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 world economy.

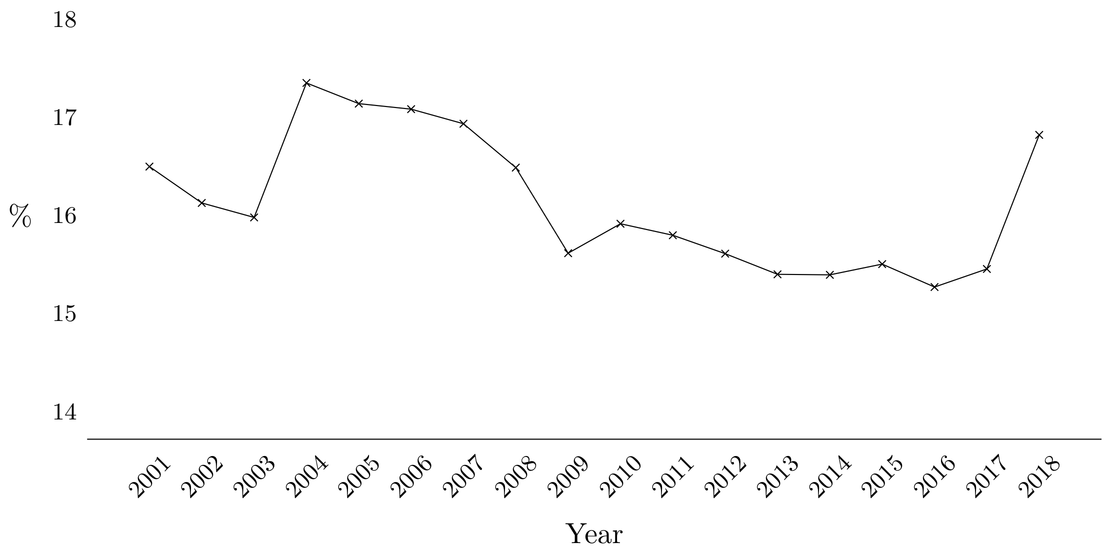

Figure 1.1: Global manufacturing value added as percent of GDP [2].

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.

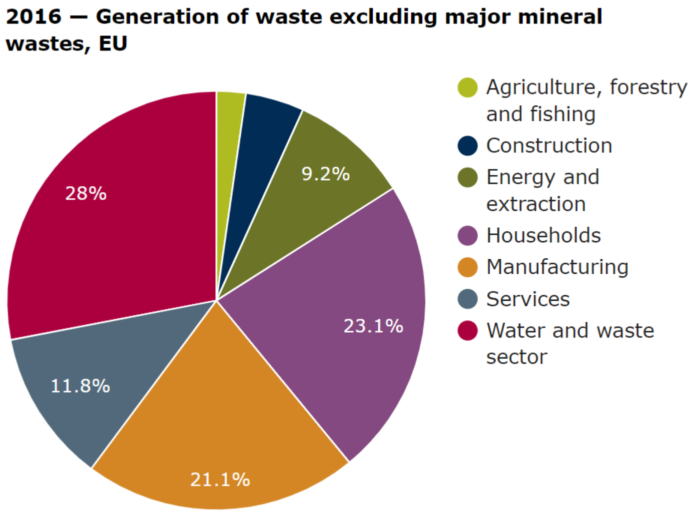

Figure 1.2: Waste generation from industries in EU [3].

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 the wear and tear of machine and human labour, 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, Chapter 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. Firstly, 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 specialized equipment operating 24 hours a day to make the exact same product, which makes this type of manufacturing system highly specialized, 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.

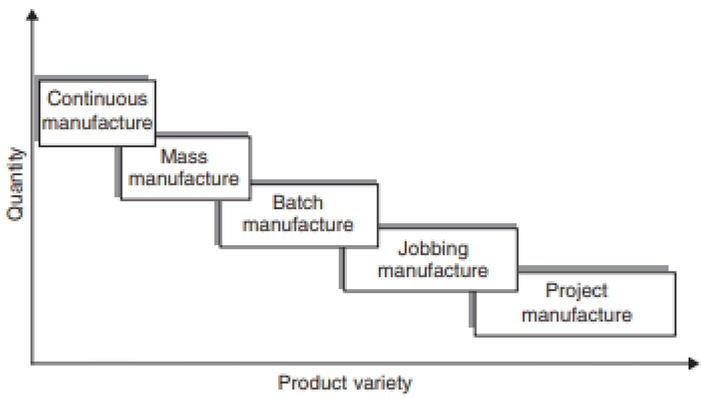

Figure 1.3: Quantity versus product variety in the different production systems [4, Figure 1.9].

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 manufacture 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. As a baseline 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 subsection 1.2.2, subsection 1.2.2, and subsection 1.2.2

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

1.2.3 Using OEE

A company that specialises in OEE and manufacturing improvements is Vorne Industries, who have been using it for many years and built a company on the basics of OEE. Vorne offer a number of solutions and products but the companies basis is based on OEE and Lean [11]. Vorne for example have displays and scoreboards to show current manufacturing numbers, such as cycle time, OEE procent, down time and reject count. Vorne also have other initiatives to improve productivity, increase capacity, reduce cycle times and reduce manufacturing costs. Vorne does this using real time sensoring of every production line. At each process they will measure down time, run time, total count, good count and can therefore provide a real time OEE and showcase these on for example displays in a companies office or production, thus showcase where improvements can be made. This numbers and calculations can also be outputted into an excel worksheet or likewise [12].

There are many other companies that sell both hardware and software solutions to improve manufacturing effectiveness such as Amper [13], Sistemas OEE [14] and OAL [15]. All these companies use OEE as a tool to monitor and improve production lines with the own hardware and software solutions.

1.2.4 Factory simulation

Factory simulation is the process of using a computer model to understand and improve a real manufacturing system. Simulation technology allows manufacturing companies to analyze 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 optimized. 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 [16].

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. This leads to the following problem statement: *How is it possible to develop a software solution capable of simulating the OEE of manufacturing processes for the purpose of increasing the OEE, thus reducing waste?*

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

3 | System Description

In accordance with the problem statement, the purpose of this project is to develop a software solution capable of simulating the OEE of manufacturing processes for the purpose of increasing the OEE, thus reducing waste. The purpose of this chapter is to establish the specifications for this software solution.

3.1 Flowchart

The purpose of a flowchart is to give a visual representation of activities, in this case, in the software solution. Firstly some common symbols need to be clarified, as to what they represent:

- The oval shape is the symbol for start/stop. It represents the start or end of a process.

- The rectangle is the symbol for processing. It represents the call of a function.

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

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

- The lines are used to indicate the direction of the flow.

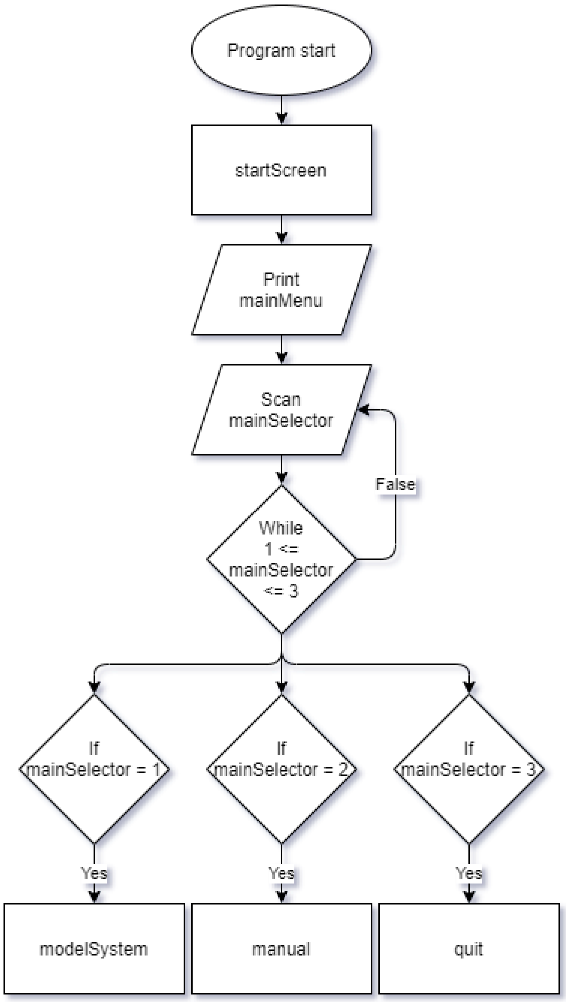

Figure 3.1: Program start

In Figure 3.1 a visual representation of the start of the program is shown. When the program is compiled, the program starts and shows the main menu. In this menu the user is asked for a input that will determine where to go next in the program.

- If 1 is entered, the program will run the function "modelSystem".
- If 2 is entered, a manual will be displayed.
- If 3 is entered, the program will shut down.
- If any other number is entered, the program will ask for an input again.

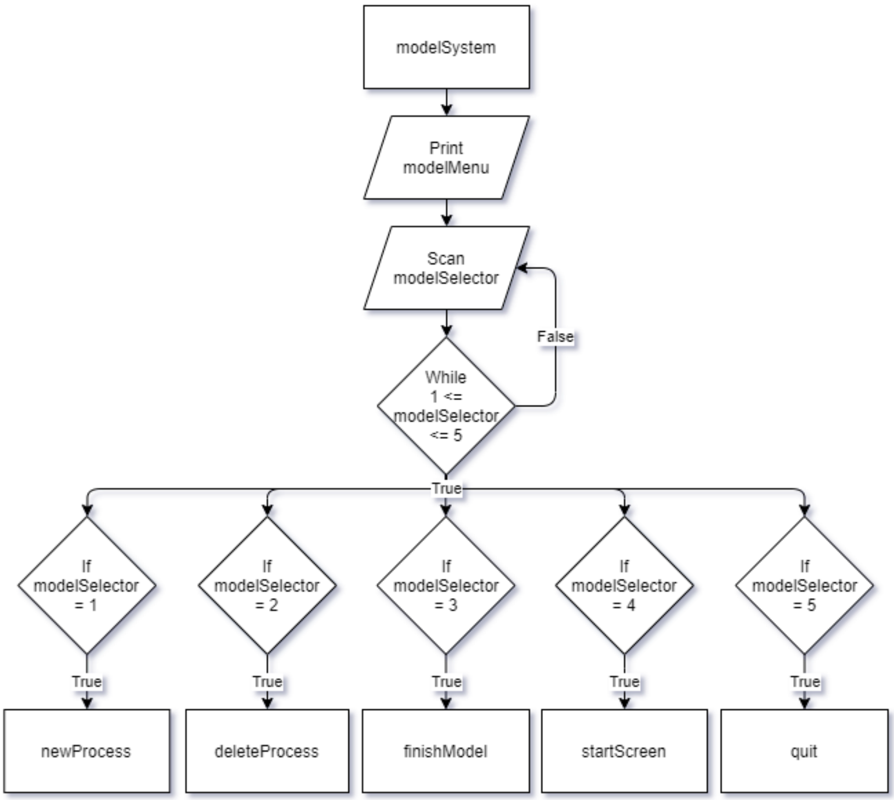

Figure 3.2: Model system

Figure 3.2 displays the "modelSystem" function that is called when chosen from the main menu.

modelSystem allows the user to model a manufacturing system, by adding the different manufacturing processes the system contains. This is accomplished by using the modelSelector that gives the user a variety of options:

- If 1 is entered, a new process is added to the system and the user is prompted to enter a name for that process.
- If 2 is entered, the latest process will be deleted from the system.
- If 3 is entered, the modelling of the system is finished.
- If 4 is entered, the user is brought back to the main menu.
- If 5 is entered, the program will shut down.
- If any other number is entered, the program will ask for an input again.

The modelled system will be displayed on the screen as the user continues to add new processes. A process is represented by a circle, and processes next to each other are connected with a line.

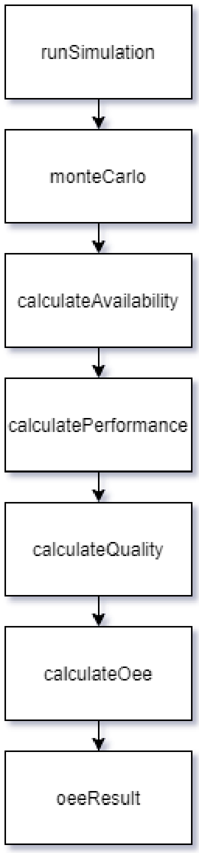

Figure 3.3: Run Simulation

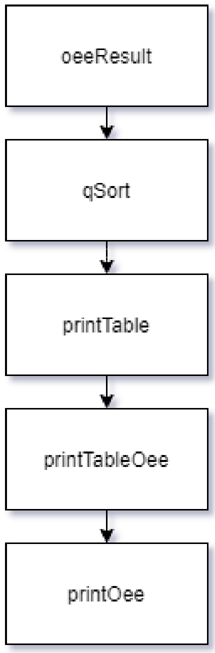

Figure 3.4: OEE Result

The results of the simulation will be shown as the last step of the program. In order to better visualize the processes created by the user, the OEE for each process will be sorted using qsort. Followed by this, a table containing the different output values for each process will be printed.

The output values displayed in the table are as follows: OEE, availability, performance, quality, amount of defects and amount of unplanned stops.

At last, the OEE value for each process will be used to generate the overall OEE for the entire manufacturing system.

3.2 System Requirements

Has to be able to take input and be able to display output.
Has to be able to quit the program at any given time in the program
Has to be able to go back to the main menu
Has to be able to take in a text FILE that outputs the manual (only if the manual is big enough)
Has to be able to scan for selector to navigate through the menus. But if the integer is not one that is on the menu, then the program will ask again.
Has to be somewhat balance user-friendliness and functionality.

3.2.1 Functional Requirements

- Calculate OEE for a simulated manufacturing process
-
-

3.2.2 Non-functional Requirements

-
-
-

Inputs: (Metrics)
Availability: Run Time, Planned Production Time and Stop Time
Performance: Ideal Cycle Time, Total Count and Run Time
Quality: Good Count and Total Count
Metrics in total: 6

Outputs:

- Overall Equipment Effectiveness (OEE)
  - Availability Loss
  - Performance Loss
  - Quality Loss
- Prediction of future OEE
  - OEE = Availability x Performance x Quality
  - OEE = (Good Count × Ideal Cycle Time) / Planned Production Time

Description of functions used in the software solution **StartScreen:**
Manual:
ModelSystem:
ModelVariables:
MakeModel:
Quit:
KørSimulering:
MonteCarlo:
Qsort:
Compare:
printTableOEE:
printTable:
plotGraph:
PrintOEE:
calculateOEE:
calculateAvailability:
calculatePerformance:
calculateQuality:

4 | Probability Theory

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.

This chapter is based on [17] unless otherwise stated.

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.

[17, p. 3]

Example 4.1 Rolling a die and observing the number.

In this case the possible outcomes are the numbers 1 through 6, hence the sample space is

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

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.

[17, p. 5]

Example 4.2 Rolling a die and observing the number. 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,... is a sequence of pairwise disjoint events, that is, if $i \neq j$, then $A_i \cap A_j = \emptyset$, then

$$P(\bigcup_{k=1}^{\infty} A_k) = \sum_{k=1}^{\infty} P(A_k)$$

[17, 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

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 $\mathbb{R}$ ($X : S \to \mathbb{R}$).

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

[17, p. 78]

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.

[17, p. 78]

Definition af cdf

4.4 Continuous Random Variables

Definition af kontinuert cdf

Definition af pdf

4.5 Distributions

Definition af expected value (kontinuert)

Definition af variance

Definition af standard deviation

4.5.1 Normal Distribution

Definition af normal distribution

Teorem med expected value og variance af normal 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.

5.1 Complexity of Algorithms

This section is based on [18, Chapter 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.

The first step needed in order to assess the computational complexity of algorithms is an estimation of the number of operations used by the algorithms. 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 $x > k$.

[18, p. 217]

Big-O notation is used to describe the growth of a function. Particularly, when some function $f(x)$ is $O(g(x))$ an upper bound is obtained in terms of $g(x)$. However, 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 $x > k$.

[18, 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 are 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.

[18, p. 227]

5.2 Sorting

Sorting algorithms is an algorithm which takes an array of different elements and sorts them in a certain order.

Algorithm 1 Quicksort

```
procedure QUICKSORT(geh)
```

5.3 Monte Carlo Simulation

Monte Carlo simulation is a type of algorithm which generates N amount of experiments where the outcome is random. This can be used in a wide variety of cases, one such example is a die. Let us say that the purpose of the experiment is to see how many times a six is rolled, let us call this M. Now the die is rolled N 9 times and we get M three times. This would mean that there according to this experiment is a 1/3 chance of getting a six, it is however common knowledge that the chance to roll a certain number on a die is 1/6 so how can this be fixed. Well Monte Carlo simulation usually simulates the experiment a great amount of times which means that law of large numbers is applicable. What can be extracted from this is that the greater the number of times the experiment is repeated the greater the accuracy of the estimate becomes. Now let us go back to the die example, before the die was only rolled 9 times, but this times it will be rolled a million times. If the die is rolled a million times then the result should be approximately 1/6.

Algorithm 2 Monte Carlo

procedure MONTECARLO(geh)

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