AALBORG UNIVERSITY
STUDENT REPORT

P1 Project
Software

Prediction of Manufacturing Processes

A Program that Solves a Problem

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Preface

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1 | Introduction

Today, basically every product used, touched, or seen is something that initially started out as one or sometimes thousands of raw materials. These products have all been manufactured. Manufactured meaning something made from raw materials by hand or machinery [1].

In Figure 1.1 the global manufacturing value added as percent of GDP (gross domestic product) is illustrated. Manufacturing value added of an economy is the estimate of net output of the manufacturing sector obtained by adding up outputs and subtracting intermediate inputs. In the last 18 years the global manufacturing value added as percent of GDP has been fairly steady between 15.2% and 17.4%. Hence, manufacturing is an essential part of the global economy.

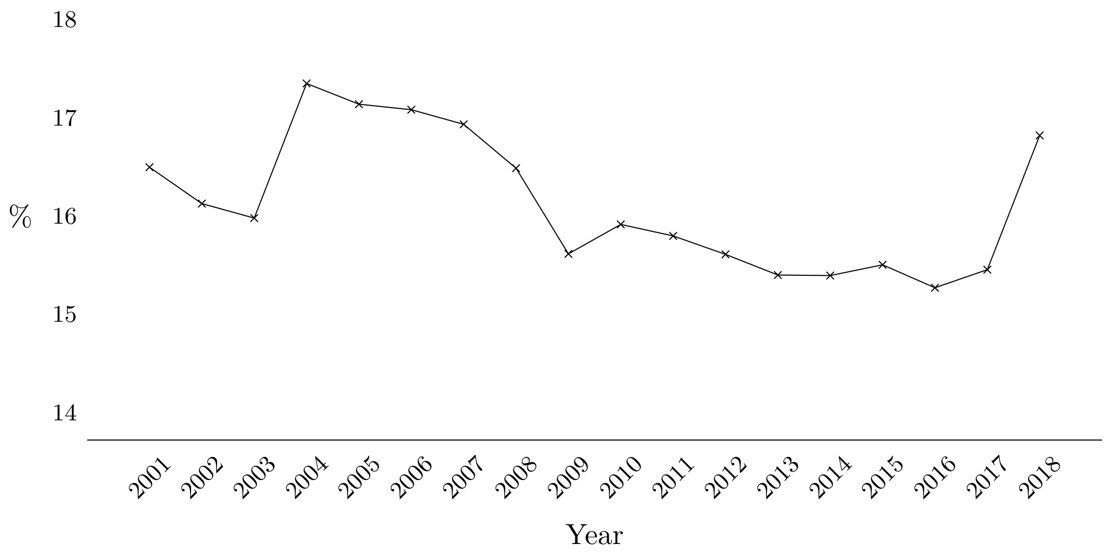

Figure 1.1: Global manufacturing value added as percent of GDP [2].

Since manufacturing is such an extensive part of the global economy, it is obviously a vast industry. Furthermore, manufacturing does not come without unnecessary expenditures and waste. For instance, in manufacturing significant amounts of physical waste is generated during the making of goods. In Figure 1.2 it is illustrated that the generation of waste from manufacturing constitutes 21.1% of the total waste generation from industries in EU. Specifically, the generation of waste in manufacturing includes the waste generated from manufacturing of foods, textiles, wood, paper, coke, chemicals, metals, electronics, transport equipment, and other machinery.

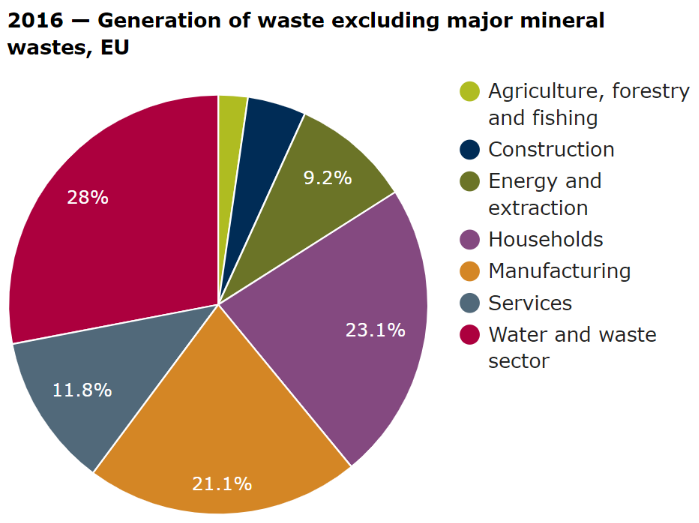

Figure 1.2: Waste generation from industries in EU [3].

Physical waste is not the only form of waste emerging in manufacturing systems. Whilst physical waste is easily measured, other forms of waste in manufacturing are equally important to consider when on the subject of manufacturing. These include human labour and the wear and tear of machines, as well as concepts such as time-efficiency and inventory management. The majority of these different types of waste are related to the effectiveness of the manufacturing

In order to understand how these different types of waste are expressed in manufacturing, as well as how to model manufacturing systems with the intent of exposing whereby and to what degree the different types of waste are generated, it is important to understand the different types of manufacturing systems and how the different types of waste are categorised.

1.1 Manufacturing

The following section is based on the source [4, Ch. 1].

Manufacturing is the action of producing a product from mostly raw materials, adding value in the process. This is done through use of human labour as well as machines and equipment, that carry out a broad range of actions in a predetermined order to produce the product. In today's world, this leads to the rather broad definition:

"[Manufacturing is] the making of products from raw materials using various processes, equipment, operations and manpower according to a detailed plan that is cost-effective and generates income through sales."

The manufacturing of a product is often described in a manufacturing system, which is just a series of processes, machines, etc. set together in such a way that they manufacture a product.

However, these broad definitions do not say a lot about how manufacturing is carried out in the real world. Since there is a variety of products being manufactured, many different manufacturing systems are used to describe different techniques and approaches to manufacturing. This leads to two basic categories of manufacturing systems, namely:

1. Continuous process manufacturing.

2. Discrete parts manufacturing.

1.1.1 Continuous Process Manufacturing

Continuous process manufacturing deals with continuous processes such as those found in the making of petroleum, steel, or sugar, where the product physically flows. This is sometimes confused with flow production, another term for mass production, which just refers to the fact that the assembly line is always running, and not the state of the product. Production in continuous process manufacturing often involves the use of chemicals in various stages of the production, and might also involve mechanical means, all aiding in what is basically mixing the product following a recipe. However, it is important to note that no discrete product is made during processing as the product is ever changing until finally being complete, and instead the outcome of this type of manufacturing system is often measured in volume or weight. Continuous process manufacturing often results in specialised equipment operating 24 hours a day to make the exact same product, which makes this type of manufacturing system highly specialised, thus not very flexible.

1.1.2 Discrete Parts Manufacturing

Discrete parts manufacturing deals with countable objects such as cars, toys, furniture, and the likes. These products all have the property in common of being countable. The production of discrete parts, as opposed to continuous, also allows for customisation of specific products to a certain degree, as well as the ability to order anywhere from one to many millions of the product at a time, instead of always having continuous flow.

Discrete parts manufacturing is often further broken down into systems as shown in Figure 1.3. This figure also includes continuous manufacturing, which is not a type of discrete manufacturing. These different systems mainly describe the relationship between quantity and variety of the product, where larger quantities lead to less variety, and the other way around.

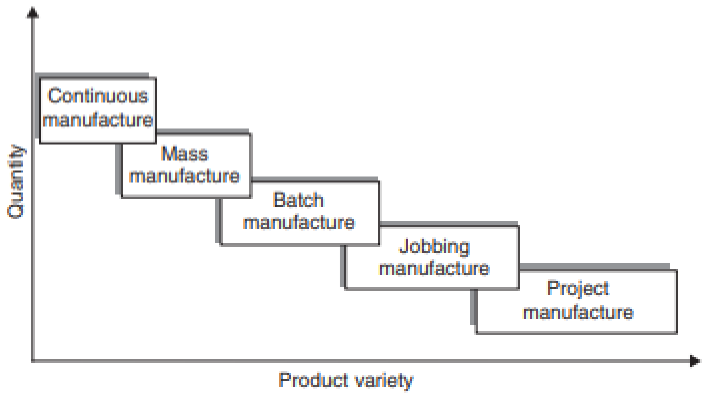

Figure 1.3: Quantity vs. product variety in the different production systems [4, Figure 1.9].

As seen in Figure 1.3, some of these different varieties of discrete manufacturing are as follows:

- Job manufacture.
- Batch manufacture.
- Mass manufacture.

Further explanation of these specific discrete manufacturing systems will be provided, as well as insight in what this means for the workforce and tools needed to manufacture products using these systems.

1.1.3 Mass Manufacturing

Mass manufacturing is all about producing high rates of a specific product. To do this, specialised equipment and processes are used, which in turn means that the workforce has a lower skill level, due to this specialised nature of the machines used in mass manufacturing. Machines in mass manufacturing are often arranged in a specific sequence to carry out their exact function one after another. To accomplish this, conveyor belts are often used to carry individual devices through the different machines in a predetermined sequence. This results in a sharp contrast to job manufacture, where an individual person can craft the entire product himself.

Mass manufacturing instead focuses on specialising individual processes in the making of the product and distributing these processes to different machines. This is much alike batch manufacturing, only on a larger scale with larger quantities and less variety. Mass manufacture is used to produce products which normally require a more steady output flow than batch manufacture, which is why it is also referred to as flow manufacturing.

1.1.4 Batch Manufacturing

Job manufacturing and batch manufacturing have quite a few similarities and are therefore often confused with one another. Normally batch manufacturing is a production of medium size lots. These lots are approximately 5-1000 units, and sometimes even more. The difference between job manufacturing and batch manufacturing is not the number of components nor the number of lots, however, it is how the manufacturing itself is conducted. With batch manufacturing similar items are produced together and each batch of components goes through one stage of the manufacturing process before going into the next stage. An example of batch manufacturing could be in a bakery where buns are prepared together, baked together, and they always stay together throughout the process.

1.1.5 Job Manufacturing

Job manufacturing is, as seen in Figure 1.3, a manufacturing system that focuses on variety and customisability as opposed to quantity. This means that lot-sizes are small, but the finished products are often unique. Manufacturing a lot of unique products requires machinery and tools which are non-specific, so they may be used for different purposes when producing different products. However, this requires the workforce to be highly skilled since they must fulfill different assignments depending on the specific variety of a product being manufactured. The same person might also be the one to make an entire individual product.

1.1.6 Project Manufacturing

The characteristics of project manufacturing are the layout of the work. The product remains in the same position through the whole process, whereas in other manufacturing processes it typically physically moves through the different phases of the manufacturing process. The reason for the product being in the same place, is usually because of its size and weight. These types of products usually have a low production rate. The workers, tools and equipment used to produce these products are gathered around the product. Subparts of the product might be manufactured outside of the manufacturing process, but are used as components in the process. The workers working on the product are usually highly able, and the handling of materials often requires a certain skill level as well. Examples of this manufacturing process are ships, buildings, bridges etc. As seen in Figure 1.3, there is a lot of variety in the products rather than quantity.

1.2 Manufacturing Effectiveness

One downside of the manufacturing industry is all the physical waste that is generated when raw materials are transformed into consumer goods. Some types of physical waste include various metals, oils, and chemicals, which may be hazardous and consequently dangerous. However, waste within the manufacturing industry is not limited to only physical waste. Non-physical waste also exists, and normally occurs during the manufacturing process. Non-physical waste is often referred to as anything that causes a time overrun or cost overrun. The awareness of the problems that lie within non-physical waste, has led to the creation of different methodologies that are targeted towards streamlining manufacturing processes and reducing waste. The most commonly heard of methodology within the bounds of manufacturing systems is Lean Manufacturing.

1.2.1 Lean Manufacturing

The term Lean Manufacturing refers to the application of Lean practices, principles, and tools to the development and manufacture of physical products. For many people, the term Lean manufacturing is synonymous with waste removal. But the ultimate goal of practicing Lean manufacturing is not simply to eliminate waste, instead it is to sustainably deliver value to the customer. To achieve that goal, Lean manufacturing describes waste as anything that requires an investment of time, money, or talent that does not create value for the customer [5].

One of the first people credited with introducing Lean practices at the workplace is the founder of Ford Motor Company, Henry Ford. Ford streamlined the process of manufacturing the Model T car by arranging workers, machines, parts, and tools in a continuous system. However, it was not until the 1930's that Toyota came up with the modern concept of Lean Manufacturing, when they invented the Toyota Production System (TPS). Toyota initiated the idea of "manufacturing to order" instead of "manufacturing to fill warehouses", because they realised products piled in warehouses without buyers were no more than just wastage. It made financial sense to base production targets on actual sales. This style of manufacturing eventually became known as Just-in-time (JIT) manufacturing [6].

TPS explicitly defines seven types of waste, which continues to be relevant in Lean manufacturing today. They are often referred to as TIMWOOD [7]:

- **Transport**
  Transportation of a product does not add any value to the product and is not a part of the manufacturing process, but it is a crucial part of the delivery of a product, hence, it can not be separated from the process.

- **Inventory**
  Unnecessary stock can be a result of overproduction. The company has bought too many materials, finished goods lying around, etc. These items are piling up in the storage and taking up too much unnecessary space.

- **Motion**
  Unnecessary movement is movement of humans and/or machines, that are inefficient, e.g. grabbing a heavy object of the floor, instead of doing it from an appropriate height. Lifting it from an appropriate height would put less strain on the person and make the activity faster and more effective. Another waste of movement is travel time between work posts.

- **Waiting**
  If everything in the manufacturing process is not working optimally at the same time, e.g. damaged machines, inefficient manufacturing methods, insufficient amount of materials, etc. This may result in the workers having to wait. Often workers are spending a lot of time waiting for experts to fix the machines, waiting on supplies and so forth, so that they are able to go back to work.

- **Overprocessing**
  Overprocessing is the usage of unsuitable techniques, unfitting tools, doing processes that are not needed by the customer, etc. All of the above are very unnecessary and will cost time and money in the end.

- **Overproduction**
  If a company is manufacturing too many products for the users, it will result in an overuse of materials, energy, and human work.

- **Defects**
  When a defect occurs, actions must be taken in order to fix the problem. This may result in waste of material, energy, rescheduling, paperwork, losing a customer, etc.

Elimination or reduction of the seven types of waste mentioned above is crucial for any manufacturing company, and if successfully done, it would lead to a more time and cost efficient production.

A variety of tools have been created to reduce waste in Lean Manufacturing, these are called Lean tools [8]. Some of the most popular tools being 5S, the 8-Step Problem Solving Process, OEE and so forth. While many of these tools primarily focus on eliminating or reducing waste, OEE's focus lies primarily on effectiveness. However, a consequence of increasing the effectiveness of a manufacturing process often results in a reduction of waste.

1.2.2 Overall Equipment Effectiveness

Overall Equipment Effectiveness, referred to as OEE, has been well known in the manufacturing industry since the 1980s and the concept itself originated from Japan. In the end of the 1990s, OEE became more accessible and feasible for companies in the western part of the world after two books on the subject of OEE, titled "OEE Toolkit" and "OEE for Operators", were published. The books were the first to ever be written about OEE, and both books are still very suitable today to get a quick insight on the subject [9].

OEE is a metric used by manufacturing companies to identify the effectiveness of their production line. OEE is based on availability, performance, and quality. This is often associated with companies that want to improve their production. Manufacturing companies make use of OEE as a benchmark to see where there is place for improvement. With the OEE metric, manufacturing companies figure out the percentage of waste within planned production time, run time, net run time and fully productive time. In general, OEE can be used to measure progress in eliminating waste from a given production asset [10].

OEE is based on the three most significant factors for manufacturing losses. These are availability, performance, and quality. OEE is based on calculations of these factors and is a number from 0% to 100%, where an OEE of 100% would be described as a perfect production.

Availability is the measure of how much time the manufacturing equipment is available. This measure considers all events that stop the planned production. These events are, for instance, equipment failures, material shortages, and planned stops. The availability is calculated as the ratio

$$\text{Availability} = \frac{Run\,time}{Planned\,production\,time},$$

where $Run\,time = Planned\,production\,time - Stop\,time$.

Performance is the measure of the ability of the manufacturing to operate at the ideal possible speed. Events that could inhibit the performance are, for instance, poor quality of raw materials, wrong temperatures, or wear and tear. The performance is calculated as

$$\text{Performance} = \frac{Ideal\,cycle\,time \cdot Total\,count}{Run\,time},$$

where $Ideal\,cycle\,time$ is the ideal time to manufacture one piece and $Total\,count$ is the total amount of manufactured pieces.

Quality is the measure of how many manufactured pieces that meet the quality standard. Pieces that do not meet the quality standard includes pieces that are reworked, downgraded, or defects. The quality is calculated as the ratio

$$\text{Quality} = \frac{Good\,count}{Total\,count}.$$

Finally, the OEE, which takes into account the availability, performance, and quality resulting in an overall measure of the truly productive manufacturing time, can be calculated as

$$\text{OEE} = \text{Availability} \cdot \text{Performance} \cdot \text{Quality}.$$

By substituting in Equation 1.2.2, Equation 1.2.2, and Equation 1.2.2, the OEE can be calculated as

$$\text{OEE} = \frac{Ideal\,cycle\,time \cdot Good\,count}{Planned\,production\,time}.$$

1.2.3 Implementation of OEE

There are many companies such as Vorne Industries, Amper [11], Sistemas OEE [12], and OAL [13] that sell both hardware and software solutions to improve manufacturing effectiveness. All these companies use OEE as a tool to monitor and improve manufacturing lines with their own hardware and software solutions.

Vorne Industries, for instance, is a company that specialises in OEE calculations for the purpose of improving the efficiency of manufacturing companies. Vorne has accomplished this by developing a tool known as XL Productivity Appliance. This tool can be applied to any manufacturing system to track production and monitor lost time. The data XL collects can be analysed immediately with built-in reports like OEE, top losses, down time, and total production timeline. The data can be visualised with live dashboards that can be customised by the user [14].

Based on the continuance of different companies whose focus lies on improving manufacturing effectiveness, it can be concluded that keeping track of manufacturing numbers is essential for a company. However, having the ability to forecast future OEE results and other manufacturing numbers would allow a company to make manufacturing changes without having to look at real-time manufacturing numbers. This can be accomplished by the use of simulation.

1.3 Simulation

"Imitation of a situation or process." such is the definition of simulation [15]. Simulation can be used for many things and in many different ways, the applications range from computer simulations to real life simulations and virtual simulations [16].

Real life simulations are, for example, drills in the military where instead of sending the soldiers directly into a battlefield without any prior experience, an environment is simulated to resemble a battlefield. By simulating different scenarios and environments, experience can be gained without any direct danger or a need to be at the exact location. This is also why environments resembling the conditions of space is created for astronauts, since it is very expensive to send humans into space.

Virtual simulations however are virtual environments generated from a computer to resemble an environment which can be directly interacted with. This is what is used in games, flight simulators, and virtual reality. In a study conducted by Gregory P. Kratzig, it was discovered that using a simulated firing range with dry-fire laser-based pistols instead of a real firing range and live weaponry, had no effect on if the new cadets could pass the pistol course-of-fire [17].

Computer simulations are used for experimenting and testing, this is where either a real situation or a hypothetical one is simulated with specific parameters, which can be altered and then changes will occur according to the implemented mathematical model, which is used for the simulation. Computer simulations are also used in companies to test a manufacturing system before creating them, to estimate and examine how effective the system performs before implementing it [18].

1.3.1 Simulation of Manufacturing Systems

Manufacturing simulation is the process of using a computer model to understand and improve a real manufacturing system. Simulation technology allows manufacturing companies to analyse and experiment with their processes in a virtual setting, reducing the time and cost of physical testing.

Simulating a manufacturing system ensures that every facet is being carefully considered and optimised. In addition to this, it is also an inexpensive and risk-free way to put a facility to the test, ensuring that production goals and quality standards are being met at the lowest possible cost. Simulation also offers a quick and efficient way to adjust parameters and simulate again, unlike spreadsheet-based analysis and forecasting that requires substantially more manual inputs [19].

In order to create a simulation of a manufacturing system, knowledge of the specific domain that the simulation is imitating is required. Without this knowledge the simulation will be inaccurate. For example, in order to create a quality simulation of a manufacturing system, a person with domain knowledge in manufacturing is needed. In order to acquire the domain knowledge that is needed, a lot of research is required [20].

2 | Problem Statement

Throughout time, the concept of manufacturing has been under constant development, which has led to the creation of different manufacturing methods. Furthermore, different methodologies have been developed to reduce waste within manufacturing, one of the most prominent being Lean manufacturing. Lean builds on the principles of limiting any activity that requires time, money, or talent that does not add value to the customer. A useful metric based on Lean principles is OEE. By computing the OEE it is possible to measure the effectiveness of a manufacturing process. Furthermore, by implementing the OEE measure in a simulation of manufacturing process, it is possible to adjust the parameters of the mathematical model used in the simulation, which allows for analysis of different organisational changes. This leads to the following problem statement:

How is it possible to develop a software solution capable of simulating the OEE of manufacturing processes in order to test organisational changes, thus reducing waste?

3 | System Description

In line with the problem statement, the purpose of this project is to design a software solution that is able to simulate the OEE of manufacturing processes in order to test organisational changes. In this chapter, the software solution based on the aforementioned problem statement will be established.

3.1 Delimitation of the Software Solution

In section 1.1 a description of different manufacturing types was given. Developing a program that can be implemented on all of these manufacturing types (continuous, mass, project, etc.), would require a comprehensive method that takes many different parameters into account. Therefore, the software solution will be narrowed down to mainly target batch and mass manufacturing, since both manufacturing types are similar in many aspects. For instance, mass manufacturing and batch manufacturing are low in product variety. Additionally, both types of manufacturing are high in quantity. Batch manufacturing and mass manufacturing are chosen for this program, because the principles of Lean and implementations of OEE can easily be applied to both manufacturing types.

The simulation in the software solution are delimited to simulating manufacturing models consisting of independent, successive manufacturing processes, contrary to simulating more complex manufacturing models consisting of interdependent processes.

3.2 Visual Representation of System

In order to envision the software solution, a series of flowcharts are presented. The purpose of these flowcharts is to give a visual representation of the software solution. First off, some common symbols need to be clarified in regards to what they represent:

- The oval shape, Figure 3.1, is the symbol for start/stop. It represents the start or end of the program.

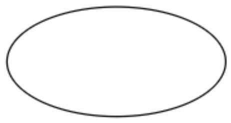

Figure 3.1: Oval shape

- The rectangle, Figure 3.2, represents the call of a function.

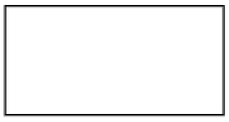
Figure 3.2: Rectangle

- The diamond, Figure 3.3, is the symbol for decisions. This symbol is used to check if a certain condition is true or false.

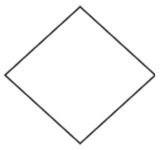
Figure 3.3: Diamond

- The parallelogram, Figure 3.4, is the symbol for input/output. It represents information which the system reads as input or sends as output.

Figure 3.4: Parallelogram

- The circle, Figure 3.5, symbolises the connection between two flowcharts. The character inside the circle indicates which connection to go to.

Figure 3.5: Circle

- The arrow, Figure 3.6, is used to indicate the order that the different functions are called.

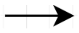
Figure 3.6: Arrow

In Figure 3.7 a representation of the start of the program is illustrated. When the program is executed, the program starts and shows the main menu. The user navigates the program by typing certain numbers. The purpose of the function getch is to circumvent the need to press enter after a number is typed. The user has three options to choose from in the main menu:

- If "1" is typed, the program will run the function modelMenu, which is shown in Figure 3.9.
- If "2" is typed, a manual will be displayed.

- If "9" is typed, the program will shut down.

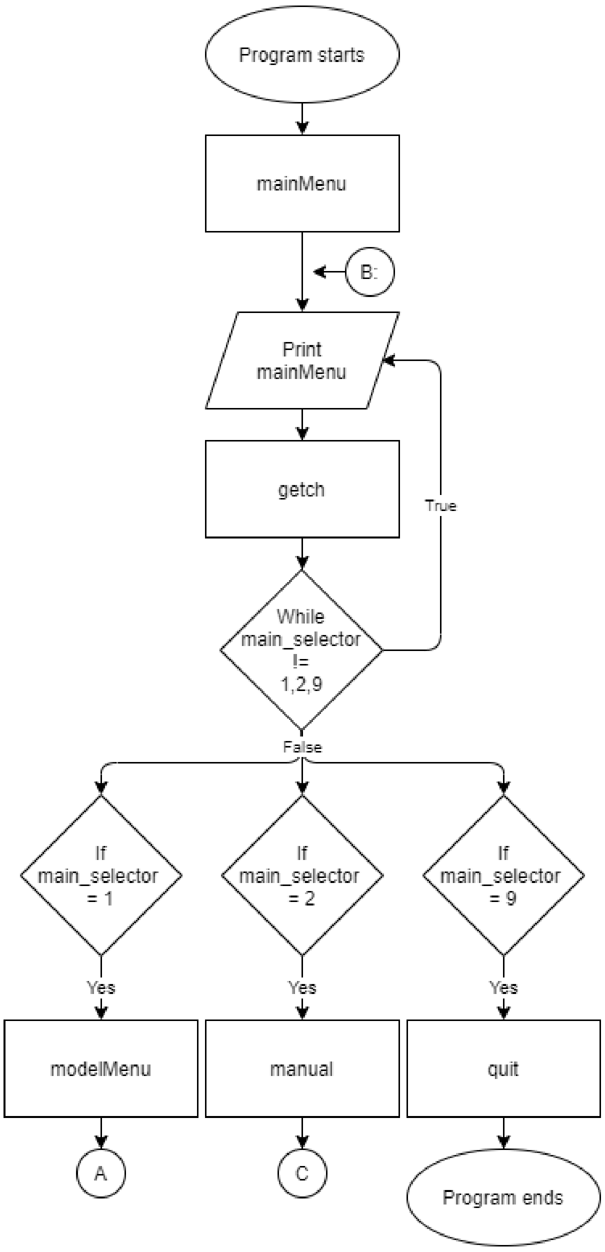

Figure 3.7: Program start.

If the user has chosen the manual, then the printManual function will be called, which prints the manual in the terminal. This part of the program is illustrated in Figure 3.8. From this part of the program, the user has the chose to return to the main menu by typing "1".

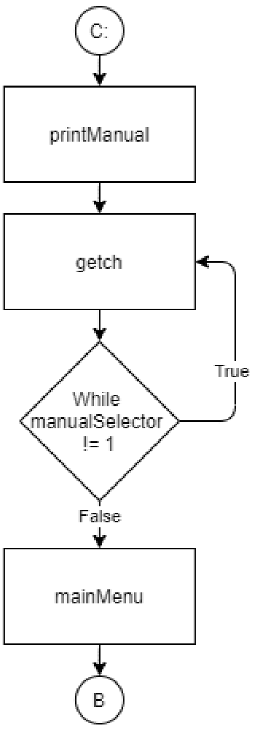

Figure 3.8: Manual.

In Figure 3.9 the modelMenu function, that is called when chosen from the main menu, is illustrated. The modelMenu allows the user to create a visual model of a manufacturing system, by entering the amount of manufacturing processes the system contains. Furthermore, the user has the option to go back to the main menu or go quit the program. This is accomplished by using the modelSelector that gives the user a variety of options:

- If "1" is typed, the user is prompted to enter the amount of manufacturing processes the system contains, and the system will create and display a model in the terminal.

- If "8" is typed, the user is brought back to the main menu.

- If "9" is typed, the program will shut down.

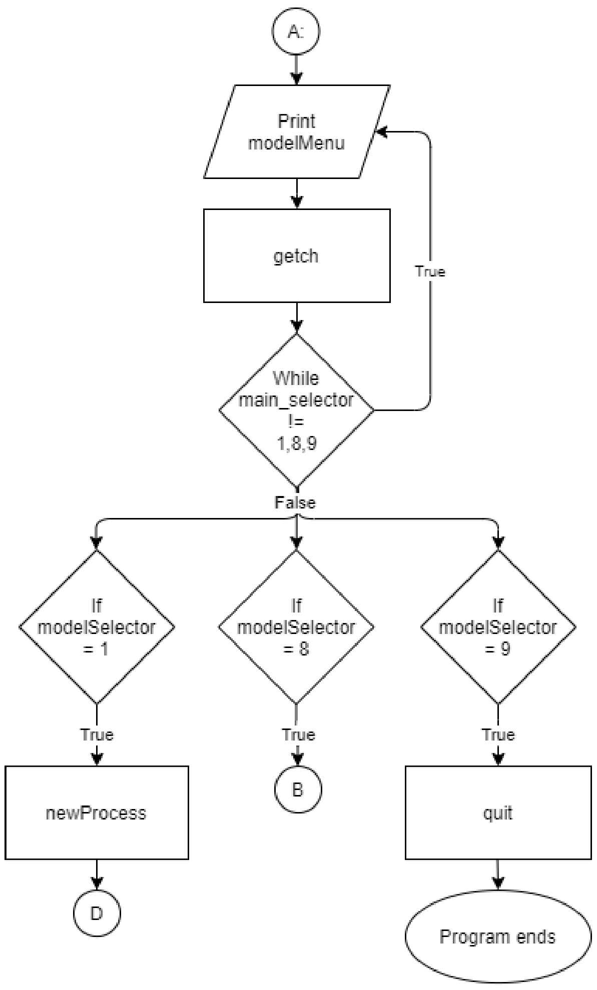

Figure 3.9: Model menu.

As mentioned before, the modelled system will be displayed on the screen after the user has chosen the desired amount of processes. The visual model will be created by the function newProcess. How newProcess works in presented in Figure 3.10. Specifically, each process will be represented by a square, and processes next to each other will be connected with a line.

After the amount of processes has been chosen and the model has been displayed in the terminal, the user has two options to choose from:

- If "1" is typed, the user is brought back to the model menu.

- If "2" is typed, the user goes forward to the next menu, which is the data menu.

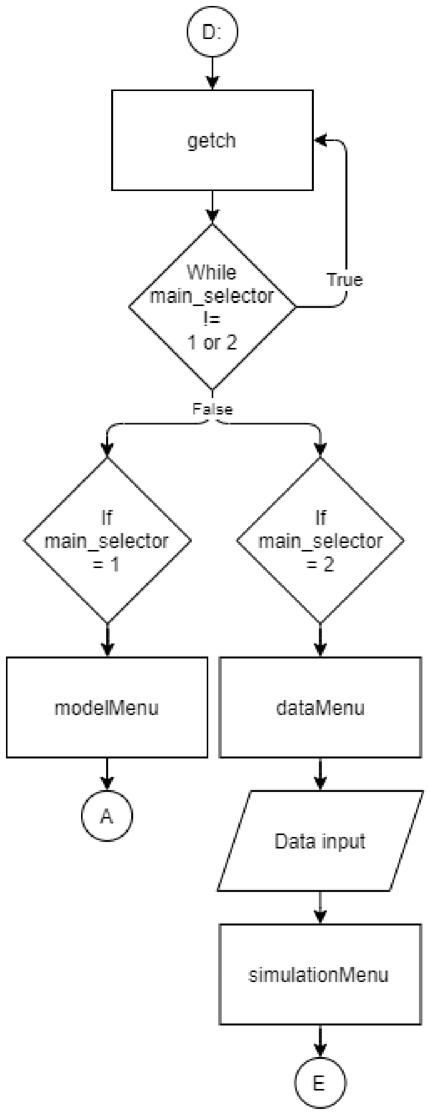

Figure 3.10: New process and data menu.

The data menu is also seen in Figure 3.10. When the user has entered the desired amount of processes, they will be prompted for the required data in the data menu. Upon doing so the simulation menu will be called. Here the menu will be printed as seen in Figure 3.11. The options in the simulation menu are as follows:

- If "1" is typed, the program will run the simulation and print the results.
- If "8" is typed, the program will go back to the data menu.
- If "9" is typed, the program will shut down.

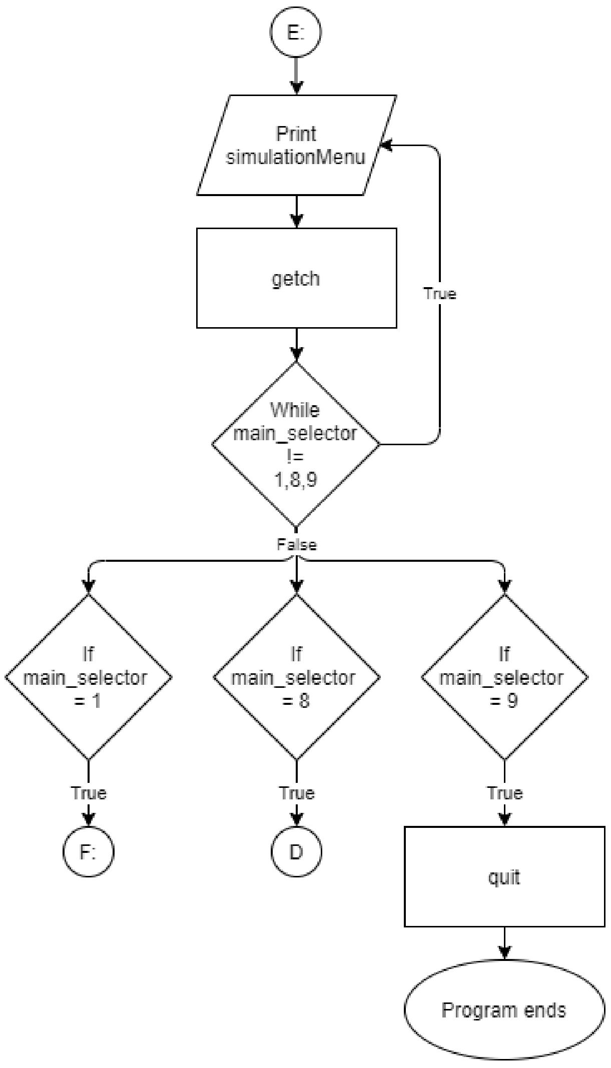

Figure 3.11: Simulation menu.

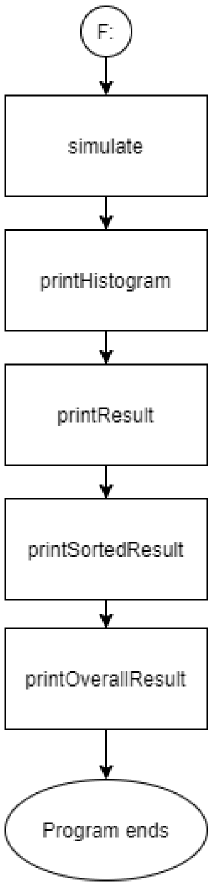

Figure 3.12: Running of simulation and printing of results.

If the user decides to run the simulation and print the results, the part of the program shown in Figure 3.12 is executed. In order to illustrate the results of the simulation, the results of each process will be illustrated in a table. These results include the OEE, availability, performance, and quality. Furthermore, another table will be created which also includes the OEE, availability, performance, and quality for each process, however, in this table the results are sorted using a sorting algorithm. More specifically, the results are sorted based on the OEE to illustrate which part of the manufacturing model is the most ineffective.

At last, the values for OEE, availability, performance, and quality for each process are used to calculate the overall values for OEE, availability, performance, and quality for the entire manufacturing system. The overall values will also be displayed.

3.3 System Requirements

In order to be able to develop the software solution that is described with flowcharts in section 3.2, some more specific requirements for the system are needed. These system requirements are laid out in functional and non-functional requirements. A functional requirement is a description of the service that the software must offer. If these requirements are not met, then the system will not function correctly. A non-functional requirement defines how the system should do it. Therefore, the non-functional requirements do not affect the basic functionality of the system [21].

Functional Requirements

1. Include a simple user interface for navigating the program.
2. Display a manual from a text file.
3. Create and display a manufacturing model consisting of independent, successive manufacturing processes based on user inputs.
4. Assign a probability distribution with parameters to each process in the manufacturing model.
5. Simulate the modelled manufacturing system.
6. Compute the availability, performance, quality, and OEE of each process and the entire model.
7. Sort the results and display them in a table.
8. Exit while not simulating or generating.

Non-functional Requirements

1. Navigate the program with input from a keyboard without the necessity to press the enter key.
2. Perform the simulation at least 100,000 times.

4 | Probability Theory

This chapter is based on [22].

Randomness is what happens in a situation where it is not possible to predict the outcome with certainty. The area of mathematics concerned with randomness is probability theory.

The purpose of this chapter is to get a basic understanding of probability theory. This theory will be used in the development of the software solution of this project. More specifically, it will be utilised in the simulation of manufacturing processes, where certain probability distributions are needed to simulate the outcome in terms of defective pieces and unplanned stops.

4.1 Sample Spaces and Events

Probability theory is used to describe different situations where randomness is present. Such situations will be referred to as random experiments. The result of a random experiment will be referred to as an outcome. For any given random experiment, there is a set of possible outcomes. The following is a definition of the aforementioned set.

Definition 4.1 (Sample Space)
The set of all possible outcomes in a random experiment is called the sample space, denoted S.

[22, p. 3]

Example 4.1 Consider the random experiment where a die is rolled and the number is observed. In this case the possible outcomes are the numbers 1 through 6, hence the sample space is

$$S = \{1,2,3,4,5,6\}.$$

$\triangle$

The sample space is the set of all possible outcomes. However, when computing probabilities it is often desired to compute the probability of a single outcome or groups of outcomes. The subset of a single outcome or a group of outcomes is defined below.

Definition 4.2 (Event)
A subset of S, $A \subseteq S$, is called an event.

[22, p. 5]

Example 4.2 Consider again the random experiment where a die is rolled and the number is observed. Two events that are possible in this case are to get an even outcome and roll at least 5. The two subsets of the sample space that the two aforementioned events respectively create are

$$A = \{2{,}4{,}6\} \quad \text{and} \quad B = \{5{,}6\}.$$

Alternatively, the two sets can be written with a verbal description as

$$A = \{\text{even outcome}\} \quad \text{and} \quad B = \{\text{at least } 5\}.$$

△

4.2 The Axioms of Probability

In the previous section the basis needed to describe random experiments in terms of sample spaces, outcomes, and events are presented. In this section the basis needed to be able to compute probabilities are presented. This basis is a definition of probability in terms of a real-valued function, which satisfies three properties referred to as the axioms of probability.

Definition 4.3 (Axioms of Probability)
A probability measure is a function P, which assigns to each event A a number $P(A)$ satisfying

1. $0 \leq P(A) \leq 1$
2. $P(S) = 1$
3. If $A_1,A_2,\ldots$ is a sequence of pairwise disjoint events, that is, if $i \neq j$, then $A_i \cap A_j = \emptyset$, then
$$P(\bigcup_{k=1}^{\infty} A_k) = \sum_{k=1}^{\infty} P(A_k)$$

[22, p. 7]

As seen in Definition 4.3 there are three different axioms of probability. The first axiom is that the probability of any event at least 0 and at most 1, which implies that the probability of any event is a nonnegative number. The second axiom is that the probability of the entire sample space is 1, which implies that that the sample space encompasses every possible outcome of a random experiment. The third and last axiom is that if some events are disjoint, then the probability of their union equals the probability of the summation of the probability of each event.

4.3 Discrete Random Variables

A convenient notation utilised to denote different outcomes of specific events is a random variable X. The value of the quantity X is thus not known before an experiment, but it becomes known after.

Definition 4.4 (Random Variable)
A real-valued random variable X is a function from the sample space S to $\mathbb{R}$ ($X : S \to \mathbb{R}$).

The definition of the random variable allows for the notation of an event as $\{X = x_k\}$ and, therefore, the notation of a probability measure as a function of an event as $P(X = x_k)$, where x_k is some outcome in the range of X.

Example 4.3 Consider once more the random experiment where a die is rolled, but let this time X denote the number. Then the range of X is $\{1,2,3,4,5,6\}$ and the associated probabilities are

$$P(X = 1) = P(X = 2) = P(X = 3) = P(X = 4) = P(X = 5) = P(X = 6) = \frac{1}{6}.$$

$\triangle$

Random variables are primarily distinguished between as random variables with countable range and random variables with uncountable range.

Definition 4.5 (Discrete Random Variable)
If the range of X is countable, then X is called a discrete random variable.

[22, p. 78]

When computing probabilities $P(X = x_k)$ for various values x_k in the range of X, it is convenient to view $P(X = x_k)$ as a function, which leads to the following definition.

Definition 4.6 (Probability Mass function)
Let X be a discrete random variable with range $\{x_1,x_2,\dots\}$ (finite or countably infinite). The function

$$p(x_k) = P(X = x_k), \quad k = 1,2,\dots$$

is called the probability mass function (pmf) of X.

[22, p. 78]

Example 4.4 Consider the random experiment of flipping a coin three times and let X denote the number of heads. Then the range of X is $\{0,1,2,3\}$ and the corresponding values of the pmf are

$$p(0) = \frac{1}{8}, p(1) = \frac{3}{8}, p(2) = \frac{3}{8}, p(3) = \frac{1}{8}.$$

$\triangle$

So far only events of the type $\{X = x_k\}$ have been considered. Another type of event is the type $\{X \leq x_k\}$, which is the event that X is less than or equal to some outcome x_k. The probability of such an event is also defined as a function.

Definition 4.7 (Cumulative Distribution Function)
Let X be any random variable. The function

$$F(x) = P(X \leq x), \quad x \in \mathbb{R}$$

is called the cumulative distribution function (cdf) of X.

[22, p. 80]

Example 4.5 Consider the aforementioned random experiment again, which is flipping a coin three times and letting X denote the number of heads. The range of X is $\{0,1,2,3\}$, and the corresponding values of the cdf are as follows.

$$F(0) = P(X \leq 0) = p(0) = \frac{1}{8},$$

since the only way to be less than or equal to 0 is to be 0. The next value $F(1) = P(X \leq 1)$ is equal to

$$p(0) + p(1) = \frac{1}{8} + \frac{3}{8} = \frac{1}{2},$$

since the events are disjoint, which then allows, by the third axiom of probability, a summation of the probability of each event. The values $F(2) = \frac{7}{8}$ and $F(3) = 1$ are computed likewise. $\triangle$

Some properties of the cdf that apply for any random variable are described in the following theorem.

Theorem 4.8
Let X be any random variable with cdf F. Then

1. $P(a < X \leq b) = F(b) - F(a), \quad a \leq b$
2. $P(X > x) = 1 - F(x). \quad x \in \mathbb{R}$

[22, p. 84]

4.4 Continuous Random Variables

As mentioned before, random variables are distinguished by their range. A discrete random variable has a countable range, whereas a continuous random variable has an uncountable range. However, this is not sufficient to define a continuous random variable.

Definition 4.9 (Continuous Random Variable)
If the cdf F is a continuous function, then X is said to be a continuous random variable.

[22, p. 83]

The cdf is defined identically for discrete and continuous random variables. For discrete random variables the pmf is also defined, which is a function that assigns probabilities for values in the range of a discrete random variable. The continuous analogy to this function is the probability density function.

Definition 4.10 (Probability Density Function)
The function $f(x) = F'(x)$ is called the probability density function (pdf) of X.

[22, p. 84]

In Figure 4.1 the relation between a pdf and the corresponding cdf is illustrated. In accordance with Definition 4.10 the pdf follows the slope of the cdf.

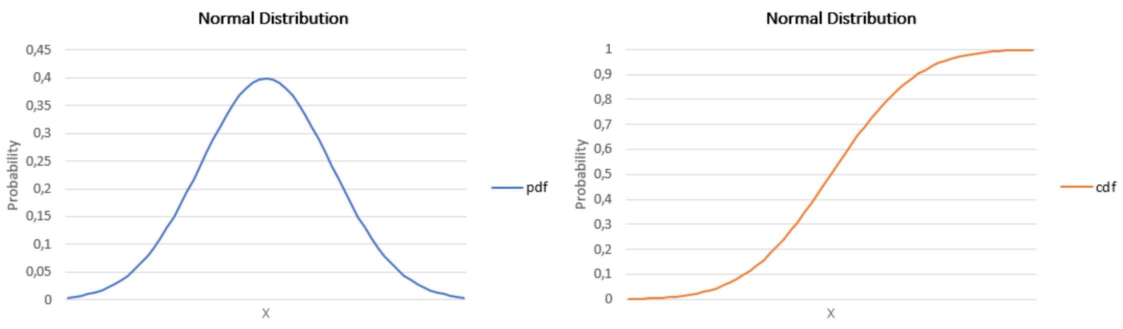

Figure 4.1: A pdf and the corresponding cdf.

4.5 Probability Distributions

A probability distribution is a function that gives the probability of the different possible outcomes of a random experiment or event. Some important terms needed in order to describe some different probability distributions are now presented.

Definition 4.11 (Expected Value)
Let X be a continuous random variable with pdf f. The expected value of X is defined as

$$E[X] = \int_{-\infty}^{\infty} x f(x) dx.$$

[22, p. 98]

The expected value is a generalisation of a weighted average. The expected value is sometimes denoted by μ. The integral limits are $-\infty$ and ∞, however when applying the definition in practice, the limits are determined by the range of X. It is necessary to choose limits such that $f(x)$ is positive between the limits and not outside of the limits.

The expected value gives information on where X is on average. To get more information about a probability distribution, a measure for the variability of the random variable is beneficial. This variability of a random variable is called the variance.

Definition 4.12 (Variance)
Let X be a random variable with expected value μ. The variance of X is defined as

$$Var[X] = E[(X - \mu)^2].$$

[22, p. 105]

The variance is sometimes denoted as σ^2.

Since the values of $Var[X]$ are squared, they do not express the same unit of measure as the data. Thus, the following definition is often used.

Definition 4.13 (Standard Deviation)
Let X be a random variable with variance $\sigma^2 = Var[X]$. The standard deviation of X is then defined as $\sigma = \sqrt{Var[X]}$.

[22, p. 105]

A probability distribution, where the probability of each outcome is equivalent, is called a uniform distribution. The pdf is in this case constant on an interval.

Definition 4.14 (Uniform Distribution)
If the pdf of X is

$$f(x) = \frac{1}{b-a}, \quad a \leq x \leq b$$

then X is said to have a uniform distribution on $[a,b]$, written $X \sim$ unif$[a,b]$.

[22, p. 91]

In Figure 4.2 the pdf of a uniform probability distribution is illustrated.

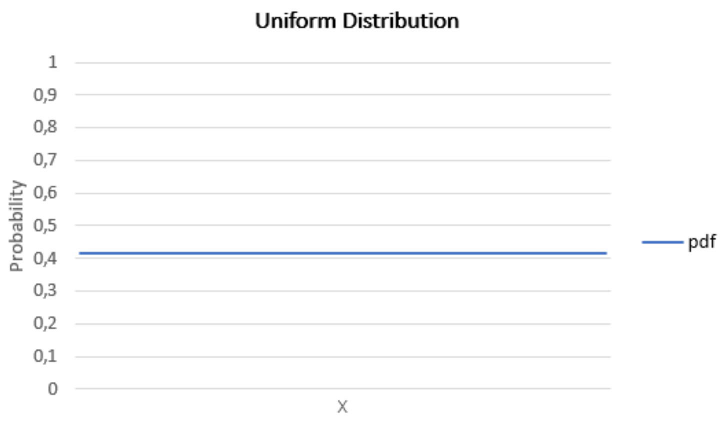

Figure 4.2: The pdf of a uniform probability distribution.

The following probability distribution is a distribution that pertains to a huge variety of situations. For instance, it is often applied in situations where there are measurement errors due to randomness or noise [23] or used describe the behaviour of stock market prices [24]. Furthermore, it can, for instance, be used to describe data from pharmaceutical manufacturing processes [25].

Definition 4.15 (Normal Distribution)
If X has the pdf

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}, \quad x \in \mathbb{R}$$

it is said to have a normal distribution with parameters μ and σ^2, written $X \sim N[\mu,\sigma^2]$.

[22, p. 127]

In Figure 4.1 the pdf of a normal distribution is illustrated.

The pdf of the normal distribution is symmetric around the expected value μ.

Theorem 4.16
If $X \sim N[\mu,\sigma^2]$, then $E[X] = \mu$ and $Var[X] = \sigma^2$.

[22, p. 128]

Note that the second parameter, in the definition of the normal distribution, is the variance. In some other cases the normal distribution is defined with the standard deviation as the second parameter.

Another probability distribution is the exponential distribution. This type of probability distribution is applicable for modelling processes that involve time interval between events. This could, for instance, be the time interval between two manufacturing processes [26].

Definition 4.17 (Exponential Distribution)
If the pdf of X is

$$f(x) = \lambda e^{-\lambda x}, \quad x \geq 0$$

then X is said to have an exponential distribution with parameter $\lambda > 0$, written $X \sim \exp(\lambda)$.

In Figure 4.3 the pdf of an exponential probability distribution is illustrated.

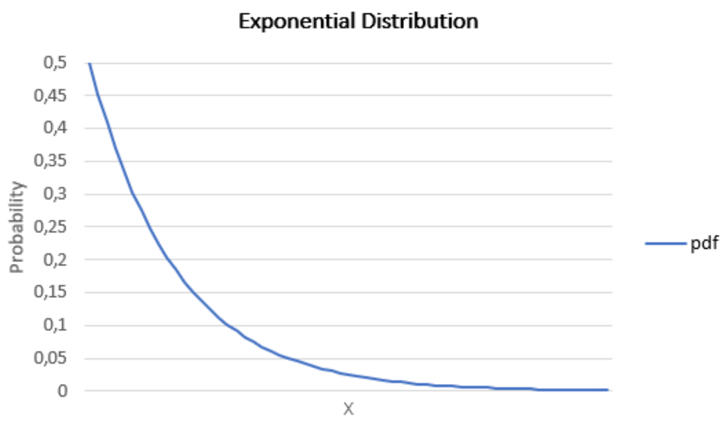

Figure 4.3: The pdf of an exponential probability distribution.

5 | Algorithms

An algorithm is a finite sequence of instructions, which are implementable in a computer, needed to perform calculations or to solve a specific type of problem.

This chapter describes some different algorithms that are needed in order to develop the software solution for this project. These algorithms will be used in the software solution for sorting data, simulating manufacturing processes, and sampling from probability distributions.

5.1 Complexity of Algorithms

This section is based on [27, Ch. 3].

When working with algorithms it is important to be able to assess the computational complexity of the algorithms. The computational complexity is utilised to measure the computer memory and processing time required by the algorithms to solve specific problems of a particular size. Hence, when the computational complexity of different algorithms are obtained, they can be compared in order to determine which is the most efficient.

In order to assess the computational complexity of algorithms, an estimation of the number of operations used by the algorithms is needed. The amount of operations used by an algorithm can be expressed in terms of a function. Big-O notation is used to estimate the amount of operations an algorithm uses with regards to the size of the input.

Definition 5.1 (Big-O Notation)
Let f and g be functions from the set of integers or the set of real numbers to the set of real numbers. We say that $f(x)$ is $O(g(x))$ if there are constants C and k such that

$$|f(x)| \leq C|g(x)|$$

whenever $x > k$.

[27, p. 217]

Big-O notation is used to describe the growth of a function. Particularly, when some function $f(x)$ is $O(g(x))$, the function $f(x)$ is asymptotically bounded by the function $g(x)$. Thus, an upper bound is not ensured for all values of x, but only in the limit.

Example 5.1 Consider the function $f(x) = 2x^2 + 3x + 2$ and assume that it is desired to determine whether $f(x)$ is $O(x^2)$. In order for this to be true, Definition 5.1 has to be satisfied. Hence, there has to exist constants C and k such that

$$|f(x) = 2x^2 + 3x + 2| \leq C|x^2|, \quad \text{for } x > k.$$

It is observed that when $x > 1$ then $1 < x^2$ and $x < x^2$. Furthermore, the absolute values can be omitted since both functions are positive when $x > 1$. Thus, it follows that

$$2x^2 + 3x + 2 \leq 2x^2 + 3x^2 + 2x^2 = 7x^2 \quad \text{for } x > 1.$$

Consequently, the constants can be chosen as $C = 7$ and $k = 1$. $\triangle$

If a lower bound is desired, big-Omega notation can be used.

Definition 5.2 (Big-Omega Notation)
Let f and g be functions from the set of integers or the set of real numbers to the set of real numbers. We say that $f(x)$ is $\Omega(g(x))$ if there are constants C and k with C positive such that

$$|f(x)| \geq C|g(x)|$$

whenever $x > k$.

[27, p. 227]

The constants C and k in Definition 5.1 are referred to as witnesses to the relationship $f(x)$ is $O(g(x))$. The constants C and k in Definition 5.2 are likewise referred to as witnesses to the relationship $f(x)$ is $\Omega(g(x))$.

In order to establish that some function $f(x)$ is $O(g(x))$, it is only necessary to find one pair of witnesses C and k such that $|f(x)| \leq C|g(x)|$ whenever $x > k$. Likewise, to establish that some function $f(x)$ is $\Omega(g(x))$, it is only necessary to find one pair of witnesses $C > 0$ and k such that $|f(x)| \geq C|g(x)|$ whenever $x > k$.

In order to show this, assume, without loss of generality, that C and k are one pair of witnesses to the relationship $f(x)$ is $O(g(x))$. Then, any pair C' and k', where $C < C'$ and $k < k'$, is also a pair of witnesses, since $|f(x)| \leq C|g(x)| \leq C'|g(x)|$ whenever $x > k' > k$. Thus, only one pair of witnesses is needed.

If it is desired to obtain both a lower bound and an upper bound on the size of some function $f(x)$ in respect to a reference function $g(x)$, then big-Theta notation can be applied.

Definition 5.3 (Big-Theta Notation)
Let f and g be functions from the set of integers or the set of real numbers to the set of real numbers. We say that $f(x)$ is $\Theta(g(x))$ if $f(x)$ is $O(g(x))$ and $f(x)$ is $\Omega(g(x))$. When $f(x)$ is $\Theta(g(x))$, we say that f is big-Theta of $g(x)$, that $f(x)$ is of order $g(x)$, and that $f(x)$ and $g(x)$ are of the same order.

[27, p. 227]

Example 5.2 Consider again the function $f(x) = 2x^2 + 3x + 2$, which previously was determined to be $O(x^2)$. Assume now that it is desired to determine whether $f(x)$ is also $\Omega(g(x^2))$. In order to determine this, $f(x)$ has to satisfy Definition 5.2. Hence, there has to exist a pair of witnesses such that

$$|2x^2 + 3x + 2| \geq C|x^2|, \quad \text{for } x > k \text{ and } C > 0.$$

It is obvious to see that by choosing $C = 1$ then the equation is satisfied for all positive real numbers x, thus it suffices to choose $k = 0$.

It has now been determined that $f(x)$ is $O(x^2)$ and $f(x)$ is $\Omega(g(x^2))$, thus by Definition 5.3, $f(x)$ is $\Theta(g(x^2))$. △

5.2 Sorting Algorithms

When working with data, sorting is often applied. Techniques that sort data are known as sorting algorithms [28, p. 134].

A sorting algorithm is an algorithm that puts elements of a list in a certain order. Within computer science sorting algorithms are used to produce more understandable output. Any kind of data set can be sorted. To give an example, the grades from a class of students can be sorted from the highest grade to the lowest grade [29].

Throughout time, a lot of different sorting algorithms have been developed. Some of the different sorting algorithms are listed below:

- Bubble sort
- Selection sort
- Quick sort
- Merge sort
- Heap sort
- Insertion sort

Some of the algorithms have different time complexities. Therefore, some of the algorithms sort faster than others, due to a lower complexity. In Table 5.1 a comparison of the different time complexities is shown.

Algorithm	Best-case	Average-case	Worst-case
Selection sort	$\Omega(n^2)$	$\Theta(n^2)$	$O(n^2)$
Bubble sort	$\Omega(n)$	$\Theta(n^2)$	$O(n^2)$
Insertion sort	$\Omega(n)$	$\Theta(n^2)$	$O(n^2)$
Heapsort	$\Omega(n\log_2(n))$	$\Theta(n\log_2(n))$	$O(n\log_2(n))$
Quicksort	$\Omega(n\log_2(n))$	$\Theta(n\log_2(n))$	$O(n^2)$
Mergesort	$\Omega(n\log_2(n))$	$\Theta(n\log_2(n))$	$O(n\log_2(n))$

Table 5.1: Algorithm and time complexity [30].

As shown in Table 5.1, quicksort is one of the most efficient sorting algorithms. Furthermore, the quicksort algorithm is implemented in the qsort function, which is defined in the standard library in C.

5.2.1 Qsort

The qsort function is designed to sort an array of elements of any data type. The qsort function takes in four parameters in order to sort an array [31]:

- The array that needs to be sorted.

- The total amount of elements in the array.
- The size in bytes of each element in the array.
- A compare function.

The compare function is a boolean function that compares two elements, which determines the order that the array is sorted.

In order to understand the quicksort algorithm that qsort implements, the algorithm is illustrated in Figure 5.1. The figure shows how the quick sort algorithm splits an array into smaller arrays recursively until all the elements are separated in a certain order.

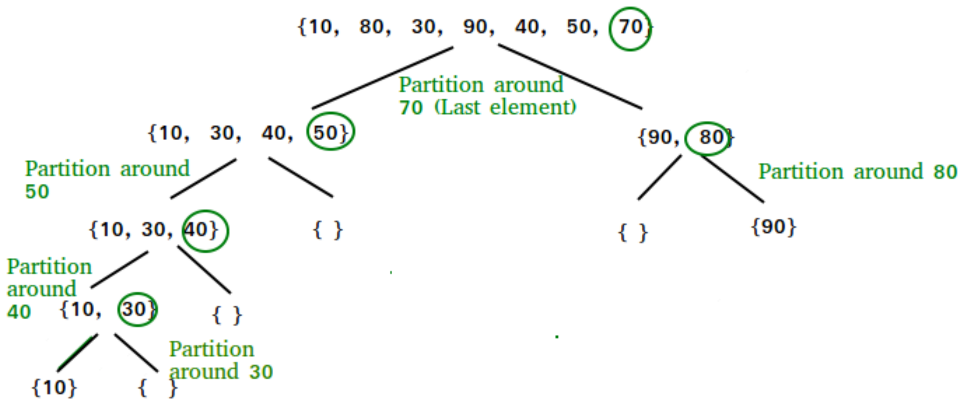

Figure 5.1: Quicksort algorithm graphical [32]

5.3 Monte Carlo Simulation

This section is based on [33, p. 507-508].

Monte Carlo simulation is an algorithm where an experiment is conducted N times and the outcome of each experiment is random. Suppose a certain event occurs M times. Then an estimate of the probability of M occurring can be found as M/N.

Assume that the purpose of an experiment is to count how many times a six is rolled, let this number be denoted by M. If the die is rolled nine times and the outcome, where a six is rolled, occurs three times, then $M = 3$. According to this experiment the probability of rolling a six is estimated to be $M/N = 1/3$. However, the actual probability of rolling a six is 1/6. This discrepancy occurs due to the limited amount of simulations performed.

If the amount of simulations performed is increased, then the estimation of the probability will become more accurate. This is known as the law of large numbers. According to the law, the average of a random experiment approaches the expected value as $N \to \infty$.

5.4 Inverse Transform Sampling

Inverse transform sampling is a method for generating random samples from any probability distribution given its cdf. In order to derive the method of inverse transform sampling, some preliminary theory of functions is needed.

5.4.1 Preliminary Theory of Functions

Functions are also sometimes called transformations. Inverse transform sampling is feasible due to some different properties of the functions that are involved in the method. These different properties are presented below.

The first property is injection. An injective function maps distinct elements of its domain to distinct elements of its codomain.

Definition 5.4 (Injective)
A function f is said to be one-to-one, or an injection, if and only if $f(a) = f(b)$ implies that $a = b$ for all a and b in the domain of f. A function is said to be injective if it is one-to-one.

[27, p. 150]

Another class of functions, that is important for deriving the inverse transform sampling method, is monotone functions.

Definition 5.5 (Monotone Function)
A function $f : A \to \mathbb{R}$, where $A \subseteq \mathbb{R}$, is increasing, if for $x_1, x_2 \in A$ applies that

$$x_1 < x_2 \Rightarrow f(x_1) \leq f(x_2),$$

and strictly increasing if

$$x_1 < x_2 \Rightarrow f(x_1) < f(x_2).$$

Decreasing ($\geq$) and strictly decreasing ($>$) are defined analogously. A function is said to be monotone if it is increasing or decreasing. And a function is said to be strictly monotone if it is strictly increasing or strictly decreasing.

A class of functions, that maps distinct elements of its domain to distinct elements of its codomain, is strictly monotone functions. Hence, strictly monotone functions are injective.

Injective functions have a certain property, which is presented in the following definition.

Definition 5.6 (Inverse Function)
Let f be an injective function from the set A to the set B. The inverse function of f is the function that assigns to an element b belonging to B the unique element a in A such that $f(a) = b$. The inverse function of f is denoted by f^{-1}. Hence, $f^{-1}(b) = a$ when $f(a) = b$.

[27, p. 150]

5.4.2 The Method

The inverse transform sampling method is used to generate random samples from any probability distribution given its cdf. Specifically, the method is used to generate values of a random variable X, whose probability distribution can be described by the cdf $F(x)$, from $U \sim$ unif[0,1]. The advantage of generating numbers from a uniform distribution is, that it can be accomplished in practice with a random number generator. However, in this case the numbers will not be completely random, but pseudorandom.

In order to perform this method, a transformation $T : [0,1] \to \mathbb{R}$, such that $T(U) = X$, is desired. By Definition 4.7 the cdf of X is

$$F(x) = P(X \leq x).$$

Applying that $T(U) = X$ yields

$$P(X \leq x) = P(T(U) \leq x).$$

The transformation T has to be strictly monotone, since the transformation then is injective, and then there exists an inverse transformation of T, which allows for

$$P(T(U) \leq x) = P(U \leq T^{-1}(x)).$$

Since $P(U \leq y) = y$ when $U \sim$ unif[0,1], then

$$P(U \leq T^{-1}(x)) = T^{-1}(x).$$

Thus, the cdf $F(x)$ is the inverse function of T. Therefore,

$$T(u) = F^{-1}(u), \quad u \in [0,1],$$

which means it is possible to generate values of X from $F^{-1}(U)$.

Example 5.3 Assume that it is desired to apply the inverse transform sampling method to generate random samples from the exponential distribution

$$f(x) = \lambda e^{-\lambda x}, \quad x \geq 0.$$

The first step is to obtain the cdf of the exponential distribution. By Definition 4.10 the cdf is obtained by integrating the pdf. The cdf is therefore

$$F(x) = \int_0^x \lambda e^{-\lambda x} = 1 - e^{-\lambda x}.$$

Given the cdf $F(x)$ it is desired to generate values of a random variable X, whose probability distribution is described by the cdf $F(x)$, from $U \sim$ unif[0,1]. Thus, the transformation $T(u) = F^{-1}(u)$ is now needed. The inverse cdf F^{-1} is derived as

$$\begin{aligned} u &= 1 - e^{-\lambda x} \\ 1 - u &= e^{-\lambda x} \\ ln(1-u) &= -\lambda x \\ X &= \frac{-ln(1-u)}{\lambda}. \end{aligned}$$

Hence, it is now possible to generate values of X from $F^{-1}(U) = \frac{-ln(1-u)}{\lambda}$. △

6 | Development of Solution

In this chapter the development of the software solution is detailed. The solution is created based on the system description in Chapter 3. Furthermore, it is developed for the purpose of satisfying the system requirements that are described in Section 3.3.

All figures, that are referred to in this chapter, are situated in Appendix A.

6.1 Description of Solution

This section gives a thorough walk-through of the software solution and specifies the implementations of the functional requirements from section 3.3.

The proposed solution is a software program written in ANSI C and is derived from chapter 3.

6.1.1 User Interface

When the program is executed, the main menu is displayed in the terminal. The main menu consists of three options, as showed in Figure A.1. The user selects one of the three options by using the number keys on the keyboard. Which key to press is indicated to the left of the option. To maintain consistency throughout the program, the "Go back" and "Quit program" options are always accessed through the same keys in all the menus. Additionally, the "Go back" and "Quit program" keys are located far away from the other menu keys to prevent misclicks that would unintentionally quit the program or go back. Modifications like these allows the user to easily navigate through the program. Therefore, requirement 1 is met.

6.1.2 Manual

When "Manual" is chosen from the main menu, the manual will be displayed. The manual includes a description of how the program functions and specifies what data that needs to be obtained before using the program. The manual can be seen in Figure A.2 and Figure A.3.

In section 3.3 requirement 2 is met with the following code shown in Listing 6.1. More specifically, the file is being opened and read on line 9. The file is then being printed when line 17 is initiated.

```
1 void manual(void){
2     int amount_of_processes = 1, total_count = 500;
3     process manual_processes[1];
4     FILE *file_pointer;
5     char c;
6 
7     printf(ANSI_UNDERLINED_PRE"Manual"ANSI_UNDERLINED_POST"\n\n");
```

```

    file_pointer = fopen("manual.txt", "r");
    if(file_pointer == NULL){
        printf("Can not open file \n");
        exit(EXIT_FAILURE);
    }

    c = fgetc(file_pointer);

    while(c != EOF){
        printf ("%c", c);
        c = fgetc(file_pointer);
    }
    fclose(file_pointer);
}
```

Listing 6.1: Code of inserting the manual from text file.

6.1.3 Manufacturing Model

If "Model system" is selected in the main menu, the user is brought to the model menu. From here, the user can open "Model manufacturing system", as shown in Figure A.4. In "Model manufacturing system" the program prompts the user to enter the amount of manufacturing processes the manufacturing system consists of, as shown in Figure A.5.

After entering the amount of manufacturing processes the program will display a manufacturing model of individual successive manufacturing processes, which is showed in Figure A.6.

In Listing 6.2, the code for displaying the manufacturing model is shown. A square of asterisks is printed for each manufacturing process. The number in the middle indicates which manufacturing process the square represents.

```
void newProcess(int *amount_of_processes){
    int i;

    printf("Enter the amount of manufacturing processes: ");
    scanf(" %d", amount_of_processes);
    printf("\n");

    for(i = 1; i <= *amount_of_processes; i++){
        printf("* * * * *\n");
        printf("*       *\n");
        printf("*%4d   *\n", i);
        printf("*       *\n");
        printf("* * * * *\n");

        if(i != *amount_of_processes)
            printf("    |\n");
    }

    printf("\n1. Return to model menu\n");
    printf("2. Finish model");
}
```

Listing 6.2: Code of printing manufacturing model.

After the manufacturing system has been modelled, the user is given two options. The user can either return to the model menu or finish the model. If the user returns to the model menu, the program will initiate the model menu. From here the user can model a new manufacturing system if the first one was not desirable. If finish model is chosen, the user will be prompted to input data for each manufacturing process, as shown in Figure A.7 and Figure A.8.

As shown in Listing 6.2 the program is capable of creating and displaying a linear manufacturing model. Therefore, requirement 3 is met.

6.1.4 Probability Distribution

After entering the total count of products for the entire manufacturing system, the program will prompt for the following values for each process. This is also shown in Figure A.8.

- Planned production time in minutes.
- Ideal cycle time in minutes.
- Type of probability distribution for defects (normal distribution or exponential distribution).
  - Mean and standard deviation if normal distribution is selected.
  - Lambda if exponential distribution is selected.
- Type of probability distribution for unplanned stops (normal distribution or exponential distribution).
  - Mean and standard deviation if normal distribution is selected.
  - Lambda if exponential distribution is selected.

Requirement 4 has been met when the user has successfully assigned values to each manufacturing process.

Inverse Transform Sampling

Listing 6.3 shows the section of the program that performs inverse transform sampling.

The function inv_cdf_normal from line 1 through 3, performs inverse transform sampling of a single sample on an approximation of the inverse cdf of the standard normal distribution. The approximation is then scaled to any normal distribution, by multiplying the standard deviation and adding the mean. There is no closed form expression of the normal cdf, instead an approximation of the inverse cdf of the standard normal distribution was applied. The function that generates the approximation can be found in the C file from the following source: [34]

The function inv_cdf_exponential from line 5 through 7 performs inverse transform sampling of a single sample on the inverse cdf of the exponential distribution.

The function sample from line 9 through 11 generates a sample in the interval [0,1].

```
1 double inv_cdf_normal(double mean, double std_deviation, double
    sample){
2     return r8_normal_01_cdf_inverse(sample) * std_deviation + mean;
3 }
4
5 double inv_cdf_exponential(double lambda, double sample){
```

```c
    return -(log(sample)) / lambda;
}

double sample(void){
    return (double)rand() / (double)RAND_MAX;
}
```

Listing 6.3: Code for inverse transform sampling.

6.1.5 Simulation

The simulation menu is shown in Figure A.9. The user is brought here after assigning data to each process. From here the user has the option to run a simulation based on the modelled manufacturing system. Hence, requirement 5 has been met. The user also has the option quit the program or go back if any data was entered incorrectly.

Listing 6.4 displays the code that simulates all manufacturing processes by generating data for defects and unplanned stops that follows a normal or exponential distribution.

```c
double simulate(process processes[], int *amount_of_processes){
    int i, j;

    srand(time(NULL));

    for(i = 0; i < *amount_of_processes; i++){
        if(processes[i].mean_defects != -1)
            for(j = 0; j < NUM_SIM; j++)
                processes[i].defectsArr[j] = inv_cdf_normal(
                    processes[i].mean_defects, processes[i].
                    std_deviation_defects, sample());
        if(processes[i].lambda_defects != -1)
            for(j = 0; j < NUM_SIM; j++)
                processes[i].defectsArr[j] = inv_cdf_exponential(
                    processes[i].lambda_defects, sample());
    }

    for(i = 0; i < *amount_of_processes; i++){
        if(processes[i].mean_US != -1)
            for(j = 0; j < NUM_SIM; j++)
                processes[i].stopsArr[j] = inv_cdf_normal(processes
                    [i].mean_US, processes[i].std_deviation_US,
                    sample());
        if(processes[i].lambda_US != -1)
            for(j = 0; j < NUM_SIM; j++)
                processes[i].stopsArr[j] = inv_cdf_exponential(
                    processes[i].lambda_US, sample());
    }

    return EXIT_SUCCESS;
}
```

Listing 6.4: Code of the simulation.

6.1.6 Computations

Followed by the simulation, the program will compute the OEE, availability, performance, and quality for each process as described in subsection 1.2.2. Consequently, requirement 6 is met.

Listing 6.5 displays the code that computes OEE, availability, performance, and quality. To see the entirety of the defects function and the stops function go to Listing A.1.

```
/*Computes the expected value of defects for a single manufacturing
    process.*/
double defects(process process){
}

/*Computes the expected value of unplanned stops for a single
   manufacturing process.*/
double stops(process process){
}

/*Calculates the availability of a single manufacturing process.*/
double calculateAvailability(double run_time, process process){
    return run_time / process.planned_production_time;
}

/*Calculates the performance of a single manufacturing process.*/
double calculatePerformance(double run_time, process process, int
   total_count){
    return process.ideal_cycle_time * total_count / run_time;
}

/*Calculates the quality of a single manufacturing process.*/
double calculateQuality(double good_count, int total_count){
    return good_count / total_count;
}

/*Calculates the OEE of a single manufacturing process.*/
double calculateOEE(double availability, double performace, double
   quality){
    return availability * performace * quality;
}
```

Listing 6.5: Code of the computation of OEE and its components of each process

6.1.7 Results

The results of the simulation are shown as the last procedure of the program. An example of results is shown in Figure A.10. As seen in the example, the program will display histograms for defects and unplanned stops for each process. The histograms clearly illustrate which distribution type was chosen. Followed by this, the program displays the OEE, availability, performance, and quality for each manufacturing process, in a table sorted from first to last process and in another table sorted from lowest to highest OEE. At last, the overall OEE, availability, performance, and quality for the entire manufacturing system are displayed.

```
void printOverallResult(int amount_of_processes, process processes
   [], int total_count){
```

```c
    int i;
    double OEE, availability_total = 0, performance_total = 0, quality_total = 0, availability_mean, performance_mean, quality_mean;

    for(i = 0; i < amount_of_processes; i++){
        availability_total += calculateAvailability(processes[i].planned_production_time - stops(processes[i]), processes[i]);
        performance_total += calculatePerformance(processes[i].planned_production_time - stops(processes[i]), processes[i], total_count);
        quality_total += calculateQuality(total_count - defects(processes[i]), total_count);
    }

    availability_mean = availability_total / amount_of_processes;
    performance_mean = performance_total / amount_of_processes;
    quality_mean = quality_total / amount_of_processes;

    OEE = calculateOEE(availability_mean, performance_mean, quality_mean);

    printf("\n___________________________________\n");
    printf(ANSI_UNDERLINED_PRE "|            Total OEE            |" ANSI_UNDERLINED_POST "\n");
    printf(ANSI_UNDERLINED_PRE "| OEE            |  %12.3f  |" ANSI_UNDERLINED_POST "\n", OEE);
    printf(ANSI_UNDERLINED_PRE "| Availability   |  %12.3f  |" ANSI_UNDERLINED_POST "\n", availability_mean);
    printf(ANSI_UNDERLINED_PRE "| Performance    |  %12.3f  |" ANSI_UNDERLINED_POST "\n", performance_mean);
    printf(ANSI_UNDERLINED_PRE "| Quality        |  %12.3f  |" ANSI_UNDERLINED_POST "\n", quality_mean);
}
```

Listing 6.6: Code of sorting and displaying results.

6.1.8 Exit the Program

The function quit from Listing 6.7 can be accessed at any point of the program, except when simulating and generating data.

When the function is called the terminal is cleared and the program terminates. Hence, requirement 8 is fulfilled.

```c
int quit(void){
    system("clear");
    printf("The program has shut down.\n");
    exit(EXIT_SUCCESS);
}
```

Listing 6.7: Code of the exit process

7 | Discussion

In this chapter the errors of the program are discussed. Afterwards, the results are discussed. Lastly, other possibilities to add in the program, which could have resulted in improvements are discussed.

7.1 Errors

In menu ... When pressing the wrong keys, the key pressed will be printed in the terminal, and will not be removed as in the other menus, like the main menu. This small detail has a big impact on the visual aspect.

7.2 Results

7.3 Improvements

In the dataMenu, the user is, as mentioned before, able insert values for, planned production time, ideal cycle time, lambda etc. But the developers have not set any restrictions (boundaries?) on which values the user can enter, except the restriction of the data types themselves. To implement a boundary of some sort would be optimal, so the calculations would be correct.

In the program it is possible to go back in all menus except continuing through to "finish model". This means, that when you have chosen the amount of manufacturing processes and navigate further into the program, the only way to re-enter the amount of processes is to quit the program after entering all the data in the dataMenu. It would have been a neat detail to be able to quit the program and go back, whilst entering the data in the dataMenu.

When the user has entered all the data necessary and the program has printed the results on the screen, the program does not save the results. If the user wants to save the results, he has to manually copy it into a textfile. The better option would be for the program to do this automatically after the results have been printed.

There is still room for improvement when it comes to the program. One such thing is that currently the program is only able to simulate linear processes. If the program was able to simulate non linear processes, then it would be more commercially viable since more companies would be able to use the program.

One aspect that is possible to improve would be automatic insertion of data. How this could be done is by installing hardware on the machines that would collect and store the necessary data to calculate and simulate OEE. By doing this OEE could be monitored real time and be stored so it can be used for simulations.

Another aspect which could be improved upon is storing the different values of the program. This could be improved by making the user able to create presets so they wouldn't have to enter every single piece of information every time they simulate the same process. This is useful if they want to change a single piece of the data, but keep the rest the same and implementing this would save time. Also if the results were saved in a text file, so the user doesn't have to write it all down or take screenshots of it, additional time would be saved.

7.4 Perspective

8 | Conclusion

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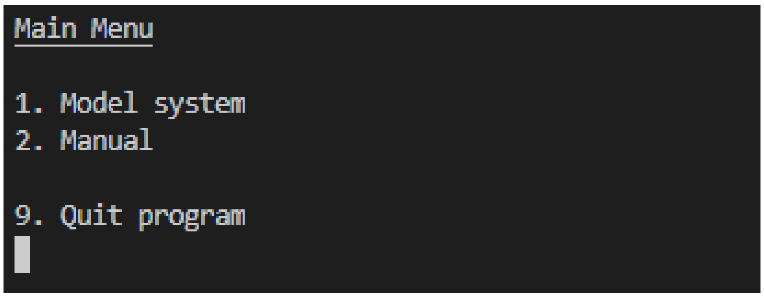
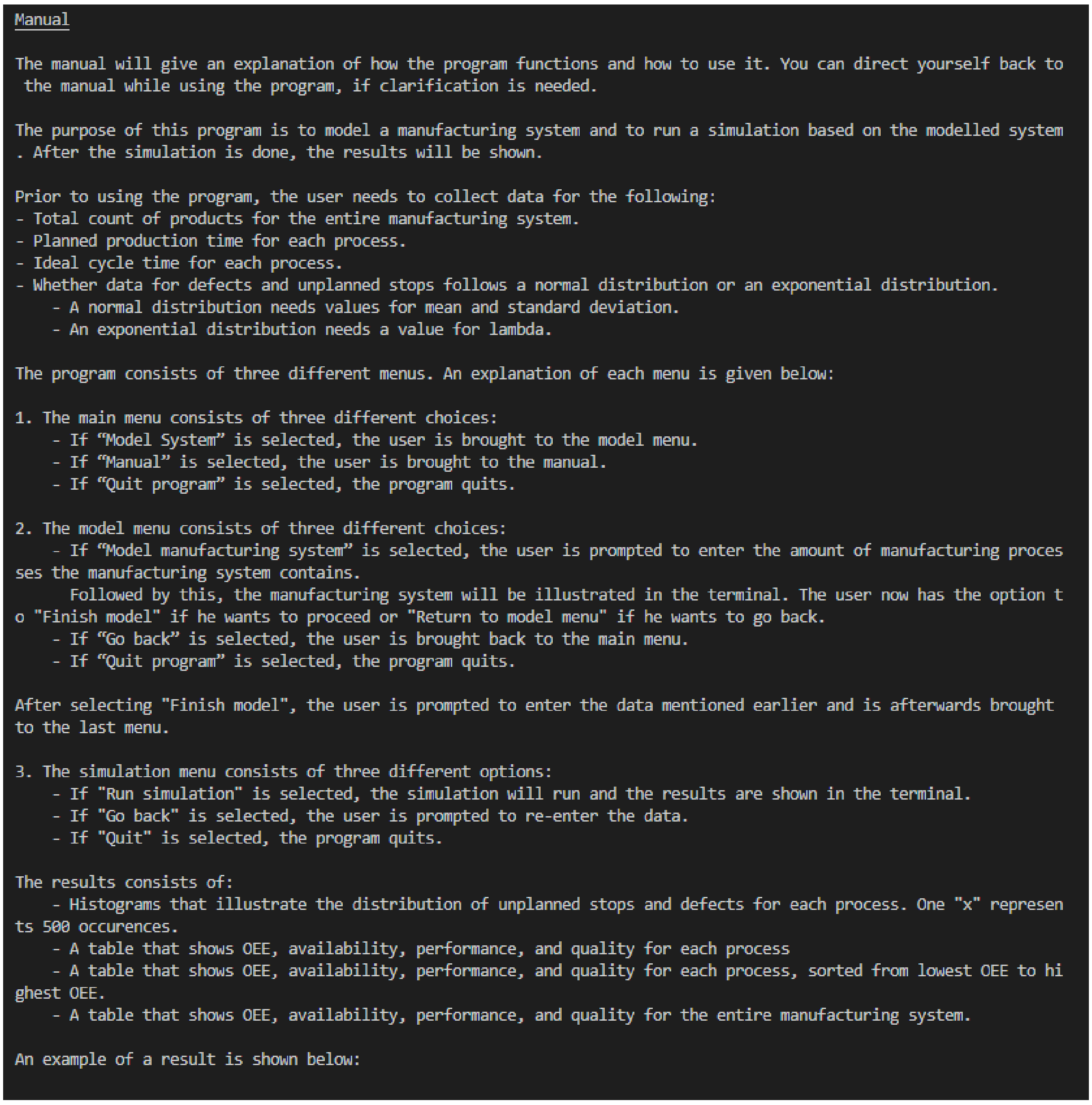
Appendices

A | Program



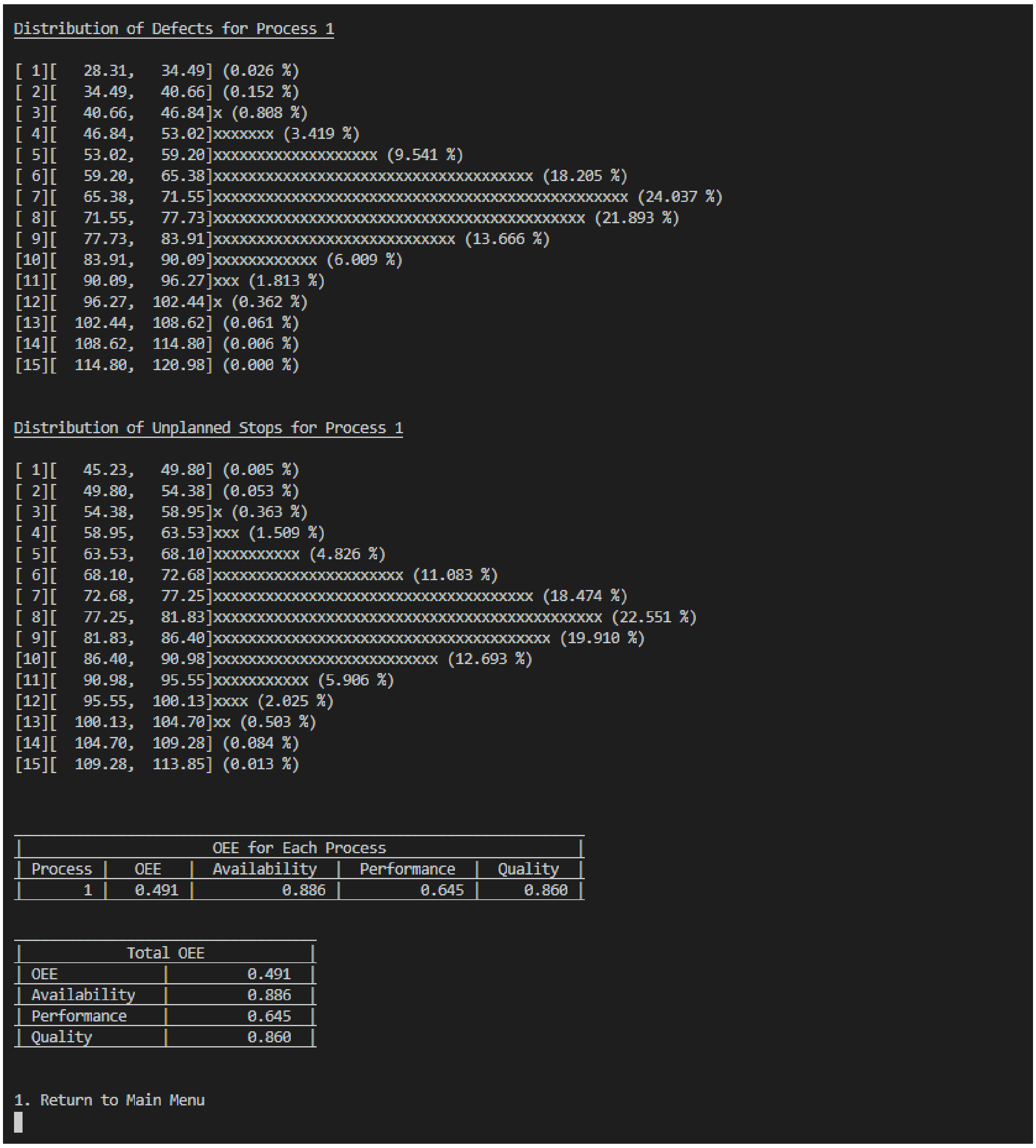
```
Main Menu

1. Model system
2. Manual

9. Quit program
```

Figure A.1: Program Main Menu.



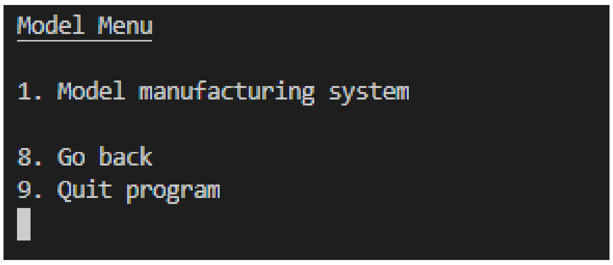
```
Manual

The manual will give an explanation of how the program functions and how to use it. You can direct yourself back to
 the manual while using the program, if clarification is needed.

The purpose of this program is to model a manufacturing system and to run a simulation based on the modelled system
. After the simulation is done, the results will be shown.

Prior to using the program, the user needs to collect data for the following:
- Total count of products for the entire manufacturing system.
- Planned production time for each process.
- Ideal cycle time for each process.
- Whether data for defects and unplanned stops follows a normal distribution or an exponential distribution.
    - A normal distribution needs values for mean and standard deviation.
    - An exponential distribution needs a value for lambda.

The program consists of three different menus. An explanation of each menu is given below:

1. The main menu consists of three different choices:
    - If “Model System” is selected, the user is brought to the model menu.
    - If “Manual” is selected, the user is brought to the manual.
    - If “Quit program” is selected, the program quits.

2. The model menu consists of three different choices:
    - If “Model manufacturing system” is selected, the user is prompted to enter the amount of manufacturing proces
ses the manufacturing system contains.
      Followed by this, the manufacturing system will be illustrated in the terminal. The user now has the option t
o "Finish model" if he wants to proceed or "Return to model menu" if he wants to go back.
    - If “Go back” is selected, the user is brought back to the main menu.
    - If “Quit program” is selected, the program quits.

After selecting "Finish model", the user is prompted to enter the data mentioned earlier and is afterwards brought
to the last menu.

3. The simulation menu consists of three different options:
    - If "Run simulation" is selected, the simulation will run and the results are shown in the terminal.
    - If "Go back" is selected, the user is prompted to re-enter the data.
    - If "Quit" is selected, the program quits.

The results consists of:
    - Histograms that illustrate the distribution of unplanned stops and defects for each process. One "x" represen
ts 500 occurences.
    - A table that shows OEE, availability, performance, and quality for each process
    - A table that shows OEE, availability, performance, and quality for each process, sorted from lowest OEE to hi
ghest OEE.
    - A table that shows OEE, availability, performance, and quality for the entire manufacturing system.

An example of a result is shown below:
```

Figure A.2: First part of the Manual in the Program.



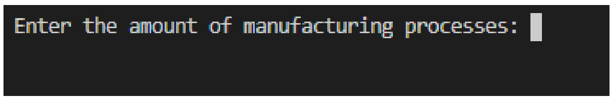
```
Distribution of Defects for Process 1

[ 1][   28.31,    34.49] (0.026 %)
[ 2][   34.49,    40.66] (0.152 %)
[ 3][   40.66,    46.84]x (0.808 %)
[ 4][   46.84,    53.02]xxxxxxx (3.419 %)
[ 5][   53.02,    59.20]xxxxxxxxxxxxxxxxxxx (9.541 %)
[ 6][   59.20,    65.38]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (18.205 %)
[ 7][   65.38,    71.55]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (24.037 %)
[ 8][   71.55,    77.73]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (21.893 %)
[ 9][   77.73,    83.91]xxxxxxxxxxxxxxxxxxxxxxxxxxxx (13.666 %)
[10][   83.91,    90.09]xxxxxxxxxxxx (6.009 %)
[11][   90.09,    96.27]xxx (1.813 %)
[12][   96.27,   102.44]x (0.362 %)
[13][  102.44,   108.62] (0.061 %)
[14][  108.62,   114.80] (0.006 %)
[15][  114.80,   120.98] (0.000 %)


Distribution of Unplanned Stops for Process 1

[ 1][   45.23,    49.80] (0.005 %)
[ 2][   49.80,    54.38] (0.053 %)
[ 3][   54.38,    58.95]x (0.363 %)
[ 4][   58.95,    63.53]xxx (1.509 %)
[ 5][   63.53,    68.10]xxxxxxxxxx (4.826 %)
[ 6][   68.10,    72.68]xxxxxxxxxxxxxxxxxxxxxx (11.083 %)
[ 7][   72.68,    77.25]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (18.474 %)
[ 8][   77.25,    81.83]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (22.551 %)
[ 9][   81.83,    86.40]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (19.910 %)
[10][   86.40,    90.98]xxxxxxxxxxxxxxxxxxxxxxxxxx (12.693 %)
[11][   90.98,    95.55]xxxxxxxxxxx (5.906 %)
[12][   95.55,   100.13]xxxx (2.025 %)
[13][  100.13,   104.70]xx (0.503 %)
[14][  104.70,   109.28] (0.084 %)
[15][  109.28,   113.85] (0.013 %)


_________________________________________________________________
|                      OEE for Each Process                     |
| Process |  OEE  | Availability | Performance  | Quality  |
|       1 | 0.491 |        0.886 |        0.645 |    0.860 |


__________________________________
|            Total OEE           |
| OEE            |        0.491  |
| Availability   |        0.886  |
| Performance    |        0.645  |
| Quality        |        0.860  |


1. Return to Main Menu
```

Figure A.3: Second part of the Manual in the Program.



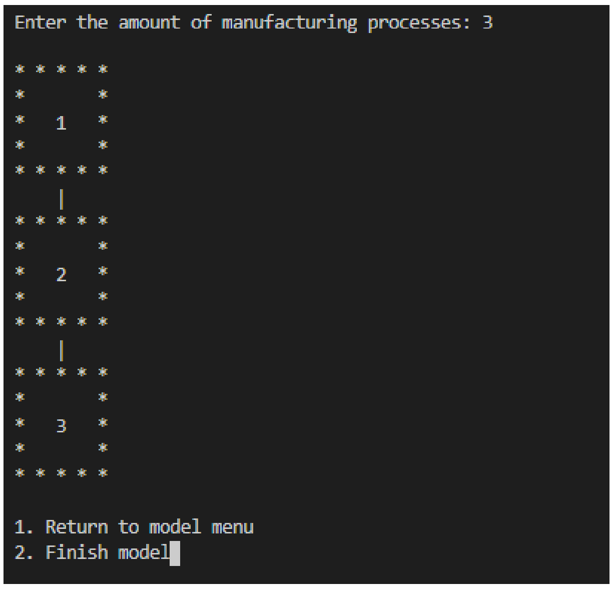
```
Model Menu

1. Model manufacturing system

8. Go back
9. Quit program
```

Figure A.4: Model menu in the Program.



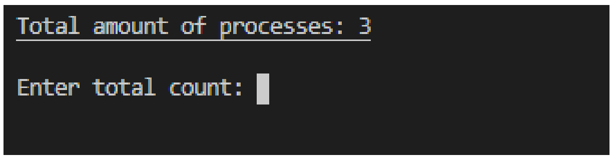
```
Enter the amount of manufacturing processes:
```

Figure A.5: First step in Model manufacturing system.



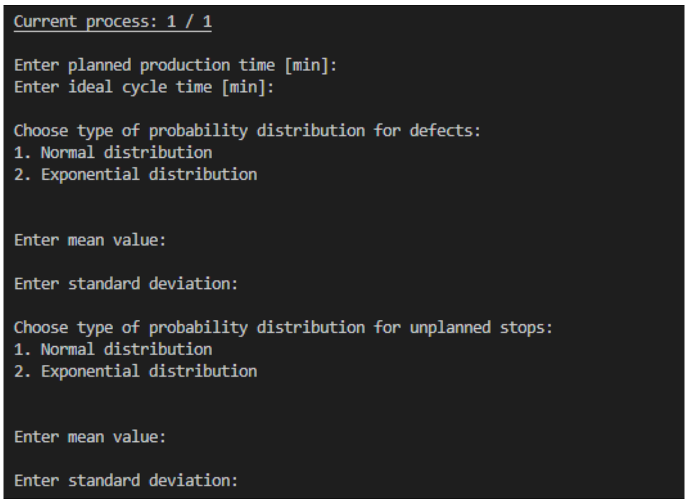
```
Enter the amount of manufacturing processes: 3

* * * * *
*       *
*   1   *
*       *
* * * * *
    |
* * * * *
*       *
*   2   *
*       *
* * * * *
    |
* * * * *
*       *
*   3   *
*       *
* * * * *

1. Return to model menu
2. Finish model
```

Figure A.6: Second step in Model manufacturing system.



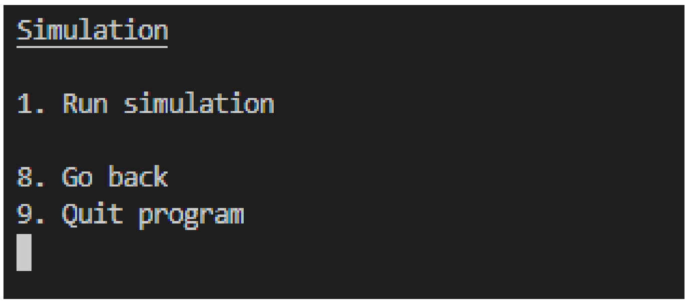
```
Total amount of processes: 3

Enter total count:
```

Figure A.7: Third step in Model manufacturing system.



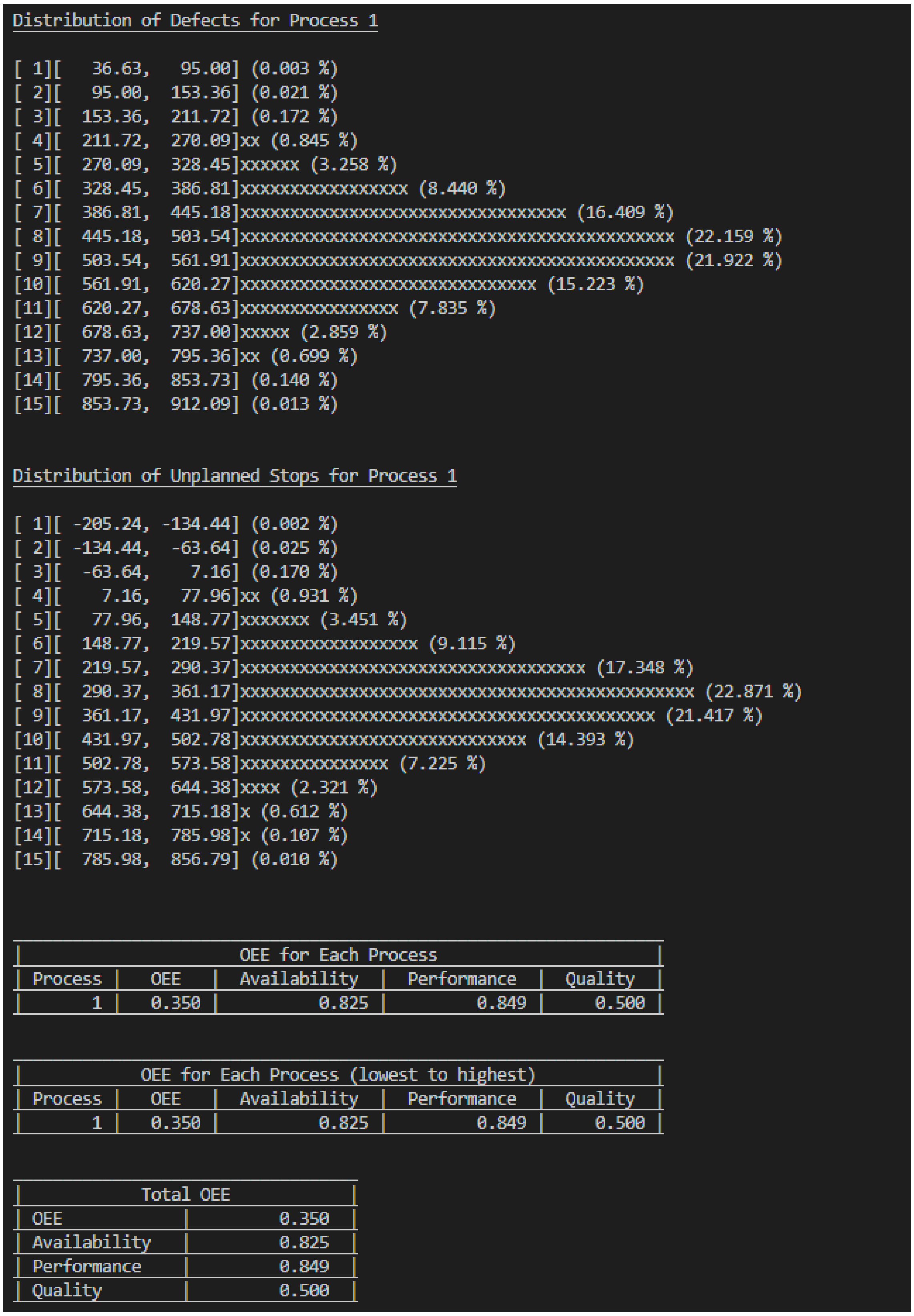
```
Current process: 1 / 1

Enter planned production time [min]:
Enter ideal cycle time [min]:

Choose type of probability distribution for defects:
1. Normal distribution
2. Exponential distribution


Enter mean value:

Enter standard deviation:

Choose type of probability distribution for unplanned stops:
1. Normal distribution
2. Exponential distribution


Enter mean value:

Enter standard deviation:
```

Figure A.8: Fourth step in Model manufacturing system.



```
Simulation

1. Run simulation

8. Go back
9. Quit program
```

Figure A.9: Simulation menu in the Program.



```
Distribution of Defects for Process 1

[ 1][   36.63,   95.00] (0.003 %)
[ 2][   95.00,  153.36] (0.021 %)
[ 3][  153.36,  211.72] (0.172 %)
[ 4][  211.72,  270.09]xx (0.845 %)
[ 5][  270.09,  328.45]xxxxxx (3.258 %)
[ 6][  328.45,  386.81]xxxxxxxxxxxxxxxxx (8.440 %)
[ 7][  386.81,  445.18]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (16.409 %)
[ 8][  445.18,  503.54]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (22.159 %)
[ 9][  503.54,  561.91]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (21.922 %)
[10][  561.91,  620.27]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (15.223 %)
[11][  620.27,  678.63]xxxxxxxxxxxxxxxx (7.835 %)
[12][  678.63,  737.00]xxxxx (2.859 %)
[13][  737.00,  795.36]xx (0.699 %)
[14][  795.36,  853.73] (0.140 %)
[15][  853.73,  912.09] (0.013 %)


Distribution of Unplanned Stops for Process 1

[ 1][ -205.24, -134.44] (0.002 %)
[ 2][ -134.44,  -63.64] (0.025 %)
[ 3][  -63.64,    7.16] (0.170 %)
[ 4][    7.16,   77.96]xx (0.931 %)
[ 5][   77.96,  148.77]xxxxxxx (3.451 %)
[ 6][  148.77,  219.57]xxxxxxxxxxxxxxxxxx (9.115 %)
[ 7][  219.57,  290.37]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (17.348 %)
[ 8][  290.37,  361.17]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (22.871 %)
[ 9][  361.17,  431.97]xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx (21.417 %)
[10][  431.97,  502.78]xxxxxxxxxxxxxxxxxxxxxxxxxxxxx (14.393 %)
[11][  502.78,  573.58]xxxxxxxxxxxxxxx (7.225 %)
[12][  573.58,  644.38]xxxx (2.321 %)
[13][  644.38,  715.18]x (0.612 %)
[14][  715.18,  785.98]x (0.107 %)
[15][  785.98,  856.79] (0.010 %)



| OEE for Each Process                                       |
| Process |  OEE  | Availability | Performance   | Quality |
|       1 | 0.350 |        0.825 |         0.849 |   0.500 |


| OEE for Each Process (lowest to highest)                   |
| Process |  OEE  | Availability | Performance   | Quality |
|       1 | 0.350 |        0.825 |         0.849 |   0.500 |


| Total OEE                    |
| OEE            |       0.350 |
| Availability   |       0.825 |
| Performance    |       0.849 |
| Quality        |       0.500 |
```

Figure A.10: Example of the Result of a simulation in the Program.

```
/*Computes the expected value of defects for a single manufacturing
    process.*/
double defects(process process){
    int i;
    double defects_total;

    for(i = 0; i < NUM_SIM; i++)
        defects_total += process.defectsArr[i];

    return defects_total / NUM_SIM;
}

/*Computes the expected value of unplanned stops for a single
   manufacturing process.*/
double stops(process process){
    int i;
    double US_total = 0;

    for(i = 0; i < NUM_SIM; i++)
        US_total += process.stopsArr[i];

    return US_total / NUM_SIM;
}
```

Listing A.1: Code of the computation of defects and unplanned stops