Development of a simulation tool for process representation and performance analysis

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Development of a simulation tool for process representation and performance analysis

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Abstract
This master thesis describes the development of a presentation tool and performance analysis tool for MSPP. The use of 3D models in Virtual Reality environments and animation of models is investigated for increased understanding of the production facility. For performance analysis, a simulation tool is constructed to investigate the differences of preventive and failure based maintenance on system availability and throughput. Cost of events related to availability have been included to support decisions for customers of MSPP.
Acknowledgement

This master thesis is the final product of my study at the University of Technology Eindhoven, Faculty of Industrial Engineering and Innovation Sciences. The project is executed at the departments of Project Engineering and Service Department of Marel Stork Poultry Processing located in Boxmeer.

From the University I would like to thank my mentor, dr. Hao Peng for her supervision during this thesis. I have really enjoyed our cooperation and the helpful support that she provided during the project. I would also like to thank dr. ir. Joachim Arts, my second supervisor for his time and effort he put in our discussion sessions.

At Marel, I want to start by thanking my supervisor at project engineering Joris Arts. I would also like to thank my colleagues of the project engineering department for creating a nice working environment. Next, I would like to thank Robert Lemmens of the Service Department for his feedback and discussions during the many meetings we had.

Finally, I would like to thank my family and friends for supporting me during my master thesis project and study at the TUe. It has been a wonderful time.

Martijn van de Koolwijk
Boxmeer, September 2014
Executive summary

Introduction
This report is a result of a master thesis project performed at Marel Stork Poultry Processing located in Boxmeer. In order to facilitate customer decision making and provide added value to the customer, this project is looking into the possibilities to visualize poultry processing plants comprising a process representation and the several options from which a customer can choose. The performance under investigation include the throughput of the system combined with the availability of machines. Together the process representation and performance analysis provide better understandings and insights of system behaviours. The goal of this project is to demonstrate a process representation and to map out the possibilities of simulation tools in general. Describe how a company like Marel can utilize the advantages of simulation tools in the long run. The main research question for this project is defined as:

How can we facilitate sales process and customer service based on a simulation tool for process representation and performance analysis?

Research framework
In operation management research an early contribution towards a methodology model has been made by Mitroff et al. (1974). The Mitroff model is an accepted model in operations management and is based on methods initially used when operations research emerged. The model provides guidance in structuring research and to identify the processes and stages that should be followed. It comprises the following four phases which jointly create the operations research approach: conceptualization, modelling, model solving and implementation. In this project the model solving phase does not apply. The simulation tool is used for evaluation. However, the simulation model will be validated which is the arrow between the scientific model and the reality, problem situation.

Conclusion and recommendations
In order to create a feasible solution the process representation and performance analysis have been separated. For the process representation a start has already been made by Marel. The department of Project Engineering has created 3 dimensional models in contrast to the current static 2 dimensional paper drawings. Switching between the two and its perceived benefits have been investigated. Opportunities for the 3d models are a Virtual Reality environment and an animated flow of products to understand the processes in the factory.

Within Marel, the Service Department is responsible for the maintenance of equipment. Each plant of Marel has the ability to acquire the services of the Service Department and benefit from the added value. Preventive maintenance is to reduce the effects of breakdowns and maximize production system availability. A performance analysis for different types of maintenance gives insights to the added value of the service department.

For the performance analysis, the function of equipment in manufacturing is to support the production of products for downstream customers. This inherent capability of equipment is main-
tained by maintenance practices. According to Löfsten (2000) the majority of plants use Total
Maintenance Cost (TMC) and availability to measure the maintenance performance. Measuring
maintenance performance is helpful when evaluating the effectiveness of maintenance decisions.
Such decisions are the choice for preventive or failure based maintenance. According to Li et al.
(2009) throughput analysis is important for the design, operation and management of produc-
tion systems. The availability, throughput and cost of a system are identified as key pieces of
information which is absent to customers.

In order to verify the simulation model, an analytical model is developed. The results of the ver-
ification show the differences between preventive and failure based maintenance. Three different
configurations have been investigated, the single module, system operating independently and a
system operating dependently without idle failures. Both systems contain six modules in series.
All three simulations show comparison with the analytical model. However, the independent
simulation shows higher values in repairs which is unrealistic in comparison with the analytic
model. The difference between the analytical model and simulation model are small, this could
increase when the range of modules raises, or repair times increase.

For ease of use, the modular incorporation of simulation files as used in this report results in
the independent operation of modules. When modules operate dependent on each other where
downtime influences uptime of other modules, the simulation becomes more complex to adjust
or construct. The choice between ease of use and accurate results in terms of modular mod-
elling has to be made. This chapter has given insights in the influences of decisions but have
to be analysed by accurate data in order to make a sound conclusion. The differences between
the models is expected to grow when the number of modules increases and/or the repair times
increase.

The simulation opportunities on the long run for Marel are:

- Identification of losses in the production line.
- New modules and upgrades for the production line.
- Redundancy design for the production line.
- Performance agreements level determination.
- Preventive Maintenance Schedule adjustment.
- Total cost of ownership, life cycle costing and cost of ownership insights.

**Recommendations**

Data required as input for the simulation model is currently inaccurate. Information about re-
pair times and times between failures are inconsistently logged in a maintenance log. Drawbacks
of the maintenance log are,

- The absence of motivation for repairs or repair times are missing.
- No clear classification of reason for repair. Preventive maintenance related or corrective
  maintenance related.
- Some might be maintenance related where others are accident related.
- System downtime has to be separated from module downtime.
By increasing the reliability and accuracy of the data, the output of the simulation model will be more reliable and accurate. The determination of parameters for simulation input can be achieved by conducting censoring to data. This is particularly useful for datasets which are not complete, or tests have not been run to completion. That is, components have been exchanged before they have failed.

Limitations
For this report, the constructed models use input from fictive data. The differences between preventive maintenance and failure based maintenance are based on the same dataset, subject to preventive maintenance, which might not be highly desirable. This is chosen due to data limitations for analysis. A future difference can be computed by applying two different lifetime distributions which take into account a different wear pattern caused by the maintenance strategies. Two actions for determining the failure based maintenance repairs has been proposed in the increase of repair time, and the multiplication by repairs by a certain factor.
Contents

1 Introduction 1
   1.1 Marel ................................................. 1
       1.1.1 Process explanation .......................... 2
       1.1.2 Sales and Service ............................. 3
   1.2 Problem context .................................... 3
       1.2.1 Current situation ............................... 3
       1.2.2 Desired situation .............................. 4
   1.3 Assignment ......................................... 4
   1.4 Research questions ................................ 4
   1.5 Methodology ........................................ 4
       1.5.1 Conceptualization ............................. 5
       1.5.2 Modelling ...................................... 5
       1.5.3 Validation ..................................... 6
       1.5.4 Implementation ............................... 6
   1.6 Deliverables ....................................... 6
   1.7 Outline ............................................ 6

2 Conceptual model 7
   2.1 Production process ................................. 7
       2.1.1 Areas ......................................... 7
       2.1.2 Modules ....................................... 9
       2.1.3 Transportation line ............................ 9
   2.2 Service Department and maintenance .............. 9
       2.2.1 Maintenance Policy ........................... 9
       2.2.2 Type of failure ................................ 11
       2.2.3 Repair action ................................ 12
       2.2.4 Yield loss ................................... 12
       2.2.5 Rework ....................................... 12
   2.3 Objectives of the simulation study ............... 13
       2.3.1 Presentation tool .............................. 13
       2.3.2 Simulation tool ................................. 13
   2.4 Input and Output .................................. 14
       2.4.1 Availability .................................. 14
       2.4.2 Throughput .................................. 16
       2.4.3 Cost ......................................... 17
   2.5 Assumptions and simplifications .................. 18

3 Visualization 19
   3.1 Current situation .................................. 19
       3.1.1 Customer process .............................. 19
       3.1.2 Customer contact .............................. 20
## 3.1.3 Transition

### 3.2 Improvement

#### 3.2.1 Virtual reality

#### 3.2.2 Flow of material

### 3.3 Requirements

#### 3.3.1 Usability

#### 3.3.2 Relevance of information

#### 3.3.3 Level of detail

### 3.4 Added value

#### 3.4.1 Influencing factors

### 3.5 Software

## 4 Modelling

### 4.1 Availability simulation

#### 4.1.1 Breakdown parts

### 4.2 Performance measures

#### 4.2.1 Availability performance

#### 4.2.2 Throughput performance

#### 4.2.3 OEE computation

#### 4.2.4 OTE computation

#### 4.2.5 Cost performance

### 4.3 Simulation Output

### 4.4 Statistical observations

#### 4.4.1 Warm-up period

### 4.5 Software and data transfer

## 5 Validation and verification

### 5.1 Analytical model

#### 5.1.1 Renewal function

#### 5.1.2 Availability

### 5.2 Verification

#### 5.2.1 Single module

#### 5.2.2 System with dependent modules

#### 5.2.3 System with dependent modules and adjusted rates

#### 5.2.4 System with dependent modules extended time

#### 5.2.5 System with independent modules

#### 5.2.6 System with independent modules and adjusted rates

#### 5.2.7 System with independent modules extended time

### 5.3 Discussion of results

### 5.4 Validation

## 6 Numerical analysis

### 6.1 Redundancy

### 6.2 Simulation opportunities

#### 6.2.1 Identification of losses

#### 6.2.2 New modules and upgrades for the production line

#### 6.2.3 Redundancy

#### 6.2.4 Performance contracts

#### 6.2.5 PMS adjustment

#### 6.2.6 TCO, LCC and COO
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Conclusion and recommendations</td>
<td>55</td>
</tr>
<tr>
<td>7.1 Conclusion</td>
<td>55</td>
</tr>
<tr>
<td>7.2 Recommendations and limitations</td>
<td>57</td>
</tr>
<tr>
<td>References</td>
<td>58</td>
</tr>
<tr>
<td>Appendices</td>
<td>63</td>
</tr>
<tr>
<td>A ACM-NT process</td>
<td>65</td>
</tr>
<tr>
<td>B ACM-NT Product Flow</td>
<td>67</td>
</tr>
<tr>
<td>C ACM-NT components</td>
<td>69</td>
</tr>
<tr>
<td>D Confidence interval</td>
<td>71</td>
</tr>
<tr>
<td>E Renewal function verification</td>
<td>73</td>
</tr>
<tr>
<td>F Random number generation</td>
<td>75</td>
</tr>
<tr>
<td>F.1 Random numbers</td>
<td>75</td>
</tr>
<tr>
<td>F.2 Probability plotting</td>
<td>75</td>
</tr>
<tr>
<td>G System downtime</td>
<td>77</td>
</tr>
<tr>
<td>H Visualization options</td>
<td>79</td>
</tr>
</tbody>
</table>
List of Figures

1.1 MSPP plant layout .................................................. 2
1.2 Mitroff et al (1974) research model ............................... 5

2.1 ACM-NT process .................................................. 8
2.2 Maintenance Classification ......................................... 10
2.3 Partitioning of repair times (Rausand and Høyland, 2004) .... 12
2.4 Availability cycle .................................................. 14

3.1 Customer process between Project Engineering and Sales department ........................................... 20
3.2 Customer contact information ..................................... 20

4.1 Availability of a system ............................................ 28
4.2 Series and parallel structure ....................................... 29

6.1 System reliability as a function of number and reliability of components (Lewis, 1996) ......................... 48
6.2 Redundant modules example ....................................... 49
6.3 Preventive Maintenance Schedule optimization ................. 52

A.1 Stages in a complete process ..................................... 65
A.2 ACM-NT process .................................................. 66

C.1 An example of a Preventive Maintenance Schedule (PMS) ................. 70

E.1 Exponential distribution ............................................ 73
E.2 CDF comparison with renewal ..................................... 73

F.1 Weibull probability plot including trend-line ..................... 76

G.1 Graphical representation data of system unavailability ............. 78
List of Tables

2.1 Equations for OTE by Muthiah and Huang (2007) ..................... 17
5.1 Single module comparison with preventive maintenance .................. 38
5.2 Single module comparison with failure based maintenance ............... 38
5.3 Parameters of example system ........................................... 38
5.4 System comparison with preventive maintenance and no idle failures ...... 39
5.5 System comparison with failure based maintenance and no idle failures .... 39
5.6 Parameters of example system with adjusted rates ........................ 40
5.7 System comparison with preventive maintenance and adjusted rates ........ 40
5.8 System comparison with failure based maintenance and adjusted rates ...... 40
5.9 System comparison with extended time ................................... 41
5.10 System comparison with extended time .................................. 41
5.11 System comparison with preventive maintenance ........................ 42
5.12 System comparison with failure based maintenance ....................... 42
5.13 System comparison with preventive maintenance and adjusted rates .......... 43
5.14 System comparison with failure based maintenance and adjusted rates ...... 43
5.15 System comparison with extended time .................................. 44
5.16 System comparison with extended time .................................. 44
6.1 Redundancy allocation example ............................................ 50
6.2 Redundant modules example with short repair times ........................ 50
F.1 Weibull data ................................................................. 76
G.1 Simulation data for system downtime ....................................... 77
Chapter 1

Introduction

This chapter first gives an introduction to Marel Stork Poultry Processing (MSPP) and the research assignment. Paragraph 1.1 provides background information on Marel Stork and poultry process systems and in paragraph 1.2 the problem context is stated. Next, the assignment in paragraph 1.3 and research questions in paragraph 1.4 are presented. The methodology is provided in paragraph 1.5 and deliverables in paragraph 1.6. Finally, the outline of this report is presented in paragraph 1.7.

1.1 Marel

Marel is a leading global provider of advanced equipment, systems and services to the fish, meat and poultry industry. The companies activities are divided in the following four segments: Poultry Processing, Fish Processing, Meat Processing and Further Processing. Product centers are located in Iceland, Denmark, United Kingdom, Singapore, The Netherlands and the United States. Their product range spans the entire production process, from reception of raw materials all the way through to packaging and labelling of the final products. Marel delivers integrated solutions, making it a single source provider for the process industry. Brands of Marel include Stork Poultry Processing and Townsend Further Processing. Marel is market leader in an attractive and rapidly growing industry and has a global network with close to 3700 employees in 30 countries.

Marel’s vision is to be the customers’ choice in supplying integrated systems, products and services to the poultry, fish and meat industries.

This project is conducted at Marel Stork Poultry Processing, from now on abbreviated as MSPP. MSPP concerns the poultry processing for broilers, layers, parent stock, turkeys, geese and ducks. The MSPP can be characterized as line production where birds are hung up on shackles for transportation through the plant. Along the line, numerous machines are positioned to perform operations on the birds which can be seen in figure 1.1. Not all machines have to be utilized for each end-product and can therefore be bypassed. The complete poultry process can be divided into phases, which can be divided into sub-processes, which consist of one or more modules as discussed in the next paragraph.

Systems are constructed out of modular components making upgrading and many configurations possible. The many options to choose from make each plant unique. Production steps can be conducted manually or automatically in a single system. The large variety of end-products comprise of whole bird, portion and fillet products which can be produced and packed automatically at high speed. Speeds range from 500 birds per hour (bph) up to 13,500 bph at the moment and is subject to continuous development to increase speeds.
1.1.1 Process explanation

The process of an MSPP plant can be explained by multiple phases, placed in separate areas of the factory. The various stages are presented below and a visual representation is shown in figure 1.1. Numbers one to four are located in separate areas, five till eight are located in the disassembly area. Separate areas are due to the different operating temperatures and hygiene related problems, for example, the live birds are dirty and have therefore to be separated from other areas of the plant. For sake of simplicity the process is represented in a general way. In reality different layouts, sizes and options may change processes.

1. Live bird handling. Live birds enter the plant in crates and are emptied by the GP (Grower to Processor) system.

2. Killing and de-feathering. De-feathering is crucially important for the presentation of products with skin on them. It is also a preparation step.

3. Evisceration and organ handling. This step is a preparation for chilling and other downstream operations.

4. Chilling and maturation. For optimum shelf-life, quality, freshness and food safety, end products must be chilled effectively. Chilling and maturation consist of different cooling methods.

5. Grading and distribution. The weight and quality of both whole products or parts is automatically determined in various points in the process.

6. Cut-up. The cut-up process determines which parts will be removed. Not all parts are suited for specific purposes, e.g. bruises or broken wings.

7. De-boning. Scanning of the products ensures that no containments like bone peace’s are left in the end-products.

8. End-processing and dispatch. Batching of products and creating packages for distribution to consumers.

Figure 1.1: MSPP plant layout
1.1.2 Sales and Service

Marel operates a network of sales and service units (SSU) all over the world. Most of the company’s products are manufactured in the Netherlands, USA, Iceland, Denmark, England and Slovakia with smaller production facilities in Singapore and Brazil. An SSU is the first local contact point for customers. SSU’s are responsible for settling sales, installing equipment and after sales services. Product centers are to support the SSU’s efficiency. An important factor for Marel’s success is the professional support by skilled, local service teams. They play an essential role in the driving force behind the increased income of service activities and spare parts. Second they cherish long term relationships with customers which result in future acquisitions.

1.2 Problem context

Marel builds systems which are configured per order called smart customization, and therefore in a large variety. Customers have many options to choose from and customize their system in order to fulfill their requirements. The ability to transfer visual and performance information is a key component in the acquisition phase. A current trend is that decision makers in the acquisition phase do not understand the processes, which becomes a problem.

Bengtsson and Johansson (2002) argue that there are empirical as well as theoretical reasons that computer modelling and visualization may serve as a common, efficient language among employers, employees and outside experts discussing professional matters. Differences in background and jargon between different individuals and different occupational groups may be bridged, implying that both vertical and horizontal communications are supported.

Virtual reality is a useful method to improve the understanding of the plans and to support interdisciplinary discussions. Virtual Reality (VR) allows a user to step through the computer screen into a three-dimensional (3D) world. The user can look at, move around, and interact with these worlds as if they were real (Muijber et al., 2004).

The advances in Virtual Reality technology in the last decade have provided the impetus for applying VR to different engineering applications such as product design, modelling, shop floor controls, process simulation, manufacturing planning, training, testing and verification.

In the case of Marel, the application of Virtual Prototyping (VP) which is a subsidiary of VR, could be used to prove design alternatives, to do engineering analysis, manufacturing planning, support management decisions, and to get feedback on a new product from prospective customers.

1.2.1 Current situation

Within Marel the department Project Engineering creates two dimensional (2D) layouts for customer plants based on quotations and or customer contact made by an SSU. Layouts are used to explain the process of production and to make sure the systems fit within the surroundings.

Typical problems with such traditional 2D models are that only experts understand the content fully. For increased understanding, 3D Computer Aided Design models could bridge the gap between different areas of expertise (Lindskog et al., 2013).
1.2.2 Desired situation

The desired situation is to become more transparent to the customers who do not fully understand the complete process. The first step in becoming more transparent is the change from 2D towards 3D CAD models. The change between 2D and 3D has already started at Marel and is in its implementation phase. The constructed 3D CAD models can then be used for a VR environment.

Virtual Manufacturing (VM) is one of the applications of applying VR technology in manufacturing applications. Virtual manufacturing is defined as a computer system which is capable of generating information about the structure, status, and behaviour of a manufacturing systems as can be observed in a real manufacturing environment (Muijber et al., 2004).

This project aims to investigate virtual manufacturing as a presentation tool based on a case study to make a proof of concept. The case study material is provided by Marel.

1.3 Assignment

In order to facilitate customer decision making and provide added value for the customer, this project is looking into the possibilities to visualize poultry processing plants comprising a process representation and several options from which the customer can choose. Options which may be selected are, for example, different system configurations that result in changes in performances and product flow. The performance under investigation include the throughput of the system combined with the availability of machines. Together the process representation and performance analysis provide better understandings and insights of system behaviours.

*The goal of this project is to demonstrate a process representation and to map out the possibilities of simulation tools in general. Describe how a company like Marel can utilize the advantages of simulation tools in the long run.*

1.4 Research questions

The goal of the project leads to the following general research question.

> How can we facilitate sales process and customer service based on a simulation tool for process representation and performance analysis?

The main research question will be investigated by answering the following more specific sub questions.

1. *What are the requirements of a simulation tool for process representation and performance analysis?*
2. *What are, in the long run, potential programs for the simulation tool?*
3. *What are, in the long run, opportunities of a simulation tool in general for Marel?*

1.5 Methodology

This project can be characterized as a business problem solving project. The problem of MSPP is the transfer of visual and performance information. Business problem solving projects are undertaken to improve the performance of a certain business unit or organizational unit (Aken
et al., 2012). The project satisfies the following quality criteria; performance-focused; design-oriented; theory-based; justified and client-centred. The project is focused on the major requirements of Marel by designing a production simulation model including visualization support for better understanding the processes.

In operation management research an early contribution towards a methodology model has been made by Mitroff et al. (1974). The Mitroff model is an accepted model in operations management, see figure 1.2, and is based on methods initially used when operations research emerged. The model provides guidance in structuring research and to identify the processes and stages that should be followed. It comprises the following four phases which jointly create the operations research approach: conceptualization, modelling, model solving and implementation. In this project the model solving phase does not apply. The simulation tool is used for evaluation. However, the simulation model will be validated which is the arrow between the scientific model and the reality, problem situation.

![Figure 1.2: Mitroff et al (1974) research model](image)

### 1.5.1 Conceptualization

In the conceptualization phase a conceptual model of the problem and system under investigation is developed. A broad definition of the problem to be solved is mentioned. Decisions regarding the variables which need to be included in the model, and the scope of the problem and model are addressed. Bertrand and Fransoo (2002) argue that the conceptual model should make use of a wide variety of concepts and terms which are accepted as standards published in operation management literature. The model will serve as a stable basis for subsequent development in the modelling phase.

### 1.5.2 Modelling

The modelling phase comprises the actual model building and determines the causal relationships (Bertrand and Fransoo, 2002). Two types of models can be generated, numerical analysis and/or computer simulation. When the problem is too complex for formal mathematical analysis, computer simulation techniques are used as a research tool. Although this method generally leads to lower scientific quality, the relevance of the process or problem studied may be much
higher (Bertrand and Fransoo, 2002).

Simulation implies that the researcher does not solve the model by mathematical calculus, but tries different values for decision variables of the model in order to understand the model’s output (Kleijnen, 2007). Bertrand and Fransoo (2002) argue that when research uses computer simulation a number of additional steps need to be carried out. An important step is the justification of the research method. Only results with statistical significance can be reached.

In this project the model should be a throughput analysis model which is capable of determining throughput based on availability of the system.

1.5.3 Validation

After the modelling phase, the validation takes place. Validation is performed to conclude if the model is valid, it yields acceptable results. Furthermore the model has to be verified. For the requirements, an investigation of the differences between an analytical model (idealized) and a simulation model (more realistic) is performed. The analytical model contains assumptions which are different from the simulation model. To what extend are assumptions necessary and how will they influence the models output.

1.5.4 Implementation

The last step from solution towards the problem situation is called the implementation phase. This phase comprises the actual integration of results. Specifically for this project it contains the conclusions of the project and translate them into model instructions.

1.6 Deliverables

The project will provide a proof of concept for the simulation tool. Based on case study material, the representation and the performance analysis as stated in paragraph 1.3 are elaborated.

1.7 Outline

The outline of this report is as follows. Chapter 2 presents the conceptual model. Chapter 3 contains the visualization of MSPP plants. In chapter 1.5.2 the model is constructed and in chapter 5 the model is verified and validated. A numerical analysis is presented in chapter 6. Finally, the conclusions of the thesis are provided in chapter 7.
Chapter 2

Conceptual model

This chapter contains the conceptual model as explained in paragraph 1.5. A conceptual model is a complete specification of the model to be build. Although it is an important part of developing a simulation, there is not much written about the content of a conceptual model (Robinson, 2004). The main reason for this is that conceptual modelling is more of an "art" than "science" and it is difficult to define methods and procedures, it is largely learnt by experience. Therefore the structure of this document is taken from various sources who have discussed the contents. Law and Kelton (2007) briefly describes the use of a written assumptions document. An assumptions document is not an "exact" description of how the system works, but rather a description of how it works relative to the particular issues that the model is to address. Robinson (2004) discusses the conceptual model in a broader perspective and gives a formal definition.

"The conceptual model is a non-software specific description of the simulation model that is to be developed, describing the objectives, inputs, outputs, content, assumptions and simplifications of the model"

From the definition the following sequence of activities is presented. First, the concepts of production are discussed and the principles behind certain general processes are explained followed by the objectives of the study. Second, the input and output of the model are evaluated. Third, the content of the model is dealt with. Afterwards, the assumptions about the model are given. Fourth, the simplifications and finally, the limitations are presented. This chapter ends with a short summary.

2.1 Production process

The production process is described in three separate topics, the areas of the factory, modules of in the area and the connecting transportation line. In general the production process is a disassembly process where each area produces end-products.

2.1.1 Areas

The previous chapter has briefly highlighted the production process of MSPP. In this paragraph, the process of interest will be explained and comprises the steps after chilling and maturation as shown in paragraph 1.1.1. In general these processes can be categorized as the cut-up process ACM-NT (Automatic Cutting Machines - New Technology) and consist of the grading and distribution, cut-up, de-boning and end-processing of products. See Appendix A for ACM-NT information. Roughly stated the areas of interest are displayed in figure 2.1.

- Wing area, the wing area harvests the wings of products.
• **Breast cap cutting area**, breast caps harvested are further processed apart from the transportation line at the AMF stations. Breast cap cutters are placed multiple times in a transportation line in series to make precise weight classes for the AMF stations. Most of the time the six AMF stations are used in parallel and have the same capacity as two transportation lines.

• **Leg area**, the leg area performs operations to the remaining products in the shackles after the breast caps have been removed. This area is the end of the line and batches the legs from the transportation line in crates.

• **AMF area**, the AMF stations harvest the fillet and tendons from the breast caps removed at the breast cap cutting area. This area is separated from the transportation line and can therefore operate in parallel.

![Figure 2.1: ACM-NT process](image)

Each of those areas performs operations to the product and contain a flow of material harvested from the products over conveyor lines or batching in crates. Appendix B shows the products
that follow the disassembly process. At the end, the legs are left in the shackles and collected in bins.

2.1.2 Modules

Each area in the plant contains multiple modules, a graphical representation is presented in Appendix A. Modules are essentially machines of equipment which have a specific purpose in the disassembly process. Some perform pre-processing actions for the harvesting of materials where others harvest the material. Within MSPP, the arrangement of modules within a system is called smart customization. It is the principle of customizing modules to fulfil customer requirements. Each end-product has a certain configuration of modules in the line, where not all the modules might be in use. Most of these modules have the option to be by-passed when unused. The configuration of modules is based on the planning and delivery of end-products.

Components

A module is only a small part of a total plant configuration but can still be substituted further to components and sub-assemblies. Appendix C provides more insight into the components. Each of the process lines is split up into modules which contain critical components. MSPP has classified their components into five classes, namely, A-B-C-D-E components. For sake of brevity, only the B-parts will be explained here. B-pars are critical "breakdown" parts. These are parts or assemblies of parts, which, if defective, make it difficult or impossible for production to continue. For example, entire processing units of rotary machines, motor reductors, three-phase motors, motor variators.

2.1.3 Transportation line

The transportation unit is constructed from steel lanes containing shackles in a chain to move products through the various areas and modules. The transportation lines are most of the time in parallel and operate at approximately equal speeds, it is a form of continuous processing with discrete products. The modules are placed over the transportation line to perform operations. The placement of double lines is a result from the input before the ACM-NT where speed difference determines the number of production lines. Input before the ACM-NT line is out of scope. Because the transportation line is in parallel all modules are twice in a area, this means there can be processed if only one line is operating, but will have half the throughput. Switching between lines is impossible.

2.2 Service Department and maintenance

The Service Department is responsible for the maintenance of MSPP equipment. Their services include engineer assistance in repairs, material supply for repairs, scheduling and supervision of preventive maintenance, training of maintenance crew and assistance in adjustment of modules. Each plant with MSPP equipment has the opportunity to acquire the services of the Service Department and benefit from the added value. Added value is generated by maintenance contracts in the first place. Such contracts agree on a preventive maintenance type. It should be noted that maintenance is performed by the on-site engineers and not by MSPP engineers.

2.2.1 Maintenance Policy

MSPP employs in general two maintenance policies options for their customers. The first one is applying only breakdown maintenance, that is only repair equipment when it has failed.
second one is applying preventive maintenance. Preventive maintenance is a form of maintenance that replaces parts of equipment before they have failed. Preventive maintenance exists in three classes, based on the type of customer a class is awarded. Figure 2.2 shows a diagram of the maintenance classifications. Condition based maintenance is currently in the development phase and is not treated here.

**Figure 2.2: Maintenance Classification**

- **Preventive Maintenance**
  - Failure based Maintenance
  - Preventive Maintenance
  - Condition Based Maintenance
  - $+2p$
  - $p$
  - $-2p$

**Failure based policy**

The failure based policy is essentially the baseline policy. The policy waits till a part fails and applies a corrective maintenance action. Corrective maintenance is often named repair and is carried out when an part or equipment has broken down. The purpose of a corrective maintenance action is to bring a module back into the operational state. This can be done by repairing or replacing a broken part or switching in redundant equipment. Failure based maintenance is also known as breakdown maintenance or run-to-failure maintenance.

For customers who operate without any support in maintenance from the service department the assumption that all those plants operate the failure based policy is not realistic. In reality, it is highly likely those plants perform some sort of preventive maintenance that involves functional and operational checks to verify if equipment is still operating properly. The so called first line maintenance, lubricating, tensioning and the exchange of consumable parts is carried out by the plant operators.

**Preventive Maintenance policy**

Preventive maintenance is the execution of planned maintenance when parts or equipment is functioning properly to prevent future failures. Example activities to equipment involve, inspection, adjustments, lubrication, parts replacement, calibration and repair of parts that are beginning to wear out. The purpose of preventive maintenance is to reduce effects of breakdowns and to maximize the production system availability for use when required. It is generally performed on a regular basis, regardless whether or not functionality or performance is degraded. Reasons to keep production equipment in good operating conditions are the avoidance of production disruptions, decrease production cost, enhance a high quality and maintain a high
availability.

Three common forms can be found in practice on the part level, age-based, block-based and minimal repair-based. The type of preventive maintenance applied at MSPP is a block replacement policy. The block replacement policy applies preventive maintenance on set times, $T$, $2T$, $3T$, .... Apart from individual part breakdowns repaired by corrective maintenance, the logic is to exchange a cluster of parts in an overhaul kit which are known to have a wear relationship. Preventive maintenance is performed by use of a Preventive Maintenance Schedule (PMS), depicted in Appendix C. It should be noted that certain modules contain components subject to a constant failure rate, there is no clear indication when these parts or sub-assemblies fail. Most of these parts result in an immediate line stop for repair. Due to their randomness they are omitted from the PMS schedule.

As displayed in figure 2.2 preventive maintenance exists in three subclasses, $-2p$, $p$, $+2p$. The $-2p$ class is allocated to customers with a light use of equipment, for example, customers who perform regular less aggressive cleaning for example require less maintenance. The $+2p$ is assigned to customers with a heavy use of equipment. The middle one, $p$, is the normal version. According to MSPP the three classes of preventive maintenance have the same result, that is the operational performance is assumed to be equal. What distinguishes the three from each other is the cost associated per time unit, the heavy class has the highest cost per period. All the preventive maintenance actions are executed outside the operating hours and does therefore not influence the availability of equipment. However, a trend is that plants of MSPP become utilized 24h a day 7 days a week. The preventive maintenance actions are currently performed during night between two day shifts of 8h or on Sunday when there is no production. This becomes problematic when systems are fully utilized in the future. As a result, preventive maintenance influences the availability of a system in the future.

In general, the more preventive and conditional maintenance is done, the less corrective maintenance is needed during operational hours. Timely, routine repairs circumvent large-scale repairs, adverse effects of repairs during production have major influences on scheduling and planning. Downtime cost are high and therefore undesired.

### 2.2.2 Type of failure

Within MSPP two types of failures exist in the ACM-NT lines. The first one is the *technical failure* where there is a electrical or mechanical failure. For example, when a shackle breaks or jams the transportation line. This type of failure causes the line to stop immediately for a repair action, i.e. no further processing is possible due to the series type of production. The second type is *technological failure*. These type of failures occur due to products that have not been processed correctly in the previous stages. For example, the wings have to be harvested at all times in order to be able to use the breast cap cutting modules which follow afterwards. When a product arrives at the breast cap cutting module with its wings still attached the module cannot handle the products. When the subsequent module is not able to handle the product with deviations caused by a technological failure the line is stopped and a repair action is required to the non-operating module. The technological failures can be named process failure due to the stop of subsequent processing modules. A technical failure does not always result in a technological failure, some modules can be switched off and the line is able to proceed processing. An example is the wing tip cutting. When wing tips have not been removed, the line does not stop. These failures are non-critical for the processing line and should be identified in data. Consequences of these failures is discussed in paragraph 2.2.5.
2.2.3 Repair action

The repair of a failure is partitioned into subclasses as indicated in figure 2.3. Each stage takes a small amount of time for the complete repair action. First the time to detect a failure occurs. The diagnosis of the problem follows next which is determined by the skills of the maintenance engineer. Subsequently the time to obtain parts and personnel to fix the problem can delay the repair time in the next step. When the parts and maintenance crew are unavailable the time to obtain them can range from minutes to days. When all resources are present, the repair can take place. Finally, if required the testing of the repair can assure the repair action was successful and operation is restored. For MSPP this contains mostly the adjustment of modules. All those subclasses are registered under two parameters, the Mean Time To Support (MTTS) and Mean Time To Repair (MTTR). The MTTS contains the time to detect a failure, time to diagnose the problem and the time to obtain parts and labour. The MTTR is essentially the time spend to restore the module into operational state and includes repair time and testing time. For ease of use, the total time spend to repair a failure can be expressed in the Mean Time To Restore the System (MTTRS).

![Partitioning of repair times](image)

2.2.4 Yield loss

Failure of components, sub-assemblies or complete modules may result in yield loss due to the damage or disruption of optimal processing settings. Each machine can have different impact on the yield for end-products. Hopp and Spearman (2011) state that production quantities are uncertain because the number of good parts that finish can be less than the quantity that start, named yield loss or fallout. MSPP defines yield as the capability of maximally utilizing the products capacity in terms of harvesting material. Modules, such as the AMF lines are adjusted to a specific product weight range to maximize harvesting resources, i.e. preciser harvesting.

Although the yield of a production process is customer and flock dependent, it can be modelled. Initially, the use of yield will be in the form of good products instead of harvesting material. Due to the throughput which is in terms of products the application of yield in terms of harvesting quality is applied differently. Harvesting quality deals with the kilos harvested from the processed products and can be included by taking the average weight of a product and the throughput rate.

2.2.5 Rework

When non-critical modules fail as explained in paragraph 2.2.2, the process continues where the failed module causes rework items. An example is the Wing Tip module. When this module fails the end-products require manual rework on cutting the tips of products. Most failures
cause rework items and not the stop of the line because the stop of a processing line is highly undesirable.

2.3 Objectives of the simulation study

As stated in the problem definition the desired situation is to become more transparent to the customers. This will be in two broad categories, material flow and maintenance performance presented below. Material flow will be in the form of a presentation tool, whereas the maintenance performance and throughput is in the form of a simulation tool.

Simulation is a computerized imitation of the operations of a system for the purpose of estimating its measures of performance as it evolves over time. It is executed through time to generate representative samples of the measures of performance. Simulation modelling deals with a statistical experiment whose output, representative samples, must be interpreted by appropriate statistical procedures.

2.3.1 Presentation tool

In order to facilitate customer decision making, and provide added value for the customer, this project is looking into the possibilities to visualize poultry processing plants. Visualization comprises a process representation and presentation for several options from which the customer can choose. Options which may be selected are, for example, different system configurations that result in changes in performances and product flow. The properties of the presentation tool will be further elaborated in separate chapter, chapter 3, since it is outside the scope of the simulation tool.

2.3.2 Simulation tool

The function of equipment in manufacturing is to support the production of products for downstream customers. This inherent capability of equipment is maintained by maintenance practices. Maintenance is the action necessary to sustain and restore the performance, reliability and safety of equipment (Kumar et al., 2012). It is impossible for any part to maintain its function forever, as failure and degradation of performance is inevitable. Maintenance primary function is to reduce or even eliminate the consequences of equipment failures resulting in reliable equipment that functions to the required performance.

According to Löfsten (2000) the majority of plants use Total Maintenance Cost (TMC) and availability to measure the maintenance performance. Measuring maintenance performance is helpful when evaluating the effectiveness of maintenance decisions. Such decisions are the choice for preventive or failure based maintenance as explained in paragraph 2.4.3.

According to Li et al. (2009) throughput analysis is important for the design, operation and management of production systems. Metrics for analysing the productivity of manufacturing operations from the equipment level to the system level are of increasing importance to companies seeking to continuously optimize existing operations (Huang et al., 2002). Understanding the productivity of a system typically involves the analysis and understanding of the complex layout and interconnection of many pieces of equipment.
2.4 Input and Output

In the previous paragraph the objective of the simulation tool is presented. From the objective the output can be determined and subsequently the input parameters. Input parameters can be changed to influence the output, i.e., experimental factors. This paragraph is constructed as follows, first, the availability is evaluated. Second, the throughput is discussed. Finally, the cost components are dealt with. Each of these paragraphs comprises of a definition, equation and parameters for the model.

2.4.1 Availability

The first topic of interest is the availability of a maintained system.

Definition

Availability is defined as “the probability that a system is operating satisfactorily at any point in time when used under stated conditions, where the time considered includes the operating time and the active repair time” (Stapelberg, 2009). From this definition it is obvious that any form of availability analysis is time related. The basic equation for availability is presented in equation 2.1 and figure 2.4 shows the availability cycle of a maintained system.

\[
\text{Availability} = \frac{\text{Up Time}}{\text{Up Time} + \text{Down Time}}
\]  

(2.1)

Figure 2.4: Availability cycle

By substituting the time elements of downtime, various forms of availability can be formulated. They result in differences in approaches for availability analysis as stated below.

1. Inherent availability, \( A_i \)
2. Achieved availability, \( A_a \)
3. Operational availability, \( A_o \)

Parameters

The prediction of inherent availability is based on two parameters, mean time to failure (MTTF) and mean time to repair (MTTR). It is the most basic form of availability calculation.

\[
A_i = \frac{MTTF}{MTTF + MTTR}
\]  

(2.2)

Achieved availability takes into account that equipment is subject to preventive and corrective maintenance. It is an improvement towards reality of the inherent availability. The assessment of achieved availability depends on the mean time between maintenance (MTBM), mean corrective maintenance time (MCMT) performed between cycles and the mean preventive maintenance time (MPMT) spend in a cycle. The Mean Corrective Maintenance Time is composed of the Mean Time To Repair and Mean Time To Support as discussed in paragraph 2.2.3.
The formula for calculating the *achieved availability* is as follows,

\[ A_a = \frac{MTBM}{MTBM + MCMT + MPMT} \]  

(2.3)

Where the MTBM is computed by,

\[ MTBM = \frac{T}{M(T) + T/T_{sm}} \]

(2.4)

Here, the MTBM is a variable dependent on both the planned and unplanned execution of maintenance activities. In this function, \( T \) is the total operational time and \( T_{sm} \) the time between scheduled maintenance. Dividing the total time by the expected number of failures determined by \( M(T) \) and the number of preventive maintenance actions results in the MTBM. However, at MSPP the preventive maintenance is executed at fixed time intervals set by the block policy. This results in the modification of equation 2.3. The MTBM is fixed, the corrective and preventive maintenance time is of influence to the uptime between preventive maintenance actions. The achieved availability equation applicable to MSPP is,

\[ A_a = \frac{MTBM - MCMT - MPMT}{MTBM} \]

(2.5)

*Operational availability* is again an improvement towards reality of the previous form. Operational availability takes into account maintenance and the unavailability of spares due to the logistic delays. Parameters for calculating the operational availability are, MTBM of equation 2.4 and mean down-time (MDT). Mean down-time is related to spares supply, corrective and preventive maintenance and other delays resulting to maintenance actions. The equation to calculate the *operational availability* is:

\[ A_o = \frac{MTBM}{MTBM + MDT} \]

(2.6)

Again a modification for MSPP is required. The modification is based on the same arguments as for the achieved availability. This changes the equation of operational availability to,

\[ A_o = \frac{MTBM - MDT}{MTBM} \]

(2.7)

**Data**

The ability to calculate the availability depends on key pieces of data such as the inter-arrival times of breakdowns and repair times. Generally it will only be possible to estimate those distributions. This is done after taking direct observations from an existing version of the system under study or from a similar system. The data for the availability calculation is based on a maintenance log of one of the customers of MSPP. This log contains the inter-arrival times between corrective maintenance and the times spent for repairing the failure. However, this log contains all failure data. Not all failures are preventive maintenance related and therefore has to be filtered. Examples are, when an accident with a fork lifter has resulted in the breakdown of a module, or when B-parts fail because they are not included in the preventive maintenance program. Those failures of B-parts occur at the same rate under the failure based maintenance as under the preventive maintenance policy. When determining the distributions for repair times and inter-arrival times of breakdowns the events related to preventive maintenance should be taken into account. Data logs are plant specific and are subject to influences such as process speed, operating time per day, number of days produced per year. Plants operating at higher speeds will encounter a higher loading on the production lines resulting in more wear. Increased wear will lead to more failures during operational hours. Doubts about data should be removed, a simulation model can only produce reliable output based on reliable input.
2.4.2 Throughput

Randomness in production caused by machine breakdowns or random processing times causes the number of parts produced by a production system to be random variable over a fixed time interval (Li et al., 2009). The output from a continuous material flow production system with no inter-station buffers is closely related to the total operational time of the system according to Dhouib et al. (2009). Because processing rates are deterministic and identical and furthermore if there are no inter-station buffers, then the amount of materials produced in a given period is simply the product of the processing rate and the total operational time of the system in the same period (Tan, 1998). The processing rate of a production line is determined by the line speed. Overall Throughput Effectiveness (OTE) presented by Muthiah and Huang (2007) is a metric which calculates the ratio between actual throughput and theoretical throughput for series, parallel, assembly and expansion systems. Any factory layout can be modelled using a combination of the predefined sub-systems.

Definition

The average output of a production system (machine, workstation, line, plant) per unit time (e.g., good, non-defective, parts per hour) is defined as the system’s throughput, or sometimes throughput rate (Hopp and Spearman, 2011).

Parameters

Computation of OTE is performed by the equations presented in table 2.1. It is a modified function of the theoretical Overall Equipment Effectiveness (OEE) where the performance computation is for single machines. OEE is first introduced by Nakajima (1988) for evaluating the progress of total productive maintenance. According to Nakajima (1988) six big losses are identified: equipment failure, setup and adjustment, idling and minor stoppages, reduced speed, defects in progress, reduced yield. The first two are categorized as downtime losses, three and four as reduced performance and the last two as low quality. The equation of OEE is presented below.

\[
OEE = A_{eff} \times P_{eff} \times Q_{eff}
\]  

(2.8)

The three components are calculated as follows:

\[
A_{eff} = \frac{T_u}{T_a}, 
\]  

(2.9a)

\[
P_{eff} = \frac{LS_a}{LS_{th}}, 
\]  

(2.9b)

\[
Q_{eff} = \frac{P_g}{P_a} 
\]  

(2.9c)

\[ T_u \] = Total uptime of the module
\[ T_a \] = Total actual required uptime
\[ L S_a \] = Actual line speed (during uptime)
\[ L S_{th} \] = Theoretical line speed
\[ P_g \] = Good product output (units) of the module
\[ P_a \] = Theoretical Product output (units) of the module

The actual required uptime \( T_a \) is plant specific. It is largely determined by the planning and number of shifts per day. For this report, the plant will operate 15.5 hours per day, 275 days in a year for 10 years. Because \( A_{eff} \), the availability of the system is the main driver for throughput
as stated in the definition this variable will have the most impact on throughput. Performance and quality efficiency have little impact on the OEE due to the optimized speed and high quality of processing. However, OEE metrics are related to single tools. OEE is a mechanism that works for the individual isolated equipment, but in practice no machine operates isolated in a factory. Metrics for measuring and analysing the productivity of manufacturing operations from the equipment level to the factory level are of increasing importance to companies seeking to continuously optimize existing operations (Huang et al., 2002). OTE, presented in table 2.1, is a metric to evaluate performance to the system level by taking a complex manufacturing system and treat it as a combination of simple subsystems, which are a combination of individual modules. The following parameters are applicable to OTE. \( R_{th(i)} \) is the theoretical throughput rate equal to the design line speed which is equal for a production line. Index \( i \) refers to the \( i \)th machine in the line up to the last, \( n \).

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>OTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td>( \min_{i=1,2,...,n-1} \left( \frac{OEE_i \times R_{th(i)} \times \prod_{j=i+1}^{n} Q_{eff(j)} \cdot OEE_n \times R_{th(n)}}{\min_{i=1,2,...,n} \left( R_{th(i)} \right)} \right) )</td>
</tr>
<tr>
<td>Parallel</td>
<td>( \frac{\sum_{i=1}^{n} \left( OEE_i \times R_{th(i)} \right)}{\sum_{i=1}^{n} R_{th(i)}} )</td>
</tr>
</tbody>
</table>

Table 2.1: Equations for OTE by Muthiah and Huang (2007)

2.4.3 Cost

As indicated by paragraph 2.4.1 the majority of plants use Total Maintenance Cost (TMC) and availability to measure the maintenance performance. In the acquisition phase, total cost play an important role in the decision making process. Multiple options exist for determining the cost over a period. For example, the Total Cost of Ownership (TCO) and Live Cycle Costing (LCC). Both have a broad scope of incorporated cost which are too wide for this project. The cost which are considered most important are included. For the purpose of availability and throughput simulation, the acquisition, service costs for maintenance and downtime costs will be considered.

Definition

The Total Maintenance Cost (TMC) of equipment takes into consideration the cost during operational life regarding maintenance. Cost components are fixed maintenance cost, variable maintenance cost and downtime cost.

Parameters

In order to be able to calculate the cost over a period for maintenance a clear delineation of cost components has to be made. In general all cost components should be included but detailed costs will depend upon the particular project, system or product under investigation. The cost are specified as follows,

- Acquisition cost are layout specific and are incorporated per module where each module has a fixed cost.
• Service cost depend on the installed modules and the type of maintenance executed. Cost are known for a Preventive Maintenance Schedule (PMS) length.

• Corrective maintenance cost for unplanned repair during operations time are approximately X per repair and include spares and personnel hours.

• Downtime costs are approximately Y per minute depending on the area of the plant. Areas in front of the production line have more impact on the total line then areas downstream the line.

2.5 Assumptions and simplifications

In order to create a feasible solution without stepping to much into detail, assumptions and simplifications are applied. Assumptions are ways of incorporating uncertainties and beliefs about the real world. As such, assumptions are a facet of limited knowledge. It is preferred to create simple models. Simplifications are ways of reducing the complexity of the model. The facility or process of interest is usually called a system, and in order to study it scientifically we often have to make a set of assumptions about how it works (Law and Kelton, 2007).

Saturation is a situation in which the production line is never starved in the beginning or blocked at the end. There is an infinite number of parts waiting in front of the first station and there is an infinite capacity shipping space for the parts that have completed the operation at the last station. The ideal situation of saturation is required for the determination of throughput. Blocking and starvation are outside the scope of this project.

Preventive maintenance activities are assumed to be perfect. The system is always restored in the as-good-as-new state and starts in a as-good-as-new state.

Time between failures of preventive maintenance follow a certain probability distribution derived from data. Time between failures of critical "breakdown" parts are subject to a constant failure rate and follow an exponential distribution.
Chapter 3

Visualization

This chapter discusses the visualization part of the thesis. Visualization is understood to be the modelling of a MSPP plant in either two dimensional (2d) drawings or three dimensional (3d) virtual models for communication purposes. First the current situation is described concerning the way of operating at the department of Project Engineering and the customer process. Next, the improvements are stated which increase understanding followed by the requirements of the visualization. Finally, the added value is discussed concerning the visualization and animation of product flows followed by the software choice. This chapter ends with a short chapter summary.

3.1 Current situation

As a starting point the current situation at MSPP at the Project Engineering department is presented. Here the internal processes and points of concern are discussed. MSPP builds systems which are configured per order called smart customization, and exist therefore in a large variety. Customers have many options to choose from and customize their system in order to fulfil their requirements. It is the task of the Project Engineering department to engineer the plant in the acquisition phase.

3.1.1 Customer process

In order to understand the processes involved in the acquisition of a MSPP plant this section will present a customer process diagram. The diagram, shown in figure 3.1, will compose the internal processes. The process involves two departments, the Sales department and the Project Engineering department. The Sales department is where the process starts, the customer makes contact for information or a quotation request is received. Next, the Sales department draws a flow diagram containing the requirements of the customer. Not always are the requirements completely clear at the beginning of a project and the quotation request is forwarded without a flow diagram, see section 3.1.2. The department of Project Engineering starts engineering 2d layouts for the customer.

As displayed between quotation/contact and layout there are multiple iterations. An iteration is the revision of a drawing created by the engineer which is discarded (i.e. the proposed solutions is not accepted and has to be reconstructed). Iterations have to be performed due to uncertainties or changed requirements. The amount of iterations is influenced by the complexity of the project, skills of the engineer who draws the layout, the skills of the sales representative and if the client has a clear vision of the required capabilities. Each iteration consumes a considerable amount of time from the engineer and is therefore desired to be minimized. Currently the capacity of engineers to draw layouts is limited and is an issue for MSPP. The amount of quotation requests and customer contacts are larger than the Project Engineering department
The construction of the final layout after all the requirements have been satisfied still contains one to two iterations due to minor changes. All the necessary information is included in the final layout and is sent to the customer for approval. Based on the final layout the acquisition decision is made. Concerning the decision for acquisition the following characteristics apply. A division can be made between two type of customers, those with one plant or those with multiple plants. Normally, there is a team that decides on the acquisition of the project. Such teams compose of a mixture of financial and technical stakeholders such as, production manager, maintenance manager, sourcing manager and a director/owner. In the case of a single plant customer, the decision is mostly made by only the director/owner. This is further discusses in section 3.4, added value.

The diagram shows two, in blue highlighted, areas which will be added to the existing process. The simulation which is discussed in the previous chapter and Animation which is elaborated in this chapter.

### 3.1.2 Customer contact

MSPP had multiple sales agents spread out over the world. Projects initiated in Asia for example are handled by a regional sales agent. The regional sales agent constructs a document containing the requirements of the customer. This document is sent to the Sales department in Boxmeer for elaboration. It should be noted that both the departments of Project Engineering and Sales are located in Boxmeer and handle all the projects of MSPP. As can be seen in figure 3.2 the information travels through multiple stages which is not optimal. Each stage can change the interpretation of information leading to changed or misinterpreted requirements and therefore increasing the number of iterations. To overcome this issue, with large projects the engineer from Boxmeer travels to the customers location and in close collaboration with the regional sales agent a solution is created.

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**Figure 3.1: Customer process between Project Engineering and Sales department**

**Figure 3.2: Customer contact information**

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20
3.1.3 Transition

Typical problems with traditional 2d drawings are that only experts understand the content fully. For increased understanding, 3d models could bridge the gap between different areas of expertise (Lindskog et al., 2013). Because layouts are used to explain the processes of production and to make sure the systems fit within the surroundings the understanding of such 2d drawings is crucial for MSPP. This to avoid mistakes in the installation phase when a system is acquired. The first step in becoming more transparent is the change from 2d drawings towards 3d models. A 3d model is the combination and arrangement of 3d assets in specialized software where an asset is the modular representation of a module of MSPP. Assets are part of the smart-customization principle as stated in the beginning of this section. MSPP has already started building 3d assets of its modules and is currently in the implementation phase. The department of Project Engineering has recently started training engineers to model in 3d.

3.2 Improvement

Increasing the understanding of models is crucial for MSPP. A trend is that more decision making people are financially focussed and do not understand the 2d drawings and the production processes. As stated in the previous section the transition is already made towards 3d models which could increase customer understanding. This section explores the opportunities with 3d models. First the concept of virtual reality (VR) is presented. Next the animation concept is discussed.

3.2.1 Virtual reality

According to Muijber et al. (2004), Virtual Reality (VR) is a rapidly developing computer interface that strives to immerse the user completely within an experimental simulation. Within a VR environment, the user is able to look at, move around, and interact with a 3d world through the computer screen as if it were real. The article states a classification between the sense of immersion and the degree of presence it provides. The VR applications applied in manufacturing can be divided into three groups, namely, operations management, design, and manufacturing processes. Each group composes of several subgroups, for operations management they are planning, simulation and training. For Design it is prototyping and for manufacturing processes they are, machining, assembly and inspection. Existing VR technology has been applied to solve clients’ real-world problems, and has increased profitability, decreased time to market, and increased worker safety. If VR technologies are effectively implemented, it can result in improved product design, with superior quality leading to better customer satisfaction.

Recently, Chandrasegaran et al. (2013) stated that the simulation of environments or processes that would occur in the manufacture, assembly environment or use of a product is critical in providing information that would help support decisions earlier in the design process. According to Bick et al. (1998), VR is able to solve technical and industrial problems in a highly efficient manner and highlights the layout planning for new plant installations. With the VR environment it is possible to simulate and observe the manufacturing process in a close-to-reality presentation. This guarantees primarily a better understanding of manufacturing sequences and helps in the early detection of errors. The customer can be integrated into the construction process and an interactive optimisation process becomes possible.

Bick et al. (1998) also concludes that visualization helps to evaluate and understand logistical simulation. The production facility can be presented, processes evaluated and judged, and optimized by means of virtual simulation. Based on a pilot implementation case, Tseng et al.
(1998) concludes that the combination of virtual prototyping and VR techniques has a tremendous potential in providing advanced visualization and manipulation capabilities for customized product development by enabling visual evaluation and acquiring the customer’s perception on the target product.

The constructed 3D models at the department of Project Engineering can be used for a VR environment. Section 3.5 evaluates the opportunities concerning software.

3.2.2 Flow of material

Where the earlier discussed use of VR is mostly for static purposes, adding the flow of material is valuable information to understand the process. MSPP is characterized as a disassembly process where whole products enter the plant and leave in parts. An animation containing the flow of material can display the distribution of products through the various modules in the production process. 3D models and animation offer several advantages, it is capable of simplifying complicated concepts and ideas, which cannot be easily represented by words or even through illustrations in 2d. A 3d animation has a superior ability to visualize movement in a way that is easily recognized. Attention is captured by an animation, the information presented by a moving image is retained by the viewer for a long period. By using an animation for a manufacturing plant specific advantages can be highlighted and communicated in an easy way. Also, it provides personality to each project making it unique for the customer. In order to make an animation effective the following section provide the requirements.

3.3 Requirements

In order to provide a good solution for an animation or VR environment, a clear delineation of the requirements has to be made. The goal is to visualize flow, where do products end up. To make effective use of an animation the requirements have been split up into three classifications usability, the relevance of information and the level of detail.

3.3.1 Usability

The proposed solution for modelling an animation or VR visualizing has to be simple and effective to use. MSPP requires the modelling part to not take more than two hours. MSPP uses for 3d modelling the software of Autodesk Inventor which is part of the Factory Design Suite (FDS). It is desired to use the models generated by the department of Project Engineering for visualization and simulation purposes. This to avoid double work by other departments in selecting the information of a particular project. One way to solve this is to keep the used programs in the FDS environment. When the software is used within the same environment it is ensured that models are interchangeable. Within the FDS package Navisworks and 3DS Max have the ability to animate models. It should be noted that the usability changes in time as the user who makes the animation learns to work with a program. This results in a decrease in modelling time in the long run. An extensive elaboration of software is presented in section 3.5.

3.3.2 Relevance of information

In general, the possibilities with an animation are unlimited. The challenge is to model only the information relevant for customers. Most of the times the information which is relevant for the customer is context related because MSPP makes customer specific plants based on their requirements. For example, a customer might have specific requirements on safety by using fences, or the collection of bulk products in boxes is important and needs enough space for fork
lifters to move around. It is up to the Sales department to recognize the relevant information for the customer and to communicate to the engineers for a VR environment. See also section 3.4.1 for the influencing factors and Appendix H for more opportunities.

Another important aspect for the customer is to view the flow of material by using an animation. Within the factory different flows exist for each end-product. End-products are collected at separate spots in the plant and include A-grade and B-grade products, bulk collection, packaging and waste collection. By visualizing the flow of the before mentioned products the customer is able to follow the products from the beginning and see the solutions proposed by MSPP. Solutions can be processing advantages by adding or switching between options.

3.3.3 Level of detail

To not generate an overload of information for the customer the level of detail should be minimized. Only the most essential information has to be modelled. As stated in relevance of information section, the flow is essential. Options for the flow are again unlimited. For a complete plant the amount and size of products, speed of the transportation line, appearance form and colors are variables. The ability to add contrast to highlight important aspects makes understanding easier as discussed earlier in the flow of material section 3.2.2. Differentiation between A-grade (high quality) and B-grade (lower quality) products can for example be done by colour or form. It should be noted that the complex structures are known to the modeller and are a threat to the level of detail. The modeller might think the information is not overwhelming but in reality it would be. Construction should be done from the view of the customer who has no prior knowledge of MSPP plants.

3.4 Added value

Animating a model is time consuming but is an added value for the customer. This section explains the advantages of animating a model and what performance it delivers.

Recently, Akpan and Brooks (2012) shows a survey outcome of 3d simulation and display performance. The strongest response was that 3d helps communicating with the customer about problems. Many of the respondents in the survey felt that using 3d resulted in a better solution. A better solution might have partly resulted from more input from and interaction with the stakeholders during the development, because the 3d display enables to relate the model more easily to the real system. If the 3d display also enables the decision maker to use the model to get a better understanding of the behaviour of the real system, then this can assist in identifying the sources of the problems in the system and in generating solution ideas (Akpan and Brooks, 2012). There were also perceived benefits in validation and verification. Model validation, the detection of errors, requires a shorter time with 3d and influences the amount of iterations between customer contact and layout as shown in figure 3.1. When the customer has an increased understanding of the model, errors are spotted earlier. For experimentation, there was some support for the claim that 3d is more effective in evaluating model behaviour. This statement might be context related but in the case of MSPP the flow of material can be evaluated and judged if the products are transported to the right locations. The main drawbacks of using 3d packages were considered to be the additional cost, time and complexity incurred for model building. Despite validation generally being quicker with 3d, most stated that the entire decision process was longer with 3d. Also, the learning curve of using 3d software is longer than compared with 2d. Although the article states that the entire process was longer, in the case of MSPP the process of model building is characterized as smart customization (i.e. arranging assets from a library) and therefore the time required is expected to be lower.
There are empirical as well as theoretical reasons that computer modelling and visualization may serve as a common, efficient language among employers, employees and outside experts discussing professional matters. The differences in background and jargon between different individuals and occupational groups may be bridged, implying that both vertical and horizontal communications are supported (Bengtsson et al., 1996; Johansson et al., 1994).

Modelling and visualization could be cost-effective ways of demonstrating layout ideas and dynamic activities, such as manufacturing, transportation and human movements, which are otherwise difficult to describe verbally or by means of paper drawings (Bengtsson and Johansson, 2002). In the paper of Bengtsson and Johansson (2002) the goal is to address how industrial professionals judge the utility of different dimensional views of a plant when planning production and working environment in industrial settings, where the dimensional view denotes the scale and scope of a visualization. The dimensional view is divided in three types of visualization, namely, shop floor, production unit and workplace views. The ability to transfer visual and performance information is a key component in the acquisition phase.

Within MSPP, psychological ownership is perceived to be an added value, the customer sees the equipment placed inside his own building. If the customer knows the building he automatically knows how the equipment is placed and where the points of concern are concerning the fitting.

3.4.1 Influencing factors

As stated in section 3.1.1 the purchase decision is made by a team or an individual owner. In the case of a team, each team member can be influenced individually. For example, the maintenance manager would like to see that all modules can be accessed easily. A production manager is interested in the possibilities of switching between different product flows, and the off-line processes. The off-line processes deviate from the main product flow and are the collection and distribution of b-grade products, bulk collection and waste. Sourcing managers and director/owner are financially focussed and are sensitive to the financial advantages a particular solution brings. With a customized animation each aspect of importance can be highlighted to convince a team member or a decision maker.

3.5 Software

As shortly is highlighted in section 3.3.1 usability, MSPP uses the FDS package as software tool for 3d modelling and creating 2d drawings. A major requirement is that the proposed software solution should be capable of using the generated 3d layouts engineered by the department Project Engineering. Multiple software tools have been tested to suit the preferences and are listed below.

- Automod by Applied Materials
- Arena by Rockwell
- Technomatix by Siemens
- 3DS max by Autodesk
- Navisworks by Autodesk

As expected the only two solutions are within the Autodesk product family. Other programs require to build the layout again or even generate a new asset library. The exchange of information and models between different vendors is limited and only possible in standardized formats.
Those formats lose a lot of information when converted and cannot find patterns included by the engineer. Within the Autodesk product family the models are interchangeable and have a lot of modelling flexibility. However, a bottleneck is the trade-off between flexibility and practical use. To be able to model complex and highly customized situations requires the program to have enough flexibility. A solution has been found in both Autodesk products, Navisworks for a VR environment and 3DS max for the animation of product flow. Unfortunately it is not possible to combine both requirements in terms of animation and VR into one program. The animation capabilities of Navisworks are too flexible to maintain a modelling time of less than two hours.

Models build by the Project Engineering department contain lots of information about the plants. The information stored in those models can be useful for other departments such as, for example, the Service department. Within the FDS environment data storage in models is available. Data can be stored to the part level where each small component of a model can contain specific information. For the Service department, the simulation data described in the conceptual model can be stored inside those models. The exchange of information is possible by a Visual Basic for Applications (VBA) code. Information is transported from the model to Excel. When data is imported to Excel many other software is able to read this format.
Chapter 4

Modelling

This chapter contains the modelling of the simulation model. The simulation model contains the computation of system availability and based on the availability a throughput determination for a production line. First, in paragraph 4.1, availability simulation is explained. The performance measures are presented in paragraph 4.2. In paragraph 4.3 the output of the simulation model is stated. The type of statistical observations is discussed in 4.4. Finally, in paragraph 4.5 the software and data transfer is dealt with.

4.1 Availability simulation

The simulation of availability is based on the generation of random numbers for up-times and downtimes with respect to a certain distribution. In order to compare the performance between preventive and corrective maintenance a distinction has to be made in terms of the cycle length. When preventive maintenance is applied, the cycle is generally shorter than the cycle for corrective maintenance. Corrective maintenance will be compared with preventive maintenance in a period of 10 years. The time length of a cycle for preventive maintenance is module specific and values can be found in a PMS. A PMS is a schedule for the block replacement policy and contains the time between preventive maintenance actions.

In paragraph 2.4.1 the computation of achieved availability is explained. The equation is slightly modified due to elimination of preventive maintenance time as discussed in 2.2.1, and is shown in equation 4.1. It is composed of up-times and downtimes which are generated by a simulation program and a correction for breakdown parts indicated by B. The breakdown parts are further elaborated in the next paragraph. The first generated uptime is compared with the interval time of the PMS and when shorter, a failure has occurred. The accompanying repair time is generated and a repair is logged. The first uptime and repair time are added into a variable named cycle. When the cycle is shorter than the length of a block in a PMS, the process of generating up-times and repair times repeats until the length of time exceeds the PMS block length. Figure 2.4 shows the up and down states and the change between them. In figure 4.1 the influences of failures on the system is shown. Due to the series arrangement of equipment, each failure results in the system to stop its production. When the system is down, other modules cannot fail because the line is stopped. Production is stopped, the transportation line does not carry products to the modules and therefore the modules are in idle state. When modules are in an idle state the loading is expected to be zero. We assume that modules cannot fail in the idle state. The simulation model will correct the up-times according to failures of other modules in the line. By recording the downtime of a module, the up-times of the other modules in the line can be extended with the recorded downtime. This way, the assumption of no failures during idle time is incorporated.
Chapter 4. Modelling

Figure 4.1: Availability of a system

\[
\text{Availability} = \frac{MTBM - MCMT - B}{MTBM} \tag{4.1}
\]

4.1.1 Breakdown parts

In order to incorporate the influences on availability by breakdown parts the following assumptions are used. Breakdown parts are assumed to be random and have an exponential lifetime distribution. The number of events in a time interval is counted by the Poisson Process with a mean rate of occurrence, \( \lambda \). The number of events in a time interval can be approximated by,

\[
m(t) = \lambda t \tag{4.2}
\]

The breakdown parts have a known repair time, multiplying the time for exchange with the rate of occurrence determines the loss of availability during operational time. Further, in this report the breakdown parts are omitted from the analysis due to lack of information about failure rates.

4.2 Performance measures

After the modules have been simulated the output of the system can be evaluated. Performance is evaluated in three paragraphs, availability, throughput and cost.

4.2.1 Availability performance

The first performance of interest concerns the output of the availability analysis. This simulation calculates the availability, the number of failures during operation time, downtime generated by failures and the system availability of the model. The model state space is composed of all modules placed in series in the production line. The range is from the first up till the \( n \)th module in a single line.

Availability

The availability of a module is computed by equation 2.1 from the conceptual model.

\[
A = \frac{Up\ Time}{Up\ Time + Down\ Time} \tag{4.3}
\]
Total number of repairs

The total number of repairs can be computed by the sum of all repairs \( R_i \) encountered by the modules in the line starting from the first \( i \), up to the last \( n \),

\[
Total\ repairs = \sum_{i=1}^{n} R_i \quad \text{for } i = 1, 2, \ldots, n
\] (4.4)

Total downtime

The total system downtime is computed by the sum of downtime \( D_i \) caused by the modules,

\[
System\ downtime = \sum_{i=1}^{n} D_i \quad \text{for } i = 1, 2, \ldots, n
\] (4.5)

System availability

In order to compute the system availability, the distinction has to be made between a series and parallel structure found in MSPP plants. Figure 4.2 shows the series structure and parallel structure. Basically the structure is divided into subsystems, where the series modules and parallel modules are combined into a single subsystem. After all subsystems have been computed, the equation of 4.6 evaluates the system availability, where \( a_i \) is the availability of a subsystem (Lewis, 1996). When the series structure is applied equation 4.6 is used, where \( a_i \) is the availability of a single module in a series line. When the modules are placed in a parallel structure, equation 4.7 is applicable. The assumption is that parallel structure has equal modules and at least one module has to work for the parallel structure to operate. If the modules are not equal, equation 4.8 is applicable. Again the assumption is that only one module has to operate for the system to operate. Parallel structures exist in the line but are placed in a series order due to the transportation line. This means that multiple modules with the same purposes are arranged in series and when one module fails, others take over and divide incoming products over the working ones.

\[
A_{series} = \prod_{i=1}^{n} a_i \quad \text{for } i = 1, 2, \ldots, n
\] (4.6)

\[
A_{parallel} = 1 - (1 - a_i)^m \quad \text{for } i = 1, 2, \ldots, m
\] (4.7)

\[
A_{parallel} = 1 - \prod_{i=1}^{m} (1 - a_i) \quad \text{for } i = 1, 2, \ldots, m
\] (4.8)

Figure 4.2: Series and parallel structure


4.2.2 Throughput performance

The computation of throughput is determined in paragraph 2.4.2. It is divided in the computation of OEE and OTE.

4.2.3 OEE computation

Throughput performance is dependent on the OEE of modules and the quality they obtain. The computation of OEE is explained in paragraph 2.4.2. The availability component is simulated, the performance efficiency component is equal for all modules in the same line since the transportation line has a constant speed. Performance efficiency is the ratio between actual line speed (LS) and theoretical line speed. The quality efficiency is dependent on the module and specified as parameter, the number of defect products produced. By taking the ratio of actual products and good products, production loss is incorporated. For the simulation the value of quality can be stated per module if the modules have different quality aspects, otherwise a value for the line can be provided. When the option to take the line quality, the value for all modules is the same.

\[
Q_{eff} = \frac{P_g}{P_a}
\]

\[
P_{eff} = \frac{LS_a}{LS_{th}}
\]

\[
P_g = \text{Good product output (units) of the module}
\]

\[
P_a = \text{Theoretical Product output (units) of the module}
\]

\[
LS_a = \text{Actual line speed}
\]

\[
LS_{th} = \text{Theoretical line speed}
\]

4.2.4 OTE computation

When the OEE values for modules are known, the system throughput can be computed by using the equation stated below. The equation is provided for series systems since all modules are aligned in series. Although the transportation line does not allow any form of parallelism, multiple modules can be installed in the series line. The modules in parallel series configuration cannot increase production since the transportation line determines the throughput rate. Paragraph 2.4.2 provides the equation as stated below,

\[
\min \left( \min_{i=1,2,...,n-1} \left( \frac{OEE(i) \times R_{th(i)} \times \prod_{j=i+1}^{n} Q_{eff(j)}}{\min_{i=1,2,...,n} (R_{th(i)})} \right), OEE_n \times R_{th(n)} \right)
\]

\[
(4.9)
\]

\[
n = \text{Number of modules in a subsystem}
\]

\[
R_{th(i)} = \text{Theoretical throughput rate of ith module}
\]

\[
OEE(i) = \text{OEE value of the ith module}
\]

\[
Q_{eff(i)} = \text{Quality efficiency for the module or line}
\]

Basically, the lowest performing module determined by the OEE value is crucial for the throughput of the line. It is assumed that lines in the ACM-NT line are identical and can be multiplied. That is, availability is assumed to be equal and the throughput per line is equal.
4.2.5 Cost performance

The third interest concerns the cost factors. To view which factors drive the total cost the most they have been separated into acquisition cost, corrective maintenance cost (CMC), preventive maintenance cost (PMC) and total maintenance cost. The total maintenance cost (TMC) is included to compare with the acquisition cost.

The plant acquisition cost can be computed by summing up the acquisition prices of all installed equipment in the line starting from the first $i$, up to the last $n$,

$$Plant\ acquisition\ cost = \sum_{i=1}^{n} acq_{i} \quad for \quad i = 1, 2, \ldots, n \quad (4.10)$$

The total corrective maintenance cost can be computed by equation 4.11.

$$Total\ CMC = \sum_{i=1}^{n} corr_{i} \quad for \quad i = 1, 2, \ldots, n \quad (4.11)$$

The total preventive maintenance cost includes the service contract cost for modules and maintenance hours. Maintenance hours are divided into MSPP engineer assistance hours and maintenance hours spent by the on-site engineers. The hours are incorporated without a cost component due to different wages for on-site engineers and different cost prices of MSPP engineers. The cost for preventive maintenance are computed by,

$$Total\ PMC = \sum_{i=1}^{n} prev_{i} \quad for \quad i = 1, 2, \ldots, n \quad (4.12)$$

The total maintenance cost is the sum of the corrective and preventive maintenance cost. Not all the cost for preventive maintenance will be expressed in Euro but partly in maintenance hours. This is chosen because the maintenance is largely executed by the internal personnel of a customer where the cost of personnel may differ. The number of hours spent for preventive maintenance are module specific and and based on the PMS.

$$TMC = Total\ CMC + Total\ PMC \quad (4.13)$$

When the throughput is known, the output in terms of kilo production and cost per kilo production can be computed. The cost per kilo production are particularly of interest for customers of MSPP. The production per hour is easily computed by taking the throughput of the system per hour and multiplying with the average product weight. Next, dividing the total cost of maintenance by the production kilos per hour times the period of investigation of equipment named cycle, which is normally 10 years, the cost per kilo production can be computed.

$$Production = Throughput \times weight \quad (4.14)$$

$$Cost_{kilo} = TMC/(Production \times cycle) \quad (4.15)$$

4.3 Simulation Output

The output of the simulation are all equations provided in this chapter. Most important are the number of failures, downtime resulting from the failures and the overall throughput of the system in the long run. A confidence interval by simulating multiple times can be generated for each variable. Based on those values the cost performance can be calculated.
Chapter 4. Modelling

- Availability per line/module
  1. Number of failures
  2. Downtime
  3. Availability

- Throughput per line
  1. OEE per module
  2. Throughput of the line
  3. Total production

- Cost per line
  1. Acquisition cost
  2. Corrective maintenance cost
  3. Preventive maintenance cost
  4. Total Maintenance cost
  5. Cost per kilo

4.4 Statistical observations

The book of Taha (2007) presents three common methods for gathering statistical observations. First, the subinterval method, second the replication method and third the regenerative (or cycles) method. For the subinterval method, suppose that the simulation is executed for $T$ time units and within this period it is desired to obtain $n$ observations. The subinterval method first truncates the initial period and then divides the simulation run into $n$ equal subintervals. The average of the performance measure within each subinterval is then used to represent a single observation. An advantage of this method is that the effect of warm-up conditions is mitigated. A disadvantage is that subintervals with common boundaries are necessarily correlated. This effect can be alleviated by extending the time for each subinterval. In the replication method, each sample of observation is represented by an independent simulation run in which the warm-up period is truncated. The calculation of the average of observations is calculated the same as for the subinterval method, however, the standard formula for variance is applicable because the intervals are not correlated. The advantage of the replication method is that each sample is truly independent due to a distinct random number stream. A disadvantage is that sample can be biased by the warm-up period conditions, which can be alleviated by expanding the time. The regenerative (cycle) method is an extended case of the subinterval method. It attempts to reduce the effect of autocorrelation that is characteristic for the subinterval method by requiring similar starting conditions for each batch. A disadvantage is that it might yield a smaller number of samples to determine the average. However, under steady state conditions, the starting points for the successive samples are more or less evenly spaced. The simulation model will use the replication method which is applicable for generating multiple simulation runs of the system.

4.4.1 Warm-up period

The warm-up period is the initial period of time before a simulation reaches the steady state behaviour. In the initial period the simulation produces erratic behaviour and is usually referred as transient or warm-up period. Because this model will not have any form of queueing the steady state behaviour does not apply. The simulation runs do not contain a warm-up period and has therefore not to be adjusted.
4.5 Software and data transfer

An example simulation is programmed in Matlab. Each module is programmed in a m-file which is called upon by a simulation run. This is a modular way of constructing the simulation and making it easy to modify for different layouts. Other software, which are similar to Matlab but free are R by R foundation and Octave. Both are available on Windows. The simulation code has been tested and works on Octave. A drawback is the completeness, where Matlab has many packages available other software might need more programming. Most of these additional equations are provided in Appendix F of this report. It is even a solution to program the simulation in VBA language to execute in Excel. This would be highly desirable since data required for the simulation can be exchanged easily to Excel without any intermediate step. An option to store data for the simulation is in the Iproperties of the Autodesk product group as discussed in paragraph 3.5.
Chapter 5

Validation and verification

This chapter introduces the method to verify and validate the model. For the verification, an example module and example system will be evaluated. Based on an analytical model constructed in this chapter the output of the simulation will be compared to find deficiencies. A confidence interval for comparison is calculated based on the output gathered from the simulation model. There is an inability to gather large amounts of data from the real system to compare with the model. Therefore the model will be validated by gathering expert opinions.

According to Law and Kelton (2007), verification is concerned with determining whether the conceptual simulation model (model assumptions) has been correctly translated into a computer "program". Validation is the process of determining whether a simulation model is an accurate representation of system.

5.1 Analytical model

The verification of the model is performed by comparing the simulation model with an analytical model. The analytical model is a simplified view on the system being modelled. The modelled system in the previous chapter is capable of determining the availability of a production line subject to preventive and corrective maintenance and the throughput of the line. The analytical model will compute availability with the expected failures in an interval.

5.1.1 Renewal function

The first step for the availability calculation is the determination of the number of failures expected in a cycle. Because the life-times of modules are known and follow a probability distribution, renewal theory is applied. This concept is taken from Kumar et al. (2012), who discusses the computation of expected number of failures during time $T$. The starting point is a sequence of $X_1, X_2, ...$ of non-negative independent random variables having a common probability distribution function (Tijms, 2003). The random variable $X_k$ denotes the inter-occurrence time between the $(n-1)$ th and $n$th failure of equipment. Where,

$$ S_0 = 0 \text{ and } S_n = \sum_{i=1}^{n} X_i, \ n = 1, 2, ..., $$

$S_n$ is the time at which the $n$th event or failure occurs. For each $t \geq 0$, let

$$ N(t) = \text{the largest integer } n \geq 0 \text{ for which } S_n \leq t $$

Then the random variable $N(t)$ represents the number of failures or events up to time $t$. The counting process $\{N(t), t \geq 0\}$ is called the renewal process generated by the inter-occurrence times $X_1, X_2, ...$. The renewal function is defined by
\[ M(t) = E[N(t)], \quad t \geq 0 \]

Assuming the probability distribution function \( F(x) \) of the inter-occurrence times has a probability density \( f(x) \). The renewal function \( M(t) \) satisfies the integral equation (Tijms, 2003).

\[ M(t) = F(t) + \int_0^t M(t-x)f(x)dx, \quad t \geq 0 \quad (5.1) \]

This function computes the expected number of failures in an interval based on lifetime probability distributions. The numerical computation of the renewal function is performed by a discretization method. This method discretizes the time in small parts and computes the recursively the renewal function. For a fixed \( t > 0 \), the interval \([0,t]\) is partitioned into \( 0 = t_0 < t_1 < \ldots < t_n = t \). The interval is split up into small parts forming a grid, with a grid size \( h > 0 \), where \( t_i = ih \). In practical cases a four digit accuracy is obtained for a grid size ranging between \( 0.05 - 0.01 \). When using long periods for the renewal function the grid size may be lower for faster computation, in this case a sensitivity analysis can determine the correct grid size. According to Tijms (2003) the recursion scheme is able to resist the accumulation of round-off errors as \( t \) gets larger. This makes it suitable for the computation of larger time intervals expected in the failure based maintenance policy.

**Verification of Renewal approximation**

Because the renewal function is approximated, the algorithm has to be checked on errors. Two types of verification are applied to test the correctness of implementation. The first test is to generate the renewal function for the Exponential distribution. The renewal function should then return \( \lambda t \). The second test is to take a large mean value of a distribution and to plot the renewal function along side the CDF of the distribution. For a low value of the renewal function, \( M(t) \) should be equal to the CDF. Both test have yielded correct results and can be found in Appendix E.

An assumption of the renewal function is that the repairs are of negligible duration. The uptime is by far larger than the downtime of MSPP equipment, \( up >> down \). Therefore the renewal function is a good approximation of the expected number of repairs in a cycle.

**5.1.2 Availability**

Implementing the expected number of repairs in the achieved availability function is the next step. The renewal function is used to determine the amount of failures in a cycle.

\[ A_a = \frac{MTBM - MCMT}{MTBM} = \frac{t_{pm} - M(t_{pm}) \times 1/\mu}{t_{pm}} \quad (5.2) \]

The Mean Time Between Maintenance is the maintenance interval time between preventive maintenance actions denoted by \( t_{pm} \). This value is fixed for a module. The parameter Mean Corrective Maintenance Time is a variable and is computed by the renewals times the repair time. It should be noted that the renewal function assumes negligible time to repair, and thus would yield higher results in contrast to the simulation model. The repair time is computed by \( 1/\mu \) where \( \mu \) is the repair rate. The repair rate is the Mean Time To Restore a System (MTTRS) from a failure. As discussed in chapter 2 the values for failure based and preventive maintenance have different values.
5.2 Verification

To compare the analytical model with the simulation model three situations have been simulated. A single module has been simulated as presented in the next paragraph. Afterwards, a system has been simulated containing multiple modules operating dependently and is presented in paragraph 5.2.6 and at last a system with independent modules is simulated. For the dependent simulation, the modules cannot fail simultaneously. Finally, adjusted rates and extended time frames have been simulated to view differences between preventive and failure based maintenance. It should be emphasized for the difference between preventive and failure based maintenance that the analysis is based on a data set from preventive maintenance.

5.2.1 Single module

For the single module example the following parameters apply:

- The inter-arrival times of failures follow a Weibull distribution with parameters shape = 2.5 and scale = 58.
- The repair time for PM follows the Exponential distribution with mean 38 minutes and $\mu = 1,578$ per hour.
- The repair time for CM follows the Exponential distribution with mean 70 minutes and $\mu = 0,857$ per hour.
- The time between preventive maintenance is taken to be 137 days.
- The period of investigation is 2750 days.

The results of 20 runs with a length of 100 cycles is presented in table 5.1 for a preventive maintenance example and in table 5.2 for a failure based maintenance example. Both tables show that the analytical model and simulation model have similar results and that the confidence interval is situated around the analytical model. It should be mentioned that for the preventive maintenance example, the interval is shorter in comparison with failure based maintenance.
Chapter 5. Validation and verification

Preventive maintenance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean <strong>Repair time</strong> [Hours]</td>
<td>1,444</td>
<td>1,427</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,131</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[1.359; 1,527]</td>
<td></td>
</tr>
<tr>
<td>Mean <strong>Number of repairs</strong></td>
<td>2,248</td>
<td>2,253</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,075</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[2,200; 2,296]</td>
<td></td>
</tr>
<tr>
<td>Mean <strong>Availability</strong></td>
<td>0,9993</td>
<td>0,9993</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>6,1e – 5</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9992; 0,9993]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Single module comparison with preventive maintenance

Failure based repairs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean <strong>Repair time</strong> [Hours]</td>
<td>33,491</td>
<td>33,59</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,595</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[33,110; 33,871]</td>
<td></td>
</tr>
<tr>
<td>Mean <strong>Number of repairs</strong></td>
<td>53,024</td>
<td>53,035</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,281</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[52,844; 53,204]</td>
<td></td>
</tr>
<tr>
<td>Mean <strong>Availability</strong></td>
<td>0,9992</td>
<td>0,9992</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,0001</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9992; 0,9992]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Single module comparison with failure based maintenance

5.2.2 System with dependent modules

The system is constructed of six in series placed modules of the ACM-NT cut-up line. The parameters for the simulation model are presented in table 5.3 and are fictive numbers inspired by a maintenance log. When taking into account that modules cannot fail simultaneously, that is, they are idle when other modules have broken down. Under the idle state modules do not suffer from loading. The output from analysis where the idle failures have been corrected is presented in table 5.4 for preventive maintenance and in table 5.5 for failure based maintenance. The simulation contains the output of 20 runs with a length of 100 cycles.

<table>
<thead>
<tr>
<th>Module</th>
<th>alpha</th>
<th>beta</th>
<th>C\text{acq}</th>
<th>C\text{ser}</th>
<th>PMS interval</th>
<th>Repair time PM</th>
<th>Repair time CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,5</td>
<td>58</td>
<td>25,000</td>
<td>32,000</td>
<td>137</td>
<td>38</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>2,0</td>
<td>115</td>
<td>15,000</td>
<td>12,000</td>
<td>275</td>
<td>45</td>
<td>62</td>
</tr>
<tr>
<td>3</td>
<td>2,2</td>
<td>70</td>
<td>75,000</td>
<td>60,000</td>
<td>275</td>
<td>70</td>
<td>127</td>
</tr>
<tr>
<td>4</td>
<td>3,0</td>
<td>25</td>
<td>125,000</td>
<td>80,000</td>
<td>137</td>
<td>52</td>
<td>69</td>
</tr>
<tr>
<td>5</td>
<td>1,5</td>
<td>150</td>
<td>60,000</td>
<td>55,000</td>
<td>206</td>
<td>33</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>2,0</td>
<td>91</td>
<td>80,000</td>
<td>46000</td>
<td>137</td>
<td>75</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 5.3: Parameters of example system

Both tables show minor differences between the analytical model and the simulated values. The differences can be allocated to several causes. First, the simulation takes variable repair times into account, that is, they have generated random times for repair whereas the analytical model
Chapter 5. Validation and verification

### Preventive maintenance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Repair time</strong></td>
<td>232,787</td>
<td>235,177</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>8,558</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[227,314;238,260]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Number of repairs</strong></td>
<td>266,168</td>
<td>266,896</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>3,631</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[263,846;268,491]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Availability</strong></td>
<td>0,9946</td>
<td>0,9945</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,0001</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,994;0,9947]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4: System comparison with preventive maintenance and no idle failures

### Failure based repairs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Repair time</strong></td>
<td>380,159</td>
<td>383,444</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2,925</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[378,288;382,030]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Number of repairs</strong></td>
<td>297,251</td>
<td>299,349</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1,189</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[296,491;298,011]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Availability</strong></td>
<td>0,9912</td>
<td>0,9910</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>6,7e−5</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9911;0,9912]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5: System comparison with failure based maintenance and no idle failures

contains only the mean times. Second, incorporation of the assumption where modules cannot fail during idle time has a minor effect. Table 5.11 and table 5.4 reveal small differences. The number of repairs barely has a difference but the repair time shows a few hours difference.
5.2.3 System with dependent modules and adjusted rates

The following example is included to obtain results showing a larger difference between failure based and preventive maintenance. The parameters for modules have been adjusted to mimic a reliable system. This is done by reversed engineering, parameters are set according to the PMS interval data and have a very low percentage of failures before the PMS interval time. Parameters are presented in table 5.6.

<table>
<thead>
<tr>
<th>Module</th>
<th>alpha</th>
<th>beta</th>
<th>$C_{acq}$</th>
<th>$C_{ser}$</th>
<th>PMS interval</th>
<th>Repair time PM</th>
<th>Repair time CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>300</td>
<td>25.000</td>
<td>32.000</td>
<td>137</td>
<td>38</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>620</td>
<td>15.000</td>
<td>12.000</td>
<td>275</td>
<td>45</td>
<td>62</td>
</tr>
<tr>
<td>3</td>
<td>2.2</td>
<td>780</td>
<td>75.000</td>
<td>60.000</td>
<td>275</td>
<td>70</td>
<td>127</td>
</tr>
<tr>
<td>4</td>
<td>3.0</td>
<td>320</td>
<td>125.000</td>
<td>80.000</td>
<td>137</td>
<td>52</td>
<td>69</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>560</td>
<td>60.000</td>
<td>55.000</td>
<td>206</td>
<td>33</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>2.0</td>
<td>290</td>
<td>80.000</td>
<td>46000</td>
<td>137</td>
<td>75</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 5.6: Parameters of example system with adjusted rates

The output of 20 runs with a length of 100 cycles is presented in table 5.7 for preventive maintenance and in table 5.8 for failure based maintenance. Both tables show that the simulation model performs as the analytical model would predict. The output of the analytical model is within bounds of the 99% confidence interval for each value. The difference between the preventive and failure based maintenance have increased.

**Preventive maintenance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Repair time [Hours]</td>
<td>12,28</td>
<td>12,28</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[10,91; 13,65]</td>
<td></td>
</tr>
<tr>
<td>Mean Number of repairs</td>
<td>13,71</td>
<td>14,00</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[12,56; 14,86]</td>
<td></td>
</tr>
<tr>
<td>Mean Availability</td>
<td>0,9997</td>
<td>0,9997</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>$4e-5$</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9997; 0,9997]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7: System comparison with preventive maintenance and adjusted rates

**Failure based repairs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Repair time [Hours]</td>
<td>52,16</td>
<td>52,36</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1,1</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[51,44; 52,88]</td>
<td></td>
</tr>
<tr>
<td>Mean Number of repairs</td>
<td>42,51</td>
<td>42,67</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,24</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[42,35; 42,67]</td>
<td></td>
</tr>
<tr>
<td>Mean Availability</td>
<td>0,9987</td>
<td>0,9987</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.8e-5</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9987; 0,9987]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.8: System comparison with failure based maintenance and adjusted rates
5.2.4 System with dependent modules extended time

For the adjusted rates simulation an extended time simulation is executed. This example is extended to 50 years to view the differences between failure based and preventive maintenance. The output of 20 runs with a length of 100 cycles is presented in table 5.9 for preventive maintenance and in table 5.10 for failure based maintenance. Both tables show that the simulation model performs as the analytical model would predict.

### Preventive maintenance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Repair time [Hours]</strong></td>
<td>61,41</td>
<td>61,4</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>10,45</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[54,55; 6,27]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Number of repairs</strong></td>
<td>68,57</td>
<td>70,01</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>8,75</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[62,02; 74,31]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Availability</strong></td>
<td>0,9997</td>
<td>0,9997</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>5e−5</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9997; 0,9997]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.9: System comparison with extended time

### Failure based repairs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Repair time [Hours]</strong></td>
<td>273,71</td>
<td>273,79</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2,56</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[272,03; 275,40]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Number of repairs</strong></td>
<td>222,78</td>
<td>222,84</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,64</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[222,36; 223,21]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Availability</strong></td>
<td>0,9987</td>
<td>0,9987</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1e−5</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9987; 0,9987]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.10: System comparison with extended time

Observed are the larger differences between failure based and preventive maintenance. Adjusted rates and extended time increase the differences.
5.2.5 System with independent modules

For a system with independent operating modules a simulation is constructed. Here the modules are modular programmed into a simulation for ease of use. Again the CM interval to compare results is for all modules equal and is 2750 days. Parameters used as input are found in table 5.3.

The output of 20 runs with a length of 100 cycles is presented in table 5.11 for preventive maintenance and in table 5.12 for failure based maintenance. Both tables show that the simulation model performs close to the analytical model.

### Preventive maintenance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean <strong>Repair time</strong> [Hours]</td>
<td>235,378</td>
<td>235,177</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>7,687</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[230,461;240,294]</td>
<td></td>
</tr>
<tr>
<td>Mean <strong>Number of repairs</strong></td>
<td>266,429</td>
<td>266,896</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>3,677</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[263,757;269,102]</td>
<td></td>
</tr>
<tr>
<td>Mean <strong>Availability</strong></td>
<td>0,9944</td>
<td>0,994</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,0001</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9943;0,9946]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.11: System comparison with preventive maintenance

### Failure based repairs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean <strong>Repair time</strong> [Hours]</td>
<td>383,071</td>
<td>383,444</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2,649</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[381,376;384,765]</td>
<td></td>
</tr>
<tr>
<td>Mean <strong>Number of repairs</strong></td>
<td>299,452</td>
<td>299,349</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,684</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[299,015;299,889]</td>
<td></td>
</tr>
<tr>
<td>Mean <strong>Availability</strong></td>
<td>0,9910</td>
<td>0,9910</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>6,1e − 5</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9910;0,9911]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.12: System comparison with failure based maintenance
5.2.6 System with independent modules and adjusted rates

For the independent operating modules the adjusted rate simulation executed. Parameters are equal to the dependent simulation and can be found in table 5.6.

The output of 20 runs with a length of 100 cycles is presented in table 5.13 for preventive maintenance and in table 5.14 for failure based maintenance.

<table>
<thead>
<tr>
<th>Preventive maintenance</th>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Repair time [Hours]</td>
<td>12,51</td>
<td>12,28</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2,25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[11,04;13,99]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Number of repairs</td>
<td>14,04</td>
<td>14,00</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1,69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[12,93;15,15]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Availability</td>
<td>0,9997</td>
<td>0,9997</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>5,3e−5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9997;0,9997]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.13: System comparison with preventive maintenance and adjusted rates

<table>
<thead>
<tr>
<th>Failure based repairs</th>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Repair time [Hours]</td>
<td>52,55</td>
<td>52,36</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[51,97;53,12]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Number of repairs</td>
<td>42,8</td>
<td>42,67</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0,36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[42,56;43,04]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Availability</td>
<td>0,9987</td>
<td>0,9987</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2,0e−5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9987;0,9987]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.14: System comparison with failure based maintenance and adjusted rates
5.2.7 System with independent modules extended time

Again, for the adjusted rates simulation a simulation runs is executed. This time the time frame is extended to 50 years to view the differences between failure based and preventive maintenance. The output of 20 runs with a length of 100 cycles is presented in table 5.15 for preventive maintenance and in table 5.16 for failure based maintenance. Both tables show that the simulation model performs as the analytical model would predict.

### Preventive maintenance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Repair time</strong> [Hours]</td>
<td>61,75</td>
<td>61,4</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>7,14</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[57,07; 66,44]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Number of repairs</strong></td>
<td>70,39</td>
<td>70,01</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>6,75</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[65,96; 74,82]</td>
<td></td>
</tr>
<tr>
<td><strong>Mean Availability</strong></td>
<td>0,9997</td>
<td>0,9997</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>3e − 5</td>
<td></td>
</tr>
<tr>
<td>Confidence interval 99%</td>
<td>[0,9997; 0,9997]</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.15: System comparison with extended time

### Failure based repairs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation model</th>
<th>Analytical model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Repair time</strong> [Hours]</td>
<td>273,72</td>
<td>273,79</td>
</tr>
<tr>
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Table 5.16: System comparison with extended time

Observed are the larger differences between failure based and preventive maintenance. Adjusted rates and extended time increase the differences. However, the simulation predicts more repairs as the analytical model does. This even when the analytical model assumes the negligible time to repair. It can be concluded on the basis of the differences that the independent modules simulation is not suitable.

5.3 Discussion of results

The results of the verification show the differences between preventive and failure based maintenance. Three different configurations have been investigated, the single module, system operating independently and a system operating dependently without idle failures. All three simulations show comparison with the analytical model. The independent and dependent operation of modules show only minor differences for the six simulated modules. This could increase when the range of modules raises, or repair times increase. The influences of repair rates on uptime are shown in Appendix G.
For ease of use, the modular incorporation of simulation files as used in this report results in the independent operation of modules. When modules operate dependent on each other where downtime influences uptime of other modules, the simulation becomes more complex to adjust or construct. The choice between ease of use and accurate results in terms of modular modelling has to be made. This chapter has given insights in the influences of decisions but have to be analysed by accurate data in order to make a sound conclusion. The differences between the models is expected to grow when the number of modules increases and/or the repair times increase.

From the tables presented in the verification part, the comparison between preventive and corrective maintenance yields large differences in the standard deviation. This effect is due to the short simulation of preventive maintenance in contrast to the failure based maintenance. In order to compare the results, the shorter cycles of preventive maintenance are multiplied to equal lengths of failure based maintenance. The multiplication has the effect of enlarging differences in simulation runs, and directly result in a larger standard deviation.

5.4 Validation

The validation of the model is conducted with an expert from MSPP. The validation of failure based maintenance option cannot be done due to the lack of knowledge. In order to obtain results which are in line with the opinion of the expert, adjustments have to be made. The number of repairs under preventive and failure based replacements are not in contrast with each other. When only failure based replacements are performed, the number of repairs has to be higher. This can be adjusted by a factor to raise the number of repairs. As illustrated in the following example, a motivation for the adjustment is presented.

A preventive maintenance overhaul kit would replace 10 components, and assure the module is as new again. A single corrective repair under the failure based replacement occurs in a lower rate then preventive maintenance exchanges components. The number of repairs under failure based and preventive maintenance have minor differences. It can be assumed when a failure occurs under the failure based maintenance multiple components will be replaced, and in this example expected to be 5. The difference corrected by a factor has to be around 2, to ensure the number of repairs equals or exceeds the preventive maintenance.

Preventive maintenance validation can be performed when accurate data is obtained from a plant. The data used in the verification are fictive and do not represent reality.
Chapter 6

Numerical analysis

This chapter uses the simulation model to investigate the opportunity of redundancy in a system configuration. Output of the model for redundant options is presented in 6.1. Furthermore the opportunities of a simulation tool in general are provided in section 6.2.

6.1 Redundancy

The incorporation of redundancy in the design of a system can result in achieving higher system availability. This section will describe the optimal allocation of redundancy based on specific constraints. The optimal allocation of redundancy is subject to specific constraints like, cost, space in the plant, number of units and availability level which cannot be violated. The problem of achieving optimum redundancy is treated in case only two component states are possible, the operating state and the failed state.

An option to evaluate different system configurations is to apply redundancy in modules of the system. By implementing redundancy the system, it is able to handle failures by switching between modules. Redundancy might be the solution when preventive maintenance does not do the job to secure the production. Because, when the complexity and number of components of a system increases, the reliability will decrease unless compensatory measures are taken (Lewis, 1996). In figure 6.1 it can be seen that the number of components or modules have a major influence on the reliability of a system. Here the reliability of the system versus the component reliability is plotted. Each line represents a system with a different number of components. Redundancy can be applied in two forms, the active parallel or standby parallel. The production lines of MSPP can only be fitted with the standby parallel redundancy due to the characteristic of the transfer lines. The transfer line cannot be split or merged to be operated at once on multiple modules.

The series structure of MSPP equipment, consisting of \( n \) stages, functions if and only if each stage is functioning. Failures cause the system to block or starve. Modules placed in redundancy are assumed to be equal, and have the same failure distribution. Preventive maintenance is applied to the first module. The second module will only operate when the first has failed and we assume a perfect switch. This could be useful for modules containing many crucial B-parts. In figure 6.2 the principle of redundancy is explained, here the downtime is represented out of contrast with the uptime. Normal downtimes are way shorter. If \( M1 \) fails, \( M2 \) is activated. In the mean time \( M1 \) is being repaired in the down state. When the repair has finished, \( M1 \) is activated again. The switching between \( M2 \) and \( M1 \) before \( M2 \) has failed is due to the preventive maintenance scheme which is time dependent. The modules are fully loaded, else the preventive maintenance scheme has to be adjusted for minor loading of modules. The second module, \( M2 \) will not be subject to preventive maintenance. When the module fails while the
Figure 6.1: System reliability as a function of number and reliability of components (Lewis, 1996)
first module has failed, the system is stopped. This happens only when the remaining uptime of $M_2$ is smaller then the repair time of $M_1$.

\[ Uptime(M_2) >> Downtime(M_1) \]

Because the uptime of a system is crucial for production, a downtime constraint to guarantee a certain availability for the uptime of the system can be used. The choice for a downtime constraint is taken to give insight into the loss of production hours in the long run, a fixed time interval. When designing a system, the redundancy option might decrease downtime at increased acquisition cost, but eventually resulting in lower operating cost.

\[ Downtime < D_0 \]

Some modules might be more important for system functioning than others. Which module generates the most downtime is most suitable starting point for a redundant configuration.

In the tables 6.1 and 6.2 an example of redundancy has been investigated for six modules. The properties are equal to those in chapter 5 for the corrective maintenance example. Table 6.1 shows for run 0 the initial value for Total Maintenance Cost under Total and the Downtime generated by the modules. It can be seen that all modules contribute positively to the decrease of Downtime and subsequently the Total Maintenance Cost even under increased Acquisition cost. In comparison with table 6.2 the allocation of redundancy is determined when the repair times are short. This is investigated to reveal the influences of repair times on redundancy. When the repair times are shorter, this automatically leads to a lower total downtime which is the main driver of the corrective maintenance cost. Since the downtime cost is specified per time unit, and directly linked to the corrective maintenance cost a change in downtime will also have a large impact on the allocation of redundancy. In this second example, there exist two options of redundancy which do not contribute to the decrease of Total Maintenance Cost but still decrease the Downtime. From a cost perspective they would not be placed in redundancy.

A next step could be to select the lowest TMC and take this redundancy allocation to be the best. Set this value to be the new standard and evaluate if other modules might be placed in redundant configuration to obtain the solution of interest concerning the constraints discussed earlier.
6.2 Simulation opportunities

This section investigates the opportunities of simulation in the long run for Marel in general. For each opportunity the advantages are presented.

First of all, requirements are that there is complete knowledge of breakdowns and their causes. What are the most influencing factors for certain breakdowns. Data containing repair times and interval times for repairs is crucial. Only then it is possible to obtain insights on the processing industry in terms of availability, cost figures and production efficiency to enable informed decision making.

6.2.1 Identification of losses

Faulin et al. (2010) evaluates the opportunities in terms of availability production and production efficiency, identify the bad modules or the key components for losses in availability and production, conduct a cost analysis to estimate the loss of revenue due to unavailability, identify recommended actions to improve performance, and estimate the availability and production if the recommended actions are implemented.

6.2.2 New modules and upgrades for the production line

Equipment is always subject to degradation and MSPP continuously improves, upgrades and engineers new modules. Degraded modules could be a candidate for replacement. The evaluation of new modules in comparison with degraded modules could be of interest for MSPP to improve performance at customer plants. When information is acquainted for new modules to perform better in comparison with older versions, a simulation could be able to indicate if acquiring the new version would be beneficial in terms of availability, throughput and above all, cost related. The simulation as presented in this report contains the OEE and OTE computation to view performance of modules in a single and system context. Based on these parameters, lowest performing modules can be identified. As stated in section 3.4.1 many decision makers in the acquisition phase are financially focussed. A simulation can predict the outcome of a
certain process solution.

6.2.3 Redundancy

As elaborated in the previous section, redundancy evaluation could be a solution to modules or even lines which suffer from random breakdowns caused by B-parts. Most random breakdowns cannot be coped with by applying intensive preventive maintenance.

6.2.4 Performance contracts

The thesis of Meijl (2012) is about the servitization of Marel. It is defined as “the process of creating value by adding services to products”. Marel’s service strategy is to transform from a product oriented service organization into a customer oriented service organization. This transformation gradually occurs along a continuum, the “the product-service continuum” (Oliva and Kallenberg, 2003). Meijl (2012) states that “the continuum consists of two extremes: product manufacturing firms who regard services merely as an add-on to the product, and pure service providers who regard products merely as an add-on to service”. A service organization model has been developed which describes three main stages for service offerings on the product service continuum. Namely, reactive services, proactive agreements and process performance agreements. Only the process performance agreements are of interest here.

A process performance agreement is a guaranteed certain performance level of a complete processing line, offered for a fixed price to a customer (Meijl, 2012).

The author distinguishes three sub stages in performance agreements, basic, extended and premium. The basic performance includes a process availability and uptime guaranty. Conduction of preventive maintenance is performed by MSPP excluding breakdown and consumable components which are conducted by the costumer. Extended process performance agreements are applicable on the entire maintenance, operational and preventive, of a production line. Premium process performance agreements in which the ownership and maintenance responsibility is at MSPP and offered for a certain fee per output. More specific, this agreement provides the customer an output guarantee. This stage the customer pays according to the level of usage and the offering becomes a running expense rather than an investment. MSPP becomes a service provider.

In order to specify process performance agreements, the determination of running expenses and achievable uptime guarantees can be evaluated by using simulations. Reliable output does heavily rely on the quality of input to the model.

6.2.5 PMS adjustment

The adjustments for a PMS could be evaluated by simulations. Figure 6.3 shows the cycle. When a PMS is applied, data can be gathered in cooperation with the customer about the failure behaviour. The data can be used for input in a simulation model. Different PMS intervals can be analysed by the model and if necessary adjust the PMS to minimize the failures. A PMS becomes personal to a customer and takes into account his loading to modules. This could be a solution when the classification of preventive maintenance as discussed in section 2.2.1, is not sufficient enough. There exist customers who utilize their system for only 8h per day, five days per week while others almost produce 24h per day six days a week. The ultimate case is when
a system is utilized for 30 days straight and stopped for one day to perform maintenance and
a new cycle is repeated of 30 days.

![Simulation](image)

**Preventive Maintenance Schedule**

**Customer data**

Figure 6.3: Preventive Maintenance Schedule optimization

### 6.2.6 TCO, LCC and COO

The thesis of Sprenkels (2013) discusses the Total Cost of Ownership (TCO) of a production
line in an explanatory study. The thesis identifies the part of the TCO of a production line, that
is influenced most by the design decisions and that therefore should be considered when the
production line is designed. TCO includes all costs, direct and indirect, incurred throughout the
life cycle of an asset, including acquisition and procurement, operations and maintenance, and
end-of-life management (Heilala et al., 2006). Life-cycle costing is concerned with optimizing
value for money in the ownership of a physical assets by taking into consideration all the cost
factors relating to the asset during its operational life (Woodward, 1997). Another important
concept that includes all cost related to the use and ownership of a production system is cost of
ownership (COO). The COO are the total costs per produced item, so the TCO of the system
divided by the number of items the system produces during its lifetime.

**Total Cost of Ownership parts**

Seven cost components have been identified which comprise to a large extent the relevant TCO
of a production line. Relevant means the part of the costs that is influenced by the design
decisions. The seven cost components have been taken from Sprenkels (2013) and are presented
below.

*Initial capital investments*
The initial capital investments include all of the costs made during the acquisition, purchasing
and installation of the system.

*End-of-life costs*
The end-of-life costs are the costs that are made at the end of the lifetime of the system. There
might be some costs involved in removing and disposing the machines at the end of the life of
system, these costs are called decomposition costs. It might also be the case that the machine
have some value left at the end of the life of the system. This value is called salvage value.

*Facility costs*
The facility costs are all costs that are caused by the housing of the system. This cost com-
ponent will differ a lot from company to company. In some situations it might be the case that an
entire building needs to be build and the facility costs depend largely on the size of the system,
but in other situations the company might already own a building and the facility costs reduce
to only the cleaning costs for instance.

*Operation costs*

The operation costs include all the costs that are involved with operating the system. Examples are labor costs and energy costs, but also the costs of capital tight up in the initial inventory investments.

*Maintenance costs*

Maintenance cost include all costs concerning the maintaining of the system. For instance, the cost of repairing the system when an unexpected breakdown occurs, the cost of planned maintenance actions, but also the costs of keeping spare parts on stock.

*Quality costs*

The quality costs are all the cost caused by the system not doing its job perfectly. In production systems this includes the costs of nonconforming items that cannot be sold, or penalties for items of a lower quality that need to be sold against a lower price.

*Downtime costs*

For some systems, there is a direct financial consequence of the system not functioning the way it is supposed to. These costs are referred to as down-time costs.

*Simulation and TCO*

From the seven cost components, maintenance, downtime and quality cost can be computed by a simulation model. The simulation as presented in this thesis is capable of determining the maintenance cost for either corrective repairs and preventive maintenance. For corrective repairs the accompanying downtime can be computed. The associated quality cost due to losses in the production line can be determined with a throughput model. As discussed in chapter 2, the throughput is highly dependent on the availability of a production line. The throughput model presented in this thesis is a simplified general view. Selecting the right production line for certain end-products depends on a large number of factors and is not a simple task. Again as stated in section 3.4.1, many decision makers nowadays are financially focussed. TCO is a valuable tool to explain effectively cost drivers of the production line.
Chapter 7

Conclusion and recommendations

This chapter provides the answers to the research questions presented in chapter 1. Second, recommendations and limitations are presented in the second paragraph.

7.1 Conclusion

*How can we facilitate sales process and customer service based on a simulation tool for process representation and performance analysis?*

The first chapter of the introduction has highlighted the important aspects for MSPP. On which fields they lack their skills to inform their customers about their systems and solutions. A switch between static 2d paper drawings and animated 3d computer models has been evaluated. The conceptual model states the separation of process representation and performance analysis.

**Process representation**

For the process representation part, chapter 3 about visualization explores the opportunities with 3 dimensional models. The department of Project Engineering has already started constructing 3d models of MSPP equipment. The use of 3d models in the concept of virtual reality with and without animation has been investigated.

Virtual reality is able to solve technical and industrial problems in a highly efficient manner and highlights the layout planning for new plant installations. With the virtual reality environment it is possible to simulate and observe the manufacturing process in a close-to-reality presentation. This guarantees primarily a better understanding of manufacturing sequences and helps in the early detection of errors. The customer can be integrated into the construction process and an interactive optimisation process becomes possible.

Visualization helps to evaluate and understand logistical simulation. The production facility can be presented, processes evaluated and judged, and optimized by means of virtual simulation. The combination of virtual prototyping and virtual reality techniques has a tremendous potential in providing advanced visualization and manipulation capabilities for customized product development by enabling visual evaluation and acquiring the customer’s perception on the target product.

The combination of 3d models and animation offer several advantages, it is capable of simplifying complicated concepts and ideas, which cannot be easily represented by words or even through illustrations in 2d. A 3d animation has a superior ability to visualize movement in a way that is easily recognized. Attention is captured by an animation, the information presented by a moving image is retained by the viewer for a long period. By using an animation for a
manufacturing plant specific advantages can be highlighted and communicated in an easy way. Also, it provides personality to each project making it unique for the customer.

Performance analysis

The Service Department is responsible for the maintenance of MSPP equipment. Each plant of MSPP has the ability to acquire the services of the Service Department and benefit from the added value. Preventive maintenance is to reduce the effects of breakdowns and maximize production system availability. A performance analysis for different types of maintenance can give insights to the added value of the service department.

What are the requirements of a simulation tool for process representation and performance analysis?

For process representation the requirements depend on three factors, usability, relevance of information and level of detail. Usability means that the proposed solution should be able to cope with models constructed at Project Engineering to avoid double work. The relevance of information is a challenge to only model information relevant to customers. Most of the times the information which is relevant for the customer is context related because MSPP makes customer specific plants based on their requirements. It is up to the Sales Department to recognize the relevant information for the customer and to communicate to the engineers at Project Engineering. The level of detail should be minimized to not generate an overload of information. Only the most essential information has to be modelled.

For the performance analysis, the function of equipment in manufacturing is to support the production of products for downstream customers. This inherent capability of equipment is maintained by maintenance practices. According to Löfsten (2000) the majority of plants use Total Maintenance Cost (TMC) and availability to measure the maintenance performance. Measuring maintenance performance is helpful when evaluating the effectiveness of maintenance decisions. Such decisions are the choice for preventive or failure based maintenance. According to Li et al. (2009) throughput analysis is important for the design, operation and management of production systems. The availability, throughput and cost of a system are identified as key pieces of information which is absent to customers.

This report has investigated the influences of removing idle failures during downtime by using simulation. The influences are in the case example only small, but are expected to grow when the number of modules increases and/or the repair time increases. In order to obtain accurate results, the dependent model is preferred. Further, it can be concluded for the simulation that the use of a modular approach is unsuitable and yields unacceptable results.

What are, in the long run, potential programs for the simulation tool?

The presentation tool, a solution is found in the current software package for practicality and feasibility. Within the Factory Design Suite, 3DS max and Navisworks of the Autodesk family are the selected programs. A manual has been written for the animation of a 3d computer model but is not included in this report.

For the performance simulation, Matlab, R, Octave or Excel in combination with Visual Basic for Applications are solutions. Data transfer is possible between models via FDS and Excel to other simulation packages. A modular simulation is preferred when the number of modules is large.

What are, in the long run, opportunities of a simulation tool?
Chapter 7. Conclusion and recommendations

Identify the bad modules or the key components for losses in availability and production, conduct a cost analysis to estimate the loss of revenue due to unavailability, identify recommended actions to improve performance, and estimate the availability and production if the recommended actions are implemented.

New modules and upgrades for the production line.
Equipment is always subject to degradation and MSPP continuously improves, upgrades and develops new modules. Degraded modules could be a candidate for replacement.

Redundancy.
As elaborated in the report, redundancy evaluation could be a solution to modules or even lines which suffer from random breakdowns caused by B-parts.

Performance contracts.
A process performance agreement is a guaranteed certain performance level of a complete processing line, offered for a fixed price to a customer. In order to specify process performance agreements, the determination of running expenses and achievable uptime guarantees can be evaluated by using simulations.

Preventive Maintenance Schedule adjustment.
Different PMS intervals can be analysed by the model and if necessary adjust the PMS to minimize the failures. A PMS becomes personal to a customer and takes into account his loading to modules.

Total cost of ownership, life cycle costing and cost of ownership.
TCO includes all costs, direct and indirect, incurred throughout the life cycle of an asset, including acquisition and procurement, operations and maintenance, and end-of-life management. Many decision makers nowadays are financially focussed according to MSPP. TCO is a valuable tool to explain effectively cost drivers of the production line.

7.2 Recommendations and limitations

Data required as input for the simulation model is currently inaccurate. Information about repair times and times between failures are inconsistently logged in a maintenance log. Drawbacks of the maintenance log are,

- The absence of motivation for repairs or repair times are missing.
- No clear classification of reason for repair. Failures could be preventive maintenance related or corrective maintenance related.
- Some might be maintenance related where others are accident related.
- System downtime has to be separated from module downtime.

By increasing the reliability and accuracy of the data, the output of the simulation model will be more reliable and accurate. The determination of parameters for simulation input can be achieved by conducting censoring to data. This is particularly useful for datasets which are not complete, or tests have not been run to completion. That is, components have been exchanged before they have failed which is the case in preventive maintenance.
For this report, the constructed models use input from fictive data. The differences between preventive maintenance and failure based maintenance are based on the same dataset which might not be highly desirable. This is chosen due to data limitations for analysis. A future difference can be computed by applying two different lifetime distributions which take into account a different wear pattern caused by the maintenance strategies.
References


59


Appendices
Appendix A

ACM-NT process

The process within MSPP can be characterized as line production. A transportation unit moves the products on shackles through the facility. Along the line various modules perform operations to the products. This appendix shows graphically the stages in a complete process. The in blue highlighted blocks represent the focus of the case study. Each block can contain multiple modules which are presented in the subsequent figure. Here are the processing units are shown per line. The series structure of processing is evidently shown by the arrows. However, in the process some buffers exist to accommodate disruptions in production. These are the chilling and cut up stages.

![Figure A.1: Stages in a complete process](image)

The next figure shows all the modules placed in the ACM-NT production line. Blocks represented in orange indicate the critical modules. When these modules fail the line is stopped. The blue blocks show the rework modules, producing rework items when they fail.
Figure A.2: ACM-NT process
Appendix B

ACM-NT Product Flow

A product flow is presented showing which parts are removed in the various stages. The flow is based on the case study and contains many but not all the operations which are possible by lines. However, it is possible that a product does not require all of the operations in a line. In that case, machines that perform redundant operations can be bypassed. For example, the wing process has three options resulting in different end-products.
AMF section produces Filet and Tenderloin from the breast cap

Whole bird after evisceration

Stumps removal

Neckskin removal

Wing process

AMF section produces Filet and Tenderloin from the breast cap

Spine cutting

Tail removal

Split legs

Drumstick module
Appendix C

ACM-NT components

Failure of components

Each of the process lines stated in the conceptual model is split up into modules which contain critical components. Marel has classified their components into five classes, namely, A-B-C-D-E components 1.

A-parts are consumables. These are parts that make contact with the product to be processed and have a direct effect on the technological action of the machine. So these parts should be replaced or repaired (ground) frequently. By definition A-parts must be easily accessible. For example, knives, drills, plucking fingers.

B-parts are ”breakdown” parts. These are parts or assemblies of parts, which, if defective, make it difficult or impossible for production to continue. For example, entire processing units of rotary machines, motor reductors, three-phase motors, motor variators.

C-parts are small overhaul parts. These are parts that are subject to wear and tear. As a rule these parts should be replaced at least 1x per 2 years and at most 4x per year in order to ensure that the machine works properly. For example, bearings, bearing bushes and bearing roller, springs, geared belts and V-belts.

D-parts are major overhaul parts. See C-parts, but with a time interval of 1 to 3 years. For example, spring-loaded tensioner elements, spray nozzles, grease nipples.

E-parts are condition-dependent overhaul parts. These E-parts are subject to wear and tear and will be added to an overhaul package depending on their condition at the time of inspection. They are usually replaced during a total overhaul.

The service parts coding allows composing a spare parts kit by means of a selection of one or several codes. The following five kits are distinguished. The start-up kit with A-parts. The recommended spare kit with A and B-parts. The small overhaul kit with A and C-parts. The major overhaul kit with A, C and D-parts. And finally, the total overhaul kit with A, C, D and E-parts. The times for replacement are roughly 15min for A-parts, 30min for B-parts. C-D-E-parts have to be changed within 12 hours. When preventive maintenance is applied, the times for C-D-E parts are performed outside operating hours.

1Source: T1 Standards Stork Food Systems, T0111
PMS schedule example

Besides the available spare parts kits and overhaul kits, so-called preventive maintenance schedules (PMS) are made for all AE example structures. The preventive maintenance schedule shows what overhaul work to expect for a specific machine structure in order to keep it in good mechanical condition. Per assembly, a prognosis is made concerning the overhaul operations within a certain period of time. A number of process parameters set beforehand are taken into account when determining the PMS. The preventive maintenance schedules available, serve as a basis for an initial Cost Of Spares calculation.

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Figure C.1: An example of a Preventive Maintenance Schedule (PMS)

Maintenance interval

The maintenance interval for preventive maintenance is per module different. In the PMS above the interval is for a P preventive maintenance. When -2P is advised, the interval is increased and when +2P is advised, the interval is decreased in order to minimize the expected number of failures before replacement. The maintenance actions are performed on fixed time intervals regardless of the equipments condition at that moment. The preventive maintenance can be referred to as periodic maintenance. The intervals are determined by failure rates and experiences of MSPP.
Appendix D

Confidence interval

When $X_1, X_2, ..., X_n$ are independent random variables with sufficient large $n$, usually $n \geq 30$, the random variable $\bar{X}$ may be closely approximated by a normal random variable $X'$. This is known as the central limit theorem for normal distribution and holds regardless of the underlying distribution (Winston and Goldberg, 1994; Taha, 2007) where,

$$
\mu = E(X') = E(X_1) + E(X_2) + \ldots + E(X_n)
$$

$$
\sigma = var(X') = var(X_1) + var(X_2) + \ldots + var(X_n)
$$

The two sided confidence interval for the normal distribution is given by,

$$
\mu = \bar{X} \pm z_{\alpha/2} \frac{\sigma}{\sqrt{n}}
$$

For comparing $n$ independent replication runs, i.e. no correlation, for a single variable $X$ with equal initial conditions the confidence interval $100(1 - \alpha)\%$ is computed by the $t$-distribution with $n - 1$ degrees of freedom:

$$
\bar{X} \pm t_{\alpha/2,n-1} \sqrt{\frac{S^2}{n}} \quad \text{(D.1)}
$$

where the mean and variance are unknown and calculated as follows (Law and Kelton, 2007),

$$
\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n}
$$

$$
S^2 = \frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n - 1} = \frac{1}{n - 1} \sum_{i=1}^{n} (X_i - \bar{X})^2
$$

Note that when the number of observations increases, $n$, the smaller the variance and the closer the $\bar{X}$ gets to $\mu$. Law and Kelton (2007) recommends using this interval for constructing a confidence interval.
Appendix E

Renewal function verification

In chapter 5 the verification of the renewal function is presented. For the Exponential distribution test a mean of 50 was used for a time interval of 500. The output of the renewal function is 9.990 and is in contrast with the Poisson process which indicates $\lambda t = (1/\mu) t = (1/50) \times 500 = 10$. For the CDF comparison, a Weibull distribution with $\alpha = 2.5$ and $\beta = 580$ is used.

Figure E.1: Exponential distribution

Figure E.2: CDF comparison with renewal
Appendix F

Random number generation

This appendix explains the generation of random numbers and how probability plots can be generated.

F.1 Random numbers

In order to obtain random numbers outside the standard package statistics of Matlab the equations are provided below for the Weibull and Exponential distribution. The equations can be programmed to be a function in other software. The equations assume that a source of uniform (0, 1) random numbers is available, and is represented as \( \text{rnd} \) in the equations.

\[
\text{wblrnd} = \alpha \times \left[ -\ln(1 - \text{rnd}) \right]^{\frac{1}{\beta}} \quad (F.1)
\]

Where \( \alpha \) = the scale parameter and \( \beta \) = the shape parameter of the Weibull distribution. For the Exponential distribution, the equation is presented below.

\[
\text{exprnd} = -\ln(1 - \text{rnd}) \quad (F.2)
\]

Where \( \lambda \) is the mean of the distribution. Programming these equations into functions for a simulation environment makes them easy to use. Equations are derived from Locks (1995).

F.2 Probability plotting

Information in this section can be found in Lewis (1996). Probability plotting is an extremely useful technique. With relatively small sample sizes it yields estimates of the distribution parameters and provides both a graphical picture and a quantitative estimate of how well the distribution fits the data. Again for the Weibull and Exponential distribution an example is provided.

First a Weibull distribution example. First the \( F(t) \) is computed by the following equation, note that it requires larger sample sizes. If the sample size is small, the second equation of \( F(t) \) is more applicable due to the randomness and limited amount of data which introduce more uncertainty. For large values of \( N \) they yield nearly identical results.

\[
\hat{F}(t) = \frac{i}{N + 1}, \quad i = 1, 2, 3, ... N
\]

\[
\hat{F}(t) = \frac{i - 0.3}{N + 0.4}, \quad i = 1, 2, 3, ... N
\]
Appendix F. Random number generation

\[ x = \ln(t) \]

\[ y = \ln\left(\ln\left(\frac{1}{1 - F}\right)\right) \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52</td>
<td>( F(t) = i/(N + 1) )</td>
<td>3.951</td>
<td>-2.351</td>
</tr>
<tr>
<td>2</td>
<td>66</td>
<td>0.18</td>
<td>4.189</td>
<td>-1.606</td>
</tr>
<tr>
<td>3</td>
<td>67</td>
<td>0.27</td>
<td>4.205</td>
<td>-1.144</td>
</tr>
<tr>
<td>4</td>
<td>76</td>
<td>0.36</td>
<td>4.330</td>
<td>-0.794</td>
</tr>
<tr>
<td>5</td>
<td>96</td>
<td>0.45</td>
<td>4.564</td>
<td>-0.500</td>
</tr>
<tr>
<td>6</td>
<td>98</td>
<td>0.5</td>
<td>4.585</td>
<td>-0.237</td>
</tr>
<tr>
<td>7</td>
<td>108</td>
<td>0.64</td>
<td>4.682</td>
<td>0.015</td>
</tr>
<tr>
<td>8</td>
<td>110</td>
<td>0.73</td>
<td>4.700</td>
<td>0.261</td>
</tr>
<tr>
<td>9</td>
<td>124</td>
<td>0.82</td>
<td>4.820</td>
<td>0.533</td>
</tr>
<tr>
<td>10</td>
<td>160</td>
<td>0.91</td>
<td>5.075</td>
<td>0.874</td>
</tr>
</tbody>
</table>

Table F.1: Weibull data

The next step is to plot the data of \( x \) and \( y \). The plot is depicted in figure F.1 and includes a trend-line. The trend-line, \( y = ax + b \), is used for the Least Squares Fit. For the Weibull distribution, the shape parameter is equal to the slope, \( a \). The scale parameter is estimated in terms of the slope and the intercept by, \( \exp(-b/a) \).

![Figure F.1: Weibull probability plot including trend-line](image)

For the Exponential distribution, estimation is performed on the following equations. The data for \( x \) is the data of the lifetimes. The mean of the exponential distribution is found in the trend-line at the point of \( 1/(1 - F) = 2.72 \), thus \( 2.72 = ax + b \). Where \( 2.72 = e \).

\[ y = F(t) = \frac{N + 1}{N + 1 - i}, \quad i = 1, 2, 3, \ldots N \]

\[ x = \text{data}_i \]
Appendix G

System downtime

An assumption is that modules under idle time cannot fail, when one module in a series production system stops all other modules stop processing. This means that equipment is under idle circumstances switched off. Modules which are switched off do not age and cannot fail is the assumption. It has been investigated if the influences off downtime have impact on the total system downtime. The up-times of modules are extended with the downtime of other equipment.

A simple example has been simulated to view the differences in downtime if the assumption is incorporated. For a time length of 10000 and a Exponential lifetime distribution three modules are investigated. Each having a different expected lifetime with mean $\mu_1 = 10$, $\mu_2 = 150$ and $\mu_3 = 200$. For the downtime a fraction of the expected lifetime is taken. A collection of 1000 runs has been performed for each fraction of downtime. The simulation records the uptimes, downtimes and number of repairs for the system. The data for downtime of the system is presented in table G.1 as a fraction of the total time.

The simulated values are compared with the theoretical expected values. The theoretical values are computed with the following equations:

\[
\lambda_i = \frac{1}{\mu_i}
\]

\[
Downtime = \sum_{i=1}^{n} \lambda_i \times \mu_i \times fraction
\]

\[
Unavailability = \frac{Downtime}{Timeframe}
\]

Where $\lambda_i$ is the failure rate. In table G.1 are the expected values of system downtime presented and is the ratio computed.

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Simulation</th>
<th>Expected</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>0.0148</td>
<td>0.015</td>
<td>0.987</td>
</tr>
<tr>
<td>0.01</td>
<td>0.0291</td>
<td>0.030</td>
<td>0.970</td>
</tr>
<tr>
<td>0.025</td>
<td>0.0697</td>
<td>0.075</td>
<td>0.929</td>
</tr>
<tr>
<td>0.05</td>
<td>0.13025</td>
<td>0.150</td>
<td>0.868</td>
</tr>
<tr>
<td>0.075</td>
<td>0.1828</td>
<td>0.225</td>
<td>0.812</td>
</tr>
<tr>
<td>0.1</td>
<td>0.23062</td>
<td>0.300</td>
<td>0.768</td>
</tr>
</tbody>
</table>

Table G.1: Simulation data for system downtime

Comparing shows that the influences of small fraction downtime are negligible. See for a graphical representation figure G.1. For the small fractions of uptime the expected and simulated
Figure G.1: Graphical representation data of system unavailability

values are almost equal. As the fractions get larger the difference becomes more obvious.
Appendix H

Visualization options

Options for increasing understanding of the virtual model are presented in this appendix. Most of the opportunities are applicable for an animation as well as for VR.

Differentiation between the A-grade (high quality) and B-grade (low quality) products by color or form for the animation. For example, use green squares and red squares to indicate the difference between flows. It is also an option to only change colors of transportation units such as conveyor belts. This options makes it useful to static models without animation.

Secondary transport of bulk products. Bulk products are gathered in crates or boxes and are transported by fork-lifter for example. Such transport requires enough ground space to travel through the plant. Height of constructions should be adapted to ensure the transport can pass underneath it.

Most of the constructed plants are equipped with a vast amount of conveyor belts. Those belts can make an overwhelming impression of the plant and could be minimized to the essential ones to indicate flows. A solution could be to change the transparency of those to belts or make them partly invisible.

Reference points can be added to the animation or VR environment for recognition. Examples are, pillars of the building and building walls, fork-lifter and crates to get insight into the dimensions because those are known to the viewer, and people to indicate working places.

By applying walkways, walking routes for employees and maintenance personnel can easily be highlighted and evaluated. When space requirements are to small, this is immediately visible to the viewer.

When a plant is to complex for a single representation multiple versions could be constructed to explain processes in parts. By adding layers to models the switching between versions can be achieved.