changing.

To solve this problem, first, by using MATLAB programming the feasible design space is identified based on the constraints, and then, by weighted sum technique and giving different values to the weights a set of optimal solutions can be recognized which some of them for certain weights are illustrated in Table 5.4. In this table also redundancy options and number of redundancies are shown for each machinery. It should be mentioned that for multi-objective optimization problem there is an infinite number of optimal solution and it can be achieved by changing the values of weights. It is the decision maker's job to make a preference based on the priority that he (she) defines. In my problem case, if the company's priority is just reliability which means spend maximum level of allocated money to achieve the highest reliability, the weight for reliability is one in the objective function, and as it can be seen from Table 5.4 the reliability level for this case is 0.8726 which the cost is \$50000. in the other hand if we are willing to spend the minimum cost to achieve the required reliability level, we allocate value of one for cost weight and zero for reliability weight. However, another weights can be given to the weight to find out the trade off between reliability and cost.

As the results of the optimization problem indicates, the answers that have been achieved from the heuristic model are available in the optimal set answers of optimization problem which shows that the presented heuristic model in previous section is an appropriate and time saving method to allocate optimal redundancies into the system.

There is also another way of redundancy application, which can improve the reliability and it is cold standby redundancy. One should compare the attained optimal answer for hot standby redundancy with cold standby, to choose the best answer. In the next part I will evaluate the reliability of the system by cold standby redundancy with the simulation technique.

5.2 Cold standby redundancy problem

Another type of redundancy is the cold standby component in which the redundant component will not work until a failure occurs in the main component. After failure, the standby system will start to work with the same performance of the main component. In this part, I will evaluate the reliability of the system by implementing a cold standby component for the extrusion machine. The main reason for choosing this component is, because there are two of them in parallel, if a failure happens for each of them, one can use the standby unit for both of them. But it should be taken into consideration that if the standby component is currently working, it could not be used for another machine.

One of the reasons for which I will use cold standby redundancy is that there are two extrusion components in parallel, and they have maximum failure frequency and crucial contribution to the lack of reliability in the system. Hence, a cold standby redundancy can work for both machines while it is free and there is failure in one of the extrusion machines. I chose the standby component to be the current extrusion machines that are

Table 5.4: Pareto Optimal Sets

No	w1	w2	F min	R	C(1000USD)	Ut	Mx	Prt	Slt	Pac	Ext1	Pre1	Cal1	Ext2	Pre2	Cal2
1	0.5	0.5	0.211	0.863	40	1	1	1	1	1	1	1	1	3	1	1
2	0.5	0.5	0.211	0.863	40	1	1	1	1	1	2	1	1	2	1	1
3	0.5	0.5	0.211	0.863	40	1	1	1	1	1	3	1	1	1	1	1
4	1	0	0.127	0.873	50	1	1	1	2	1	2	1	1	1	1	1
5	1	0	0.127	0.873	50	1	1	1	2	1	1	1	1	2	1	1
6	0	1	0.286	0.863	40	1	1	1	1	1	1	1	1	3	1	1
7	0	1	0.286	0.863	40	1	1	1	1	1	2	1	1	2	1	1
8	0	1	0.286	0.863	40	1	1	1	1	1	3	1	1	1	1	1
9	0.7	0.3	0.182	0.863	40	1	1	1	1	1	1	1	1	3	1	1
10	0.7	0.3	0.182	0.863	40	1	1	1	1	1	2	1	1	2	1	1
11	0.7	0.3	0.182	0.863	40	1	1	1	1	1	3	1	1	1	1	1
12	0.3	0.7	0.241	0.863	40	1	1	1	1	1	1	1	1	3	1	1
13	0.3	0.7	0.241	0.863	40	1	1	1	1	1	2	1	1	2	1	1
14	0.3	0.7	0.241	0.863	40	1	1	1	1	1	3	1	1	1	1	1
15	0.8	0.2	0.167	0.863	40	1	1	1	1	1	1	1	1	3	1	1
16	0.8	0.2	0.167	0.863	40	1	1	1	1	1	2	1	1	2	1	1
17	0.8	0.2	0.167	0.863	40	1	1	1	1	1	3	1	1	1	1	1
18	0.2	0.8	0.256	0.863	40	1	1	1	1	1	1	1	1	3	1	1
19	0.2	0.8	0.256	0.863	40	1	1	1	1	1	2	1	1	2	1	1
20	0.2	0.8	0.256	0.863	40	1	1	1	1	1	3	1	1	1	1	1

working in the system, because I have statistical data on them and I am aware of their reliability conditions.

The model that I use in Arena, and it has the same components that do not need redundancy. The only part that will change is the part for extrusion machinery. Also, there is need to add an extra decide module with appropriate logic. The standby component will be replaced by a machine only if it is free. Figure 5.2 shows the model in the Arena software for this system with cold standby redundancy.

The number of replications that can be done in the student version of Arena is limited, as aforementioned, therefore, I have done the simulation for 200 replications. The results of replications give the time between the failures of the system as in the previous model and one can find the system's reliability and mean time between failures in the system. After analyzing the results, the reliability level of the system for different periods of time is given in Table 5.5. As it can be seen from the results, one can see the reliability of the system for a period of 1 month is about 89 percent, which shows 14 percent improvement compared to the previous model, and it also can exceeds the company requirements which is 85 percent reliability for 1 month with the price of less than 50000$. The cost of this redundancy is about 20000$, which is much less than the cost of applying the hot standby component at the same reliability level. The Mean time between failures of the improved system is 49.48 days, which is about 11 days more than the previous mean time between the failures of the system. Figure 5.3 illustrates the reliability diagram of the system by cold standby redundancy and compares it to the previous conditions, for where all periods of time reliability are improved.

As a result, and based on the answers that were found for reliability improvement, it can be understood that the best solution for improving the reliability level of the system, which passes all the requirements and is the good solution, would be applying a cold standby redundancy for extrusion machines.

Table 5.5: Reliability results from cold standby model

period	failure frequency	reliability	improvement
10	4	98%	0%
20	13	94%	4%
30	23	89%	14%
40	55	73%	34%
50	101	50%	31%
60	136	32%	26%

In order to make sure that the statistical data for the time to the failure of the system in previous conditions and improved conditions are really coming from different populations and there is actual improvement, one can apply statistical tests as the t test on the data.

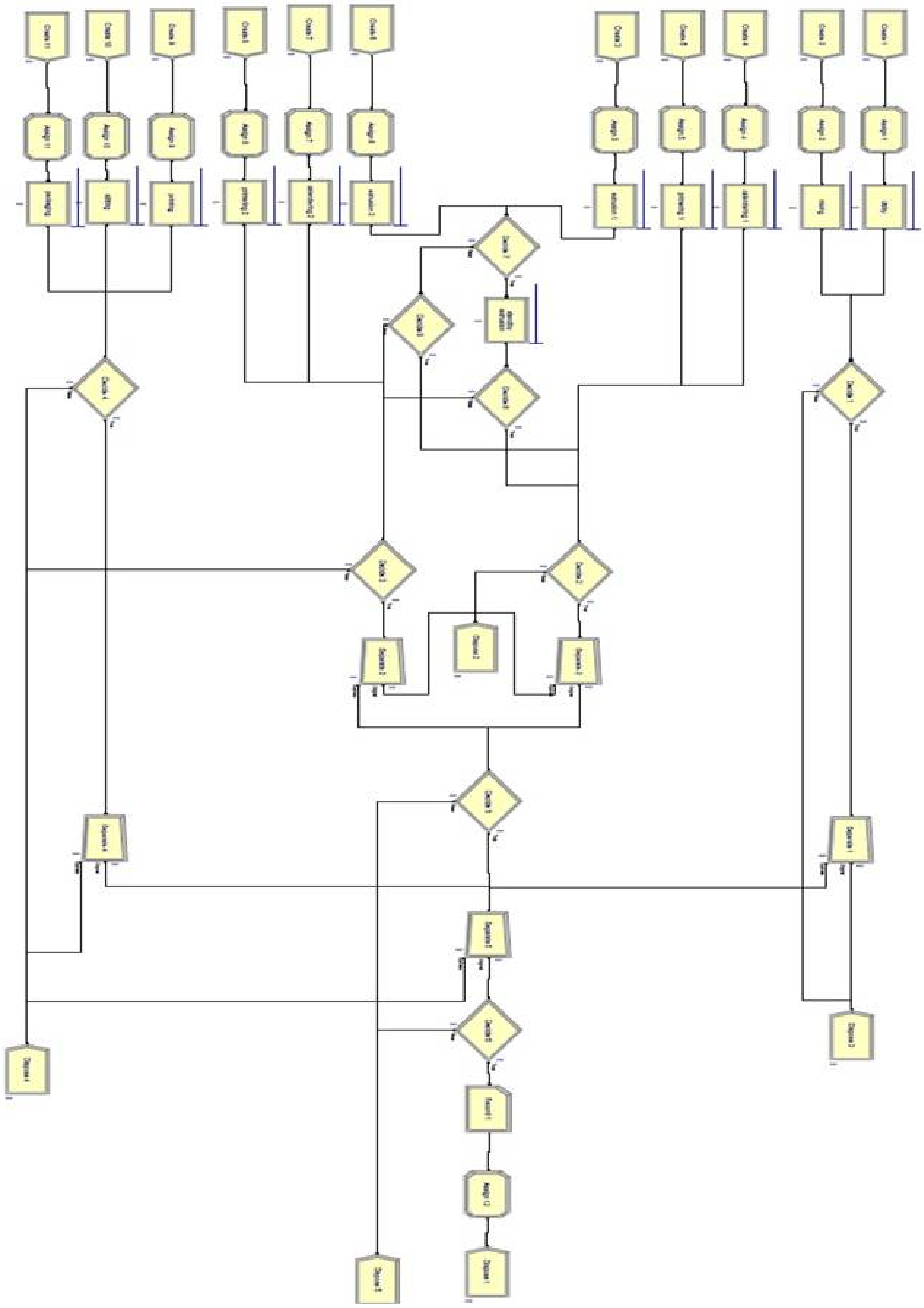


Figure 5.2: Arena model for system with cold standby redundancy

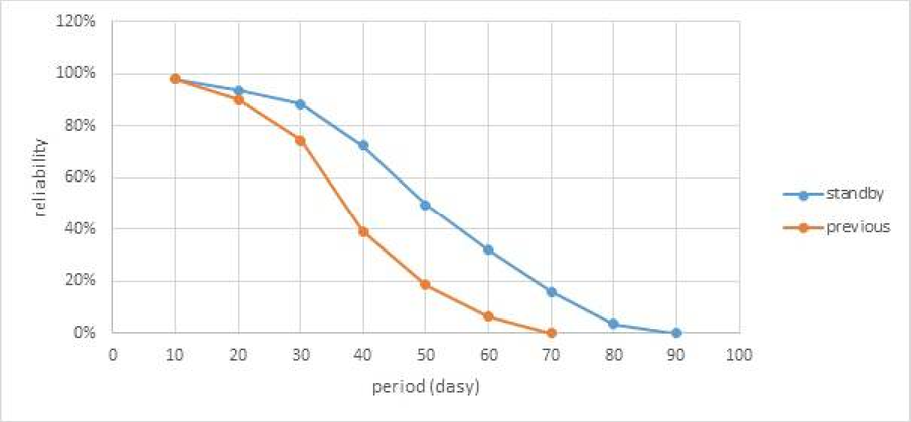


FIGURE 5.3: Reliability diagram for standby and normal systems

This way one can find the p value and confidence interval to discuss the data more reasonably. In the next part the results of t test will be presented.

5.3 Testing the primary data with secondary data

The main purpose of this section is to check the two sets of data of the model before and after the improvement to see if the sets are really different from one another or not. One of the helpful tests, which proves to be useful when one does not have information about the populations, has a sample only, and needs to test it to see whether it is truly different or not, is the t test. The null hypothesis is that the two sets of data are form the same population, and if the results of the t test show the rejection of the null hypothesis, the evidence shows they have different populations.

A summary of statistics form the sample data of the previous model and improved model is given in Table 5.6 and the box plot of observations are given in Figure 5.4.

TABLE 5.6: Data statistic for sample 1 and sample 2

Statistic	Sample 1	Sample 2
Mean	38.3	49.5
Mean interval by 95% confidence interval	35.98-40.64	47.58-51.39
Standard Deviation	13.4	18.7
Highest value	70	94
Lowest Value	2	2
Range	68	92
Median	38	50

After testing the data with the t test, the resulted T value is equal to 7.292 and P-Value is < 0.00001. This shows the difference between the samples of two models is extremely

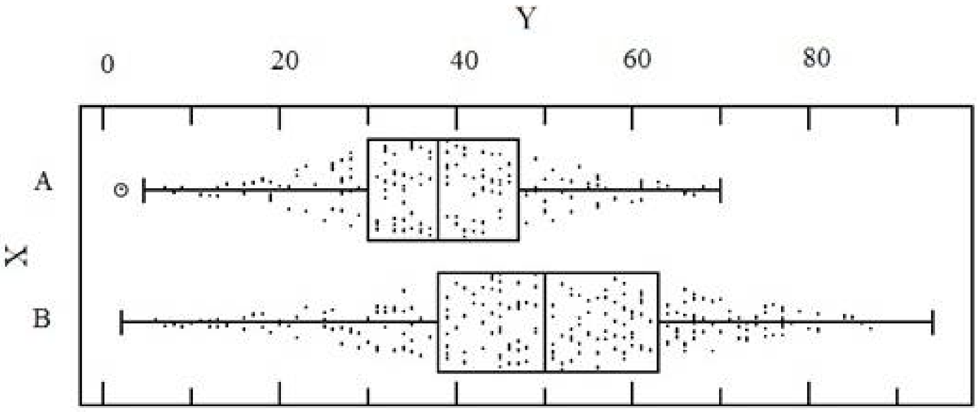


Figure 5.4: Box plot for normal and standby system

significant, so one can reject the null hypothesis, which says the data comes from the same population with a significance level of 0.05. 95 percent, the confidence interval of this difference is from -14.1745 to -8.1655. Degrees of freedom =498. The probability of this result, assuming the null hypothesis, is less than 0.0001.

Finally, one can conclude that cold standby redundancy has significant influence on the reliability of the system. It improves the reliability up to 14 percent and the mean time between failures is up to 11 days. Increasing the reliability will increase the availability of the system, which leads to more production and more profit.

Chapter 6

Conclusion

The main purpose of this study was to find the current reliability level of the Barin Plast Company, and to improve the system's reliability based on available techniques. The desired reliability level for the company is approximately to 85 percent per month under the current working conditions of the system. To assess the system's reliability in the current situation for this company, I chose to evaluate the reliability index for the system with the Monte Carlo simulation method, however there are other analytical techniques as well. The needed data to prepare the simulation model was provided by the company. The company gave me their recorded information of machinery failures for a period of 5 years, which I used to understand the nature of the failure occurrence in different machines and to find their failure probability distribution functions. Since one can fit an appropriate distribution to the data by Goodness of Fit technique, Easy fit software, which is a powerful tool for distribution fitting, was used to find the distributions for time to failure of each machine. After having reached adequate information, I modeled the system with the Arena software for simulating the real conditions on the model to understand the reliability of the entire system. After having analyzed the results of the simulation, the primary reliability level of the company was estimated to be approximately 75 percent, and the mean time between the failures of the system was approximately 38 days, which is less than the company requirements. In the next step, I tried to improve the reliability level of the system with available techniques such as hot standby and cold standby redundancies to find the optimal solution. In hot standby redundancy, the system's reliability was calculated for at most two levels of redundancy, and the best answer was suggested by considering the cost limitations of the company. To evaluate the system's reliability for hot standby redundancy, a heuristic model was presented in which by identifying the weak components and applying the redundancy for them, we can improve the reliability and find the optimal solution in shorter time. And then by solving the main problem I showed that my heuristic model is a suitable technique.

Finally, the system with a cold standby component was modeled and its reliability was evaluated, which was the maximum value with the minimum price, and this was the final suggestion given to the company. The sample data of the primary model and improved model by cold standby redundancy were tested with the t test to make sure that there is a significant difference between the population of the improved model and the previous model.

Appendix A

MATLAB Code

In this code, by doing the exhaustive numerical search, the feasible design space of the problem will be identified.

```
% Tables and Sets
ri = [1; 1; 1; 0.95; 0.93];
ci = [27; 25; 25; 30; 40];
ra = [0.61; 1; 1];
ca = [20; 20; 40];
rp = ra;
cp = ca;

yik = [1 2 3];

xa = yik;
xp = yik;

%p = [1 2 3];
%a = p;
%i = [1 2 3 4 5];

opt = zeros(200,4);
all1 = zeros(1,13);
all2 = zeros(1,13);
all31 = zeros(1,13);
all32 = zeros(1,13);
all = zeros(1,13);
info = zeros(1,13);


% Reliability and Cost for serial subsystem

e=0;
for k1=1:3
    for k2=1:3
        for k3=1:3
            for k4=1:3
                for k5=1:3
                    r5=(1-(1-ri(1))^yik(k1))*(1-(1-ri(2))^yik(k2))*(1-(1-
ri(3))^yik(k3))*(1-(1-ri(4))^yik(k4))*(1-(1-ri(5))^yik(k5));
                    e=e+1;
                    all1(e,:) =[r5,ci'*[k1-1;k2-1;k3-1;k4-1;k5-1],k1-1,k2-
1,k3-1,k4-1,k5-1,0,0,0,0,0,0];
                end
            end
        end
    end
end

% Reliability and Cost for parallel subsystem

f=0;
for l1=1:3
    for l2=1:3
        for l3=1:3
             r31=(1-(1-ra(1))^yik(l1))*(1-(1-ra(2))^yik(l2))*(1-(1-
ra(3))^yik(l3));
             f=f+1;
```

Figure A.1: Feasible domain evaluation

```
             all31(f,:) =[r31,ca'*[l1-1;l2-1;l3-1],0,0,0,0,0,0,l1-1,l2-1,l3-
1,0,0,0];
        end
    end
end

f=0;
for l1=1:3
    for l2=1:3
        for l3=1:3
             r32=(1-(1-ra(1))^yik(l1))*(1-(1-ra(2))^yik(l2))*(1-(1-
ra(3))^yik(l3));
             f=f+1;
             all32(f,:) =[r32,ca'*[l1-1;l2-1;l3-1],0,0,0,0,0,0,0,0,0,l1-
1,l2-1,l3-1];
        end
    end
end


all2 = [all31;all32];
all = [all1;all2];
al = all;

d=0;
for g=1:length(all1(:,1))
    for h=1:length(all31(:,1))
        for j=1:length(all32(:,1))
            if all32(j,:) + all31(h,:) + all1(g,:) <= 50
                d=d+1;
                info(d,:) = all32(j,:) + all31(h,:) + all1(g,:);
                info(d,1) = all1(g,1)*(1-(1-all31(h,1))*(1-all32(j,1)));
            end
        end
    end
end


%for v=1:length(info(:,2))
%    if info(v,2) > 50
%        info(v,:) = [];
%    end
%end

[~, sinfo_index] = sort(info(:,1),'descend');
optimal solution = info((sinfo index),:);


headers all =
{'reliability','Cost','Utility','Mixing','Printing','Slitting','Packaging'
,'Extrusion','Premiering','Calendaring','Extrusionb','Premieringb','Calend
aringb'};
%, 'VariableNames', headers_all
T_all = table(optimal_solution);
```

Figure A.2: Feasible domain evaluation

Appendix B

Raw data sheets

In this part, the raw statistical data which has been provided by the company has been illustrated. These data sheets shows the failure statistics for 5 years. 2010- 2014

Failure occurrence for year 2010

Month	january			february			march			april			may			june			july			august			september			october			november			december		
İntervals in month	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mixing Unit																																			1	
Extrusion Unit 1							3			6		1				3	8	9				6			7			8		5			6			5
Calendering Unit 1																																	7			
Primering Unit 1																	5																			8
Rolling Unit 1																																				
Extrusion Unit 2				4		9				6		4			8	9				6			7		4			4			4			3		
Calendering Unit 2																																			1	
Primering Unit 2																		7																		1
Rolling Unit 2																																				
Printing and Varnishing											7													5								5				
Slitting Unit									3								2											4								5
Pulverizing Unit																7																		5		
Packaging Unit									1											3									7							1
Grinding Unit										7											5													7		
Utility Unit																																				1

İnstruction: We've divided each month into three intervals, please fill in the related blank space which failure has happened by the day related to the period

Figure B.1: Failure statistic 2010

- Failure occurrence for year 2011

Month	january			february			march			april			may			june			july			august			september			october			november			december		
İntervals in month	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mixing Unit																																				1
Extrusion Unit 1		7				4						1							4			6			9			4				1	9			9
Calendering Unit 1																																			9	
Primering Unit 1																	2																			8
Rolling Unit 1																																				
Extrusion Unit 2		4								2	6				8					2					9		7			3		6		3		9
Calendering Unit 2																										6										
Primering Unit 2																		2																		1
Rolling Unit 2																																				
Printing and Varnishing																					2															
Slitting Unit								9									1									6									3	
Pulverizing Unit										9															8											
Packaging Unit								9										3										1								9
Grinding Unit									9												2										8					
Utility Unit																												5								

İnstruction: We've divided each month into three intervals, please fill in the related blank space which failure has happened by the day related to the period

FIGURE B.2: Failure statistic 2011

- Failure occurrence for year 2012

Month	january			february			march			april			may			june			july			august			september			october			november			december		
intervals in month	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mixing Unit																																				
Extrusion Unit 1		9			8			6			7				5			8				3								9				6		
Calendering Unit 1																								9												
Primering Unit 1															1																3					
Rolling Unit 1																																				
Extrusion Unit 2			8						4				5					5			6				7			8				4				7
Calendering Unit 2																																		6		
Primering Unit 2																	1																			9
Rolling Unit 2																																				
Printing and Varnishing																										5										
Slitting Unit							3								9											1								8		
Pulverizing Unit													9																5							
Packaging Unit								1							3								4							6						9
Grinding Unit										1											1											6				
Utility Unit																							7													

We've divided each month into three intervals, please fill in the related blank space which failure has happened by the day related to the period

FIGURE B.3: Failure statistic 2012

- Failure occurrence for year 2013

Month	January			february			march			april			may			june			july			august			september			october			november			december		
intervals in month	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mixing Unit																										4										
Extrusion Unit 1						4	8				9					3						1	9			5				4		8		5		
Calendering Unit 1														3																		1				
Primering Unit 1														2																			4			
Rolling Unit 1																																				
Extrusion Unit 2									4				1				6			4			2				1		7		5		7			
Calendering Unit 2																			9																	
Primering Unit 2																1																		7		
Rolling Unit 2																																				
Printing and Varnishing																												9								
Slitting Unit										4									7											9						9
Pulverizing Unit						1												4													2					
Packaging Unit					6							4								7									6						9	
Grinding Unit					9								1						9									1								1
Utility Unit																			6																	

İnstruction: We've divided each month into three intervals, please fill in the related blank space which failure has happened by the day related to the period

Figure B.4: Failure statistic 2013

- Failure occurrence for year 2014

Month	january			february			march			april			may			june			july			august			september			october			november			december		
İntervals in month	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mixing Unit								2								5										4							4			
Extrusion Unit 1				8			7						3				4					4			7				8			1	6			
Calendering Unit 1											7										2								5							9
Primering Unit 1																6																		3		
Rolling Unit 1																																				
Extrusion Unit 2	3					9								2			4						7				1	6			8					
Calendering Unit 2														7																	7					
Primering Unit 2																			5																	9
Rolling Unit 2																																				
Printing and Varnishing							5									6							9						5							1
Slitting Unit									5									9									3								1	
Pulverizing Unit											1										7												6			
Packaging Unit			5					6					3							3																
Grinding Unit						8						9						5							7							1				
Utility Unit																4																				

İnstruction: We've divided each month into three intervals, please fill in the related blank space which failure has happened by the day related to the period

FIGURE B.5: Failure statistic 2014

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