Master Thesis IEM

# Analytical model of a mold dependent production line: Applied to future thermoplastic skin panel production for Gulfstream G650 tail wings.

SUMMARY VERSION

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# Management summary

## Introduction

In the aerospace industry thermoplastic composites are also coming up more and more in the aerospace as well in the automotive industry because of their economic and technical advantages. A program, called TAPAS, has been established by several Dutch industrial companies and research institutes to further research thermoplastic composites applications. Fokker Technologies has over 25 years of experience with thermoplastic composites and is involved in this program. Fokker has done a lot of research on material properties, production techniques and on applications. One of those applications are the skin panels of the Horizontal Tail Plane of the Gulfstream G650. Fokker also made several prototypes of thermoplastic skin panels with success.

## Problem description

The project of thermoplastic skin panels is broken down in several steps aiming at consecutive Technological Readiness Levels. To reach level 6, the industrialization must be investigated. This research project is part of reaching that level. My research project investigates what a current state production line (as used for the prototypes) is capable of, in terms of throughput and Total Cost of Ownership. The production line should be able to reach a rate of 100 skin panels per year.

The production line does not exist yet, so all input data are estimated by Fokker experts. The designed production line is a serial line, with a mold-dependent part (or closed network). The skin panels are made on expensive molds in a closed network. After consolidation, the skin panels are released from the molds and further inspected and finished. The mold dependent processes are the critical part of the production line. The activities in the closed network also include handling many different parts, that must be assembled making up the product and some afterward dis-assembled as they support production.

## Approach

The problem is tackled by building and applying an analytical model (referred to as AMDA) in Excel. Input data like processing times, degree of variability, failure and repair times are included. The AMDA model is able to calculate the yearly throughput and the yearly TCO, for different scenarios. Several analyses are performed to investigate the sensitivity and the robustness of the production line. Also, these analyses give an indication where and what to improve for the future state. In the future state, several process improvements are applied.

The AMDA model is used to find the best values of number of decision variables that minimize the TCO for a predetermined throughput target per year. Only the costs that related to the decision variables are taken into account. The following decision variables are used:

- Number of resources per station (include operators for labor intensive processes or machines + operators for non-labor intensive processes)
- Number of molds
- Number of shifts per station

The AMDA and its optimization are implemented in an Excel tool using VBA and the Excel SOLVER and validated.

## Findings

The production of the prototypes is called the current state and also the starting point of this research. This current state is modelled and several conclusions can be made:

- When considering 2 molds in the closed network, the current state production line is capable of a throughput of 260 panels (130 sets) per year.
- A maximum throughput of 700 panels (350 sets) per year with multiple molds can be reached in the current state.
- The TCO for a yearly throughput target of 100 panels (50 sets) is M€ 1,5.
- The number of molds is a very important factor which determines the performance of the production line. Therefore, the mold is the bottleneck. A lot of molds, however, results in a 'saturated' production line. Therefore, the production processes must by improved as well.
- The most critical production process is the Automatic Fiber Placement (AFP) station and therefore the best candidate for process improvements. The processing time of the AFP station is namely 42% of the total processing time of the mold dependent processes.

Based on the model results of the current state, several process improvements are proposed. This results in a future state which is also modelled and the following conclusions can be made:

- The future state is capable of producing 560 panels (280 sets) per year with 2 molds in the closed network.
- The TCO for a yearly throughput target of 100 panels (50 sets) is M€ 1,4.
- Process improvements result in higher investment costs because some processes will be (partly) automated. However, the calculated TCO of the future state is even lower than the TCO of the current state. The additional investments are not proportional to the increase of the throughput. The maximum improvement in TCO, compared to the current state, at 640 panels (320 sets) per year, is 58%. The maximum improvement in throughput, compared to the current state, with 10 molds is 176%. Therefore, the process improvements, proposed in the future state, are definitely worth considering when designing the production line.

Finally, some things are recommended:

- The production of thermoplastic skin panels requires lots of different parts (+/-1000 parts). This number must be reduced to improve the robustness of the production line. It will also improve the affordability and manufacturability. Standardization of the production line should therefore be further elaborated.
- During the early stages of a design process, one should focus more on Design to Costs. This way the production costs can be reduced and better controlled.
- The AMDA model can be used for multiple other mold dependent (future) Fokker production lines.
- Process improvements are worth considering. The proposed design should be further elaborated. It requires some investments, but for relatively high production rates these investments will be worth it.

# Preface

In 2013, I have gained my Bachelor of Applied Science degree in Mechanical Engineering. After a great experience abroad in Malaysia for this study, I started with the premaster and master Industrial Engineering and Management. I have never regretted this choice and highly enjoyed this IEM program. My specialization is Production and Logistics which has been right choice after Mechanical Engineering. I became mostly interested in manufacturing research areas. My interests and background study fitted perfectly with this research project. Besides, I highly enjoyed working for Fokker Technologies. I have always had a great interest in aircrafts. So this company was perfect for finalizing my master IEM program. What I also admire is the down-to-earth mentality at Fokker. This made information gathering a lot easier.

I have liked the research project very much, as it is linked to my education and interests. To share my enthusiasm, I have put some sidesteps in this thesis. These sidesteps describe some interesting things, not directly related to this research, but nice to know. Additionally, some interesting problems were solved, e.g. the calculation of the number of shifts. A solution was hard to verify in the literature. Therefore, an assumption was made and proven by a simulation study.

I would like to thank all Fokker employees for helping me during my graduation period. Without their knowledge and experience I would have never reached these results. Especially I want to thank *Marc Koetsier* and *Michael Wielandt* for initializing this research project. Thanks for your efforts and for getting me started and helping me with this research project.

Furthermore, I would like to thank *Hans Jeurink* and *Marc van Herpt* for their supervision during my stay at Fokker. Hans, I appreciate your time and effort to review all the draft versions of my master thesis. I also appreciate the interesting discussions we have had, which helped me understanding the matter. I also thank *John Hoogenboom*, *Andre van Homoet* and *Bert Bron* for providing me with the right input data and for their time to help me.

Last, but not least, I thank my supervisors at the University of Twente, *Ahmad Al Hanbali* and *Peter Schuur* for their feedback. Your advice and knowledge have been really helpful. Ahmad, I appreciate the help to apply the AMDA method. Additionally, the feedback on this research project is appreciated as well.

My time as a student has come to an end. It was a great and interesting experience. But I am eager to use my gained knowledge and experiences in practice now. I am grateful for the past, and looking forward to the future.

*Jarne Veijer*

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# List of Abbreviations

| | |
|---|---|
| TAPAS | Thermoplastic Affordable Primary Aircraft Structures |
| TRL | Technological Readiness Level |
| HTP | Horizontal Tail Plane |
| NLR | Nationaal Lucht-en Ruimtevaartlaboratorium |
| AFP | Automatic Fiber Placement |
| NDI | Non-Destructive Inspection |
| CMS | Coordinated Measurement System |
| AMDA | Approximate Marginal Distribution Analysis |
| WIP | Work In Process |
| CQN | Closed Queueing Network |
| SCV | Squared Coefficient of Variation |
| GUI | Graphical User Interface |
| SA | Simulated Annealing |
| FMS | Flexible Manufacturing System |
| TCO | Total Costs of Ownership |

# List of Symbols

| | |
|---|---|
| $n$ | Number of molds in the system |
| $N$ | Maximum number of molds in the system |
| $c_j$ | Number of machines at station j |
| $SCV_j$ | Squared Coefficient of Variation of the processing time of station j |
| $EP_j$ | Expected Processing time of station j |
| $EP_{rem,j}$ | Expected time between arrival and first departure given that all servers are busy or expected remaining time |
| $EL_j(n)$ | Expected number of molds at station j |
| $ETCQ_j(n)$ | Expected time to clear the queue of station j |
| $EW_j(n)$ | Expected cycle time a station j |
| $TH_j(n)$ | The throughput of station j |
| $TH_0(n)$ | The throughput of the network |
| $V_i$ | Visit ratio |
| $p_j(l\|n)$ | The stationary probability of having l molds at station j with n molds in the network |
| $P_{AB}(c)$ | Probability when the neighbor solution is accepted (Simulated Annealing algorithm) |
| AS | Current solution |
| BS | Neighbor solution |
| cp | Cooling parameter |
| A | Availability |
| MTTF | Mean Time To Failure |
| MTTR | Mean Time To Repair |
| $EP_{nom,j}$ | Nominal processing time |
| $EP_{e,j}$ | Effective processing time |
| $\rho$ | Utilization |
| $R_j$ | Number of resources at station j |
| $S_j$ | Number of shifts at station j |
| $MD_j$ | Mold dependency of station j (binary) |

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*"When everything seems to be going against you, remember that the airplane takes off against the wind, not with it."*

*- Henry Ford*

# 1. Introduction

This thesis is part of the Master assignment for my study Industrial Engineering and Management at the University of Twente with specialization Production and Logistics.

This chapter gives a broad view on Fokker Technologies in section 1.1. After that, the problem description, research objective and the research questions are given in section 1.2 and 1.3. Finally, the research scope and the solution approach is described in section 1.4 and 1.5.

The purpose of this chapter is to inform about the Fokker organization and what the master thesis assignment looks like.

## 1.1 Company description

In 1911, Anthony Fokker built his first home-made aircraft which he called 'the Spider' see Figure 1-1. Eight years later he was one of the first who saw the opportunities of aviation and founded the Dutch airplane factory. By 1925, Fokker had grown to be the world's largest aircraft manufacturer and had plants in the Netherlands and the USA. For years, Fokker manufactured successfully military and commercial airplanes. In the First World War, Fokker provided the German government with military airplanes which became famous by the Red Baron. In Second World War, Fokker provided the Dutch government with airplanes like the Fokker G-1. In 1955, Fokker made one of its greatest accomplishments namely the introduction of the F27 Friendship. 750 F27s have been manufactured and it is the best-sold turboprop airplane in Western Europe of all times. This success was followed by the Fokker 50, Fokker 70 and Fokker 100 which were produced in the eighties and nineties. In 1996, Fokker had to adapt from aircraft integrator to specialist supplier due to market changes. In the same year, Fokker was acquired by Stork.

*Figure 1-1. Anthony Fokker in his 'spider'*

Today Fokker uses innovative technologies, her experience and expertise to develop distinctive products and services. This approach in the aerospace industry is called '*Aircrafting*' by Fokker. Fokker Technologies is divided into four business units:

- Aerostructures: light weight Aerostructures like tails, wing components, and the like.
- Elmo: Electrical wiring- and interconnect-systems
- Landing Gear: Landing gear of aircrafts and helicopters
- Services: Aircraft- and parts-availability services

On 31 December 2014 Fokker Technologies counted 4688 employees. Approximately 75% of these employees work in the Netherlands. The total amount in revenue in 2014 was €762 million and the EBIT totaled €47 million.

This assignment belongs to Fokker Aerostructures. This business unit has facilities in the Netherlands, USA, and Mexico. In the Netherlands, Fokker Aerostructures is located in Papendrecht, Hoogeveen and Helmond. Within Fokker Aerostructures, there are several Business lines like Large Commercial Aircrafts, Business Jets, Defense USA and EU and Special Products. Customers within these programs are Airbus, Boeing, Lockheed Martin, Patriot systems, Ariane V, etc.

In Figure 1-2 an overview is shown of the position of this assignment within Fokker. The assignment belongs to the industrialization department within Fokker Aerostructures. The topic of the assignment was originated at the R&D department and most of the required information comes from that department. Manufacturing Engineering is also a part of New Concept Development and also delivers input to this assignment. In the next section, the problem for this assignment is described.

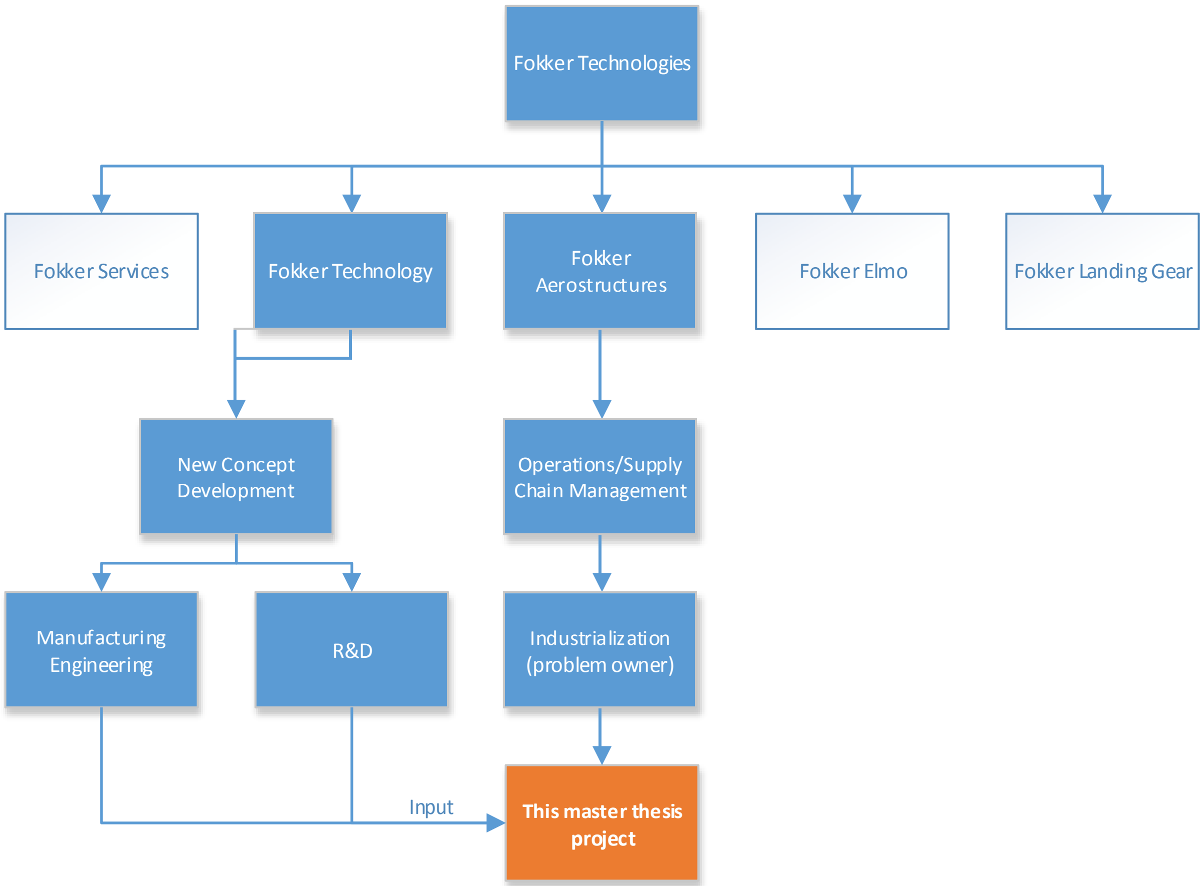


*Figure 1-2. Position of this assignment within Fokker Technologies*

## 1.2 Problem description

Fokker Aerostructures is involved in a program called TAPAS (Thermoplastic Affordable Primary Aircraft Structures). Currently, TAPAS has twelve partners in its collaboration. The focus of the program is on a decentralized partnership with Dutch industrial enterprises in cooperation with Airbus. The TAPAS program is further explained in chapter 2.

One of the products developed within TAPAS is a Horizontal Tail Plane HTP: Demonstrator 2. This Demonstrator 2 is a heavily loaded torsion box. The demonstrator represents an airliner's trailing edge flap or the tail of a business jet. One skin panel of a typical box construction was produced in thermoplastic composite.

The actual demonstrator is a redesign of the horizontal tail of the Gulfstream G650 business jet. Fokker Aerostructures headed up the development, design and construction of this demonstrator.

The product was built in 2011 and then successfully underwent a complete certification testing program in 2012. This test program on skin panels included static testing, fatigue testing, damage tolerance testing, and a maximum load test. In anticipation of the full-scale test program, fatigue was first studied extensively at panel level.

The result of the testing program concluded that thermoplastic stiffened skin panels are approximately 10 per cent lighter in weight than conventional thermosetting composite skin panels. Moreover, the cost of a thermoplastic panel is forecast to be lower, due to a number of factors, including the simplicity of producing butt-joint stiffeners.

Key technology elements include the automatic placement of skin panels plus stiffeners, and the co-consolidation of the stiffeners.

In the TAPAS2 project a complete thermoplastic torsion box is being developed, in which ribs will be joined onto the skin panels.

The HTP consist of a grid of ribs see Figure 1-4. On both sides a thermoplastic skin will be mounted. These two skins are called a set. Each skin consists of stiffeners which guarantee strength and stiffness. Figure 1-5 shows the skin with the stiffeners, placed in the longitudinal direction of the wing. Note that the inner part of the skin in Figure 1-5 is darker. This part is used for the prototype.

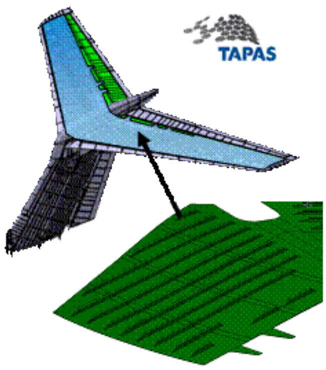


*Figure 1-3. Horizontal Tail Plane*

The production process of the skin includes four main production steps:

- *Tool preparation*: Stiffeners are placed in a mold and positioned with special tooling blocks.
- *Automatic Fiber placement (AFP)*: Robots place tapes of thermoplastic material over the mold.
- *Consolidation*: Material consolidates at a specific temperature and pressure.
- *Machining and inspection*: The shape of the skin must be milled and specific holes must be drilled. Finally, the skin is inspected.

This master thesis assignment is focused on the industrialization of the skin of the HTP. The structure of the HTP and the production steps are further elaborated in chapter 2 of this thesis.

The technical design of the thermoplastic HTP is researched and developed at R&D. Now it is transferred to the industrialization department in order to design and manage the production process.

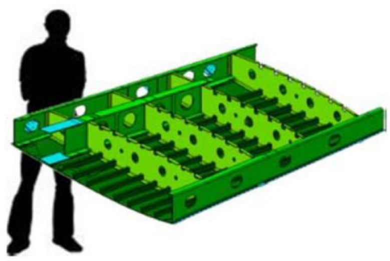

*Figure 1-4. Ribs of HTP with lower skin*

The production strategy is 'make to order' because the production of a skin will start if Gulfstream gives an order. Other characteristics of the production are further described in chapter 3. Currently, there is no factory space available and a number of production equipment, currently used at Fokker, are not suitable for the new material and the size of the HTP. The length of the HTP could be up to 11 meters which makes it hard to handle. The production equipment must be able to deal with that. How to deal with the resources of the production process is an important issue.

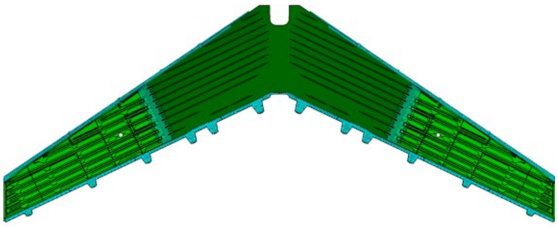

*Figure 1-5. Skin with stiffeners*

The TAPAS goal is to develop the HTP so it can be offered to the customers by the end of 2015. The objective for this assignment is to develop a production plan which must be able to produce 50 sets per year. Before this plan can be developed, the best production process must be determined, further explained in section 1.4.

This assignment includes two problem-areas namely the capacity and facility planning. The capacity planning problem is about the optimization of production steps. Important aspects are the number of resources (machines, operators and other tools), production policies (overtime, multiple shifts), variability, buffering and transportation of the product. The facility planning is about the design of the production line. Important aspects are logistic flows of the mold and tools.

## 1.3 Research objective and research questions

How to solve the problem, stated in the previous section, is described in this section. The objective is to deliver Fokker with the most effective and efficient production process for the skins. This production process is characterized by the minimum Total Costs of Ownership (TCO) with a production target of 50 sets per year. The starting point is 50 sets per year, but it is also important to determine the upper production limits. From this objective the following research question can be formulated:

*'What is the most effective and efficient production process for the production of skin panels for horizontal tail plane of the Gulfstream G650, from a green field scenario, which satisfies the requirements and what should such a facility layout look like?'*

In order to get answers to this main research question, several sub-research questions should be asked. Answering these research questions lead to an answer of the main research question. These sub- research questions are:

1. *What relevant Fokker internal information is available and what does the production process of the thermoplastic skin look like?*

Before the production line can be designed and analyzed, some general information is needed in order to understand the production steps and possibilities. Specific data are available within the TAPAS program. The answer to this research question give insight in the technical situation the production steps for the skin panel. This internal information is gathered by consulting documents, interviewing Fokker experts for specific information and analyzing similar production lines. This research question is answered in chapter 2.

2. *What literature on planning and modeling is available on this matter and can help with the production line design?*

After answering research question 1, the right method(s) must be found to solve this particular problem. Lots of literature is published about capacity planning problems, but most of them solve the problem partially. Problems with similar characteristics might help to solve this specific problem. These similar characteristics are determined by classifying the problem. There are two different techniques to solve the problem namely analytically or to use simulation techniques. The reason to do the literature study after answering research question 1 is to find relevant literature concerning this specific matter. This way the search process becomes more specific. This research question is answered in chapter 3.

3. *What is the appropriate model for modelling the production process and how to build the model?*

In research question 2, several methods for planning and modeling a production process are investigated. This knowledge is used in research question 3 to find the appropriate model for modeling this production process. This research question is answered in chapter 3 and 4.

4. *What parameters and input data are important for modeling the production process?*

Dependent on the modelling approach, the right parameters must be chosen and the best value must be found. Data like type of machines, processing times and setup times are available. Because the production line must be designed from scratch, some data are unknown. Therefore, a number of estimations need to be made based on experts' opinion. The answer to this research question provides the input parameters and data necessary for solving the problem. Also, the uncertainty of the input data is taken into account. This research question is answered in chapter 4.

5. *What is the most efficient and effective production process for 50 sets per year with a maximum of 350 sets?*
   a. *What is the most effective and efficient production process, what is its performance and how to validate the outcome?*
   b. *What is the robustness of the production line?*
   c. *What are the critical stations in the process and need to be improved?*

With the right method(s) and parameters, the production line should be modeled and evaluated. This research question is answered in several steps. First the process must be further optimized and validated (research question 5a). After that, the sensitivity of the line and machines must be determined to find the robustness of the line (research question 5b). Finally the most critical production steps concerning processing times, complexity and variability must be identified (research question 5c). A proposal is made what to do with these stations e.g. improve the process, add or change the resources. This research question is answered in chapter 5.

6. *What should a green field production facility of skin panels look like?*

The answer to this research question is a good way to present and visualize the findings of research question 5. Additionally, it is very important for Fokker to know how the design of a facility should look like. This research question is answered in chapter 6.

## 1.4 Research scope

There are multiple areas to focus on when optimizing and designing a new production facility. This includes research areas e.g. capacity planning, facility planning, supplier selection, equipment selection, facility location and supply chain management. As described in section 1.3, the main focus of this master assignment is on the capacity problem. After optimizing the production process, a preliminary facility layout is determined.

This assignment was originated at the R&D department of Fokker Hoogeveen. Therefore, it has been developed from a technical point of view. Things like material characteristics, production techniques and resource types are therefore known and serve as input for this assignment. This project uses the technical information to solve the problem from a logistical point. From this logistical point of view, the production steps are designed, analyzed, optimized and evaluated.

Two of the production processes described in section 1.2 is mainly focused on in this assignment. These processes are Tool preparation and Automatic Fiber placement (AFP). These two processes are relatively new to Fokker because they have not been used on production lines for thermoplastic products. The other production processes are already used for other production lines and therefore well-known at Fokker. Important aspects to be taken into account are the logistic processes (e.g. how to place the tooling blocks in the mold), process variability and processing times. Another important aspect to take into account is the lead times of new equipment which is to be purchased. The outcome of the latter is critical in order to reach readiness level by the end of 2015. This level concerns a prototype demonstration in a relevant environment on the ground or in space (Minning, Moynihan, & Stocky, 2003).

Finally the Total Costs of Ownership, as described in chapter 3, are related to the decision variables. Other costs like material, warranty, interest, engineering and quality costs, are not taken into account. This is because costs have no influence in finding the most effective and efficient production process. For this reason, a Return on Investment is not calculated because it requires the actual cost prices.

## 1.5 Solution approach

This section describes how the research questions, stated in section 1.3, can be solved taking into account the preconditions, stated in section 1.2.

Before the production process can be optimized, relevant information should be gathered and interpreted from internal sources and literature. This information helps to get a clear view of the situation and what has been researched already. This view is obtained by answering research question 1, 2, 3 and 4. Documentations and knowledge of these TAPAS researches are also used as input for this project in order to start the optimization steps of the process.

The optimization steps start with an analysis of the current state of the production process by the data gathered in research question 1 and 4. These data are used for modelling and analyzing the production line for thermoplastic HTP skin panels. The upper throughput bound and the sensitivity on the throughput is researched. This step gives insight in critical production steps. After that, an optimization tool is used to find the most effective and efficient production line. If the current state is determined, the requirements for the future state can be determined and optimized by the solving technique and model, chosen from the literature study. The output of this model is validated and evaluated. The output should also be robust enough to give recommendations and a good conclusion. The answer of research question 5 finally gives most efficient and effective production process.

Finally, a layout of the facility is proposed. Research question 6 focusses on this problem. The results of the model and analyses from chapter 5 are used as input for the layout of the factory. This layout is called the future state. Finally, the current and the future state are compared.

## 1.6 Deliverables

In this research project the following products will be delivered:

- Excel tool which can model and optimize the performance of the production line for thermoplastic HTP sets in terms of capacity and TCO.
- Upper production limits, sensitivity of the production line and improvement potential for each production station.
- Factory layout and rough design concepts with applied improvements.

# 2 Current industrialization situation

The first chapter described the problem and the research questions. The second chapter gives an answer to the first research question. It gives an overview of the information at Fokker internally available concerning all aspects of the production of thermoplastic skin panels. Information is acquired by interviewing employees of Fokker and consulting (TAPAS) documentation.

In section 2.1 an overview of the thermoplastic composites, their characteristics, equipment and the TAPAS program is given. Section 2.2 focusses on some industrialization projects and examples. Section 2.3 is about the skin panel and gives a description of the production steps of the skin panel of thermoset and the production process for the thermoplastic skin panel. The chapter ends with a summery in section 2.4.

The purpose of this chapter is to inform on the thermoplastic properties and how the HTP and its production processes look like. These processes are defined as the current state (see section 2.3.3). The future state is described in chapter 6.

## 2.1 Thermoplastic composites

To understand the production process of the skin panel, some general knowledge must be shared about the required material, equipment and tools. This section provides that general knowledge. First the characteristics of thermoplastic composites are described and why thermoplastics are used for the TAPAS HTP. Second the TAPAS program is further explained. A small overview of the material related terms is given. Third the equipment for the production of thermoplastic components is further explained. This section is not about the thermoplastic skin panel but about thermoplastic components in general. From section 2.4 the focus is on the production of the thermoplastic skin panel.

### 2.1.1 Material characteristics

Before the TAPAS program can be explained, some material related definitions should be explained and are given in table 1. These definitions are frequently used in this thesis and therefore useful to understand.

Thermoplastic composites are a combination of carbon, glass or aramid fibers and thermoplastic polymer. The thermoplastic polymer is impregnated into the fiber woven layers. Thermoplastic polymers have the property to melt when heated. Therefore, these composites are suitable for welding and that provides production opportunities. Thermoplastics are characterized by e.g. short production processing times, relative lower production costs, less maintenance, good reuse opportunities, high toughness and improved corrosion resistance. The fibers make the material strong in relation to weight. Thermoplastic composites are therefore lighter and stronger than metals. Applications of this material will make aircrafts lighter, stronger, safer, less noisy and more cost-effective. That is an important advantage. (Fokker Aerostructures). Thermoset composites, on the other hand, become cured when heated. Once thermoset composites are formed into a shape, it is fixed and irreversible. This material property is an essential difference between thermoplastic and thermoset composites. Due to these differences and characteristics, thermoplastic composites will be used producing TAPAS HTP.

*Table 2-1. Overview of material related terms*

| Term | Definition |
|---|---|
| Fiber woven layers | Fabric made of woven carbon, glass or aramid fibers |
| Thermoplastic polymer | Plastic material that melts when heated |
| Thermoplastic composite | Thermoplastic polymers reinforced with fiber woven layers |
| Thermoplastic component | Aircraft component made of thermoplastic composites e.g. skin panel |
| Thermoset polymer | Plastic material that irreversibly cures when heated |
| Thermoset composite | Thermoset polymers reinforced with fiber woven layers |
| Stiffeners | Extra material to stiffen the product. |

### 2.1.2 TAPAS Program

Fokker Aerostructures developed aerospace components made from thermoplastic composites for over 25 years. The emphasis on the use of thermoplastic composites comes from both weight and cost reductions. Today Fokker is the worldwide leader in this thermoplastic technology and the number of applications is growing steadily. A Thermoplastic Affordable Primary Aircraft Structures (TAPAS) program has been founded by Fokker together with other partners e.g. University of Twente. Within the TAPAS program, Fokker develops affordable components like wings, tail planes and fuselages together with Airbus and several other Dutch companies.

Thermoplastic composites are already used in the aircraft industry, but the number of applications is still limited. The objective of the TAPAS program is to further research and develop applications made of thermoplastic composites. The main focus is on primary structural parts for aircrafts.

The TAPAS program involves several stages. The initial TAPAS program finished in 2013. In this program, a thermoplastic composite skin panel prototype was developed, manufactured and tested see Figure 2-1. The successful outcome of this program resulted in a follow-up program which is called TAPAS2. This program covers more than half of the R&D budget of Fokker Aerostructures. The outcome of this project is important for the future growth of Fokker Aerostructures. The TAPAS2 program consists of five work packages. Each work package concerns the development of a specific aircraft component. Work package 3 (WP3) is about the development of a Horizontal Tail Plane (HTP) made of thermoplastic composite. In the initial TAPAS program, a prototype of the HTP was successfully manufactured and tested at the Nationaal Lucht- en Ruimtevaartlaboratorium (NLR). In the TAPAS2 program, this project is further elaborated so it can be offered to the customers by the end of 2015 (Tapas Project, sd). Therefore, the industrialization of the HTP skin is an important aspect.

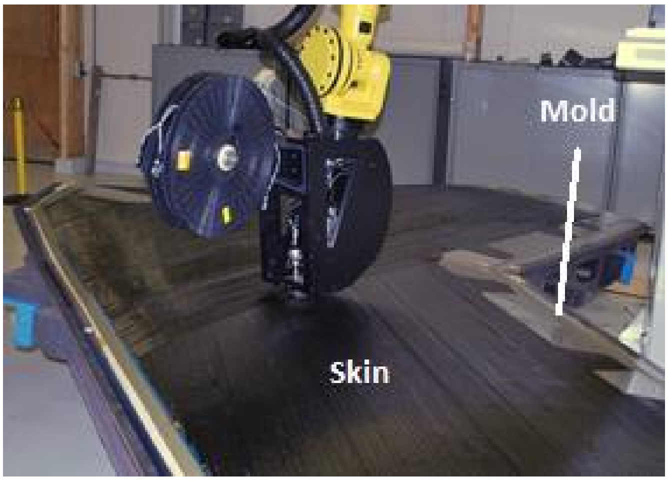

*Figure 2-1. AFP placing the skin on top of the mold by robot for a prototype*

*SIDESTEP 2: The TAPAS program involves € 24, 4 million and is supported by a major grant from the Dutch Ministry of Economic Affairs. The Dutch and French prime ministers were present at the contract signing.*

### 2.1.3 Equipment

This subsection describes the different tools and equipment which are used for the production of thermoplastic components within the TAPAS program. In section 2.3 it is described how the HTP skin panel is produced, using these tools.

*Mold and Tooling blocks*

Because of the melting behavior of thermoplastics, a mold can be used for the production of thermoplastic components. In the mold, the stiffeners for the skin panel are built up. Tooling blocks are used to keep the stiffeners on the right place in the mold as shown in Figure 2-2. (not shown) After that, the skin panel needs to be placed on the mold. Between the thermoplastic composite and the mold, a special release foil is placed to separate the product from the mold after consolidation. The mold is expensive and it is also involved in most others steps of the production steps of thermoplastic components. This makes the mold the most critical piece of equipment of the total production process.

Picture not shown

*Figure 2-2. Stiffeners in the mold (green), supported by tooling blocks (red)*

*Tape placement*

Another tool used for the production of thermoplastic components is an AFP robot. This robot is equipped with a special tool to place tapes on the mold (an example is shown in Figure 2-1). The tapes are small strips, made from the thermoplastic composite. The tape is supplied to the tool on the robot. This tool places the tape over the mold, using ultrasonic welding to fixate it in place. The material becomes hot due to high frequent local vibrations and this way it is welded to the layer below. Several layers of tape can be placed. Finally, the mold with the skin panel is packed in a vacuum bag and brought to vacuum to remove excess air. Another method is to use a tape layer. A tape layer can lay wider tapes and is faster, but only in one direction. The AFP robot can make bends but is slower compared to the tape layer.

*Autoclave*

After the intended thermoplastic composite layers of have been placed, the product must be consolidated in an autoclave. To do that the skin panel and mold must be bagged. An autoclave is a pressure chamber which uses a specific temperature and pressure to consolidate the product see Figure 2-3. The thermoplastic composite melts and the pressure consolidates the thermoplastic polymers with the fibers by fusing the layers. Once all layers are fused, the product can be removed from the autoclave and be debagged.

*Figure 2-3. Autoclave*

*SIDESTEP 3. Thermoplastic products are consolidated at a temperature of 380 degree Celsius and at a pressure of 6 bar. Therefore, the autoclave requires a lot of energy to consolidate the product. The total amount of energy an autoclave uses per product is approximately 4.6 Megawatt. Beside energy costs, the investment costs for an autoclave is also high. The expected price for an autoclave for the HTP panels is approximately 4 million euro.*

*Non-Destructive Inspection*

After consolidation, the product must be tested for product defects. This testing is done by a Non-Destructive Inspection (NDI). This means that the quality of the product can be determined without destroying the product. Several methods are suitable for such inspection like ultrasound, or X-ray equipment. For thermoplastic composites, this is usually done with ultrasound. An ultrasonic pulse with known intensity is released on the product and it moves through the material. When the pulse exits the product, its intensity is measured and compared.  This way defects can be identified.

*Machining and measuring equipment*

After consolidation and inspection, the edges of the product must be machined. Also the holes must be drilled. During machining, clamping of the product is important because thermoplastic products can be flexible. Therefore, good clamping reduces variability. After machining, the dimensions are measured. Measuring can be done by Laser-tracker or CMM equipment. Tolerances of dimensions, capacity of equipment and type of product are important aspects for choosing the right measuring equipment. Finally, the product is painted with primer and coating. To increase the bonding of the primer, the product is grit-blasted.

This section described the technical input for the assignment. In the next section, several industrialization projects and examples are explained and is analyzed on how these problems were approached.

## 2.2 Industrialization examples

Within Fokker, there is little information available on the industrialization of production lines. Most of the information must come from the knowledge of Fokker experts. Therefore, most information must be obtained by interviewing these experts which were Industrial and Manufacturing Engineers. To assure the manufacturability of these products, manufacturing concepts are made. These documents give technical details on the product and how it should be manufactured. Aspects as product handling, logistics, tooling and equipment used are further described. These documents are useful for this master assignment to obtain relevant information. This section describes industrialization aspects of projects for Airbus and what can be learned from it.

### 2.2.1 Airbus A320 rudder

A recent Fokker study on a thermoplastic product is a rudder for the Airbus A320. A deep research on industrialization has not been done for this product. Excel was used to visualize the production flow and calculate processing times and takt-times. An important conclusion of the information which was gained is that the mold is the most critical part. The mold is critical because several production steps depend on it (Gijseman, 2014). These production steps are further called 'mold-dependent' processes.

## 2.3 Production of the skin panel

In the previous sections, general information about the material, its production techniques and some industrialization projects within Fokker are given. This section builds on that information and applies it to the HTP skin panel. This section starts with the current production process of the thermoset skin panel. After that, a description of the structure or layout of the HTP is given. The section ends with the production steps of the thermoplastic skin panel. These steps are considered as the main result of this chapter. But they are also necessary to classify the problem for the second research question which is described in chapter 3.

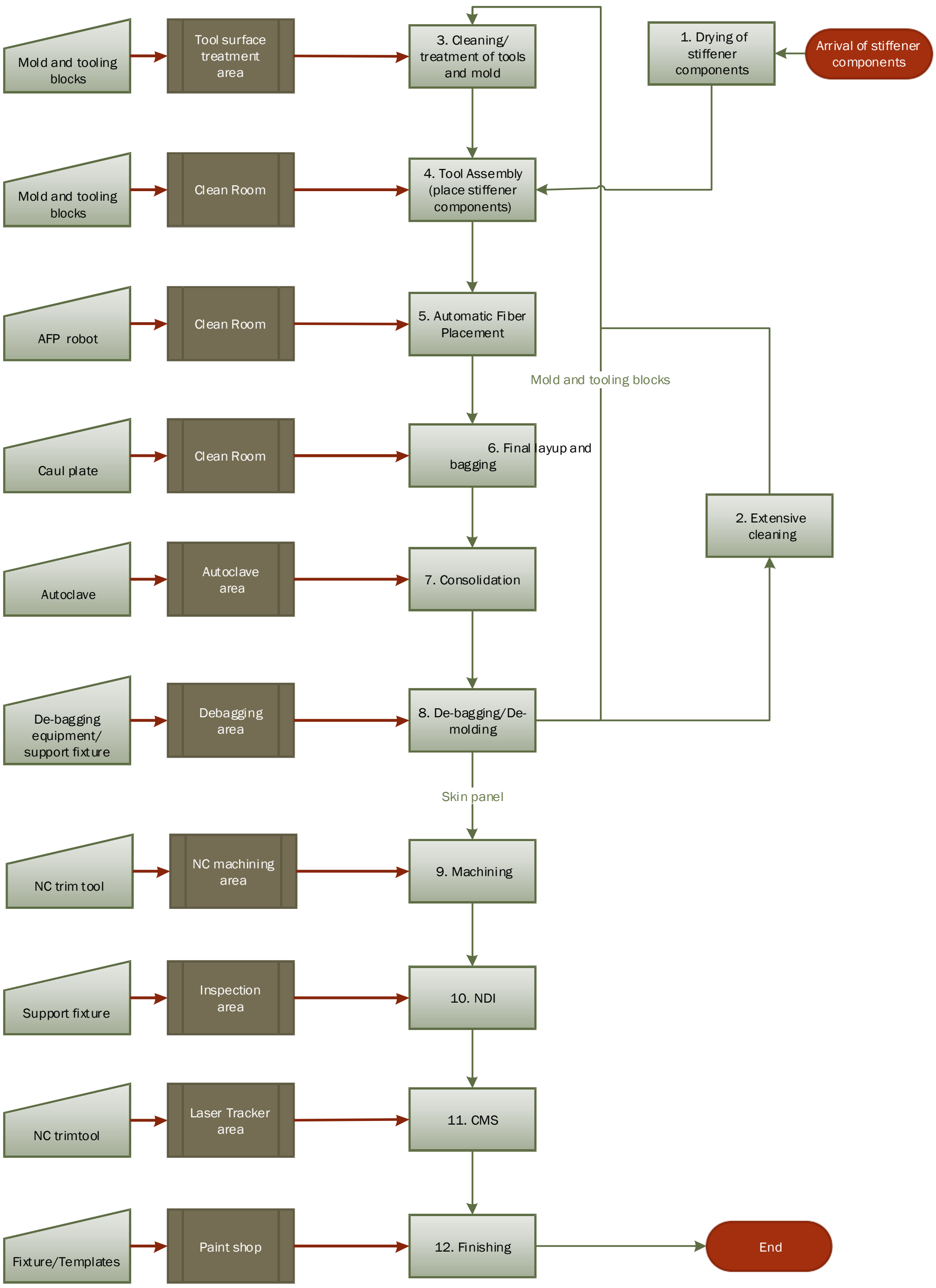


*Figure 2-4. Production steps for the production of the thermoplastic skin panel for the current state*

## 2.4 Summary

This chapter provides an answer to the first research question. Fokker Technologies is part of the TAPAS program and is worldwide leader in thermoplastic technology. Thermoplastic composites reduce weight and costs of aerospace components compared to thermoset composites.

Thermoset production of the skin panel is not comparable with the thermoplastic production process of the skin panel. The production process of the thermoplastic fuselage panels, however, has many similar production steps. The latter production process will therefore be used to generate ideas for the facility layout, described in chapter 6. From the industrialization project for A320 rudder, it is concluded that the mold is the most critical part in the total production process.

The skin panel is strengthened by multiple stringers. These stringers consist of webs, caps and fillers. And last but not least, the skin panel has a wingspan of 11 meters.

The final section of this chapter gives the current state of the production line. Figure 2-4 and Figure 4-1 gives an overview of the production processes.

The next chapter describes what external information is available, such as relevant literature and studies which can be used for modeling and planning of this particular situation.

# 3 Literature review

Now the problem has been described in chapter 2, a solution to the problem must be found. A literature study helps to find this solution and provide the answers to research question 2 and 3. This chapter describes what literature is available on planning and modelling and what an appropriate model would look like.

First the problem is classified which is described in section 3.1. Section 3.2 elaborates three approaches to model the production line: analytical, simulation or a hybrid approach. Section 3.3 describes the analytical model which is used for this master assignment. After that, the optimization method is described in section 3.4. Finally, some ideas for the design of a production line are presented in section 3.5. The chapter ends with a summary in section 3.6.

The purpose of this chapter is to present some useful ideas from literature which can help modelling and optimizing the production line. Additionally, ideas are given for the design of a future state factory.

## 3.1 Classification of the problem

To determine the right model for this production line, it is important to classify the problem. There are several reasons for problem classification according to Good (1965). First the mental clarification and communication will be improved. Second it might discover new fields of research. Third it will help for the planning of an organizational structure or machine (Good, 1965). Problem classification is also important since this research is part of the design phase of the production line. This means that there are many design uncertainties. Problem classification can help to clear these uncertainties and clarify the problem. Finally, the search process becomes more efficient since it is better known what to look for.

Like it is stated in chapter 2, current production lines at Fokker are not based on specific modelling techniques and laws. When an engineer designs a machine, laws of physics and metallurgy can help to make an efficient design. But there are no such laws for production engineers for designing an efficient production design. There is also no appropriate classification available which can classify real production systems (Maccarty & Flavio & Fernandes, 2000). Therefore, they made a review of several classifications for production systems and came up with a set of realistic classification dimensions. This section describes several classification dimensions which can be applied to the production of the skin panels.

### 3.1.1 Classification dimensions

Production systems can be classified by several dimensions e.g. physical organization, key resources and product flow control. These dimensions are important to develop a model (Askin & Goldberg, 2002). An elaborated study on production system classifications has been performed by MacCarty et al (2000). His conclusion is that each production system classification must choose between the level of detail and aggregation. MacCarty et al (2000) performed a study in which eight classification dimensions are identified. These dimensions are grouped in four characterizations namely general, product, process and assembly (Maccarty & Flavio & Fernandes, 2000). The purpose of their study is to facilitate a better understanding of real production systems which is also proved in their research paper. Several dimensions used in the studies just mentioned, can be applied to the production line of the skin panels and are stated below:

### *Layout*
Production systems can have different layouts e.g. process, product, cellular or fixed position. The production line for the skin panels is an example of a product layout. This layout is mainly characterized by high volumes and short distances (Askin & Goldberg, 2002). The skin panels go from the first station to the next. The production line is therefore an example of a serial production line. This means that each station in the line depends on the previous station. If one station finishes its job, then and only then the skin panel can move to the next station.

### *Product flow control*
Along the production line the skin panel moves from one station to the next. Since the skin panel is one product and not a continuous mass that flows through pipes or along conveyors, this production system is classified as a discrete production line.

### *Order initiation*
Like it is stated in chapter one, a skin panel is produced when Gulfstream gives the order. Therefore, the products are made according to the ´Make-To-Order' policy. This means that no inventory is used to store finished products. After the product is finished, it will be transported for assembly somewhere else.

### *Open or closed loop network*
In the production line, two parts in the production processes can be identified. First the processes dependent on the mold and its equipment. Second the processes independent on the mold and equipment (see Figure 3-1). A detailed overview of the two parts can be seen in Figure 4-1. The first part is an example of a closed loop which means that the mold and its equipment highly influences the total throughput. The second part is an open network which means that the skin panels are produced and then leave the production line. Since the mold-dependent processes are most critical and have the longest processing times (see section 5.2), the focus is on this closed loop network.

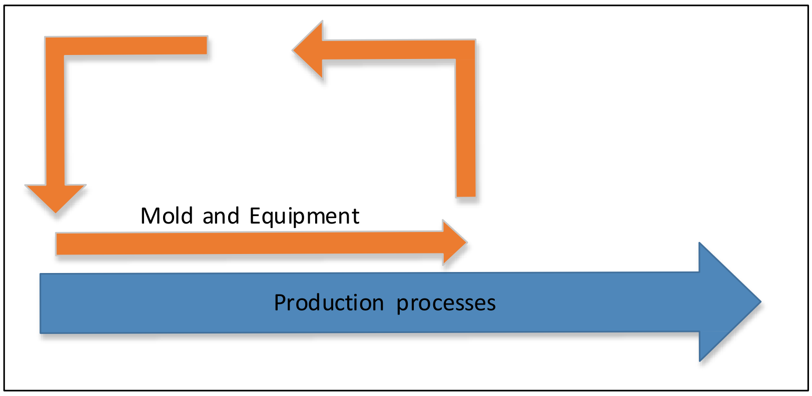


*Figure 3-1. Overview of the two parts within the production line*

### *Product variety*
The production line must produce two different skin panel types, namely the upper and lower skin panel. But the differences between both skin panels in the closed loop are negligible. The mold dependent processes are similar for both skin panel types. Therefore, the mold dependent processes

belong to a single-class system. However, the total production line is a multi-class network because some mold-independent processes steps differ per skin panel type.

*Product volume*

The target is to produce 50 sets per year, which is equal to 100 skin panels per year. Since the two skin panel types are similar, the production system is classified as a dedicated production line. The processing times per station are estimated by Fokker experts. The processing times are also subject to a certain degree of variation. The model should therefore take into account variability of processing times.

*Fabrication of Flow type*

The production consists of several production stages or stations. The product moves in one direction and therefore the production line should be modelled as a unidirectional multi-stage production system.

## 3.2 Modelling approaches

There are mainly two approaches to model a production system namely analytically or using simulation software. Since the production line for the skin panels is relatively simple, the analytical approach would be obvious. But the production line is still in its design phase and consists of several stochastic elements. In that case, simulation software would be a better option to model the production system. Both options are examined in this chapter.

### 3.2.1 Analytical approach

When the complexity of the production process is relative low, an analytical method is better (Law, 2007). Analytical models provide an exact solution which is better than the output of simulation software. Another advantage is that analytical models can be solved rapidly (Dallery & Gershwin, 1992). Law (2007) partly confirms it when he states that simulation software is time-consuming (Law, 2007). Nyhuis (2005) concludes that analytical methods have a statistical nature while simulations have a better level of detail. Besides, analytical methods require a higher modeling effort and it is harder to look from different perspectives. (Nyhuis, von Cleminski , & Fischer, 2005)

### 3.2.2 Simulation approach

Simulation models are capable of describing complex real-world systems. Additionally alternative policies can be compared by several experiments and a simulation project can be modelled for a long time frame. However, there are several disadvantages like the fact that each run is an estimation. This disadvantage can be tackled by running the model several times. Besides, simulation models are expensive and time-consuming. Finally simulation results can be impressive. The persuasive impact of a simulation might tend to place greater confidence than justified (Law, 2007). According to Nyhuis et al (2005) simulation can be a good method for exploring, designing and optimizing a complex system. It is a dynamic process which creates a higher level of detail compared to analytical methods. The amount of construction effort of simulation methods is reasonable and finally simulations are widely accepted according to Nyhuis et al (2005).

### 3.2.3 Hybrid approach

Both approaches have their advantages and disadvantages. Analytical models are exact and static while simulation models are approximations and dynamic (Hsieh, 2002). A combination of both approaches into one approach is another option. This is called a hybrid approach. Such approach gives different perspectives of the production system. A combination of analytical and simulation models might offer some of the advantages and avoid the disadvantages (Byrne & Bakir, 1999). Sargent (1994) defines a hybrid model as a mathematical model that combines simulation and analytical models. He proposes four different classes which are shown in Figure 3-2:

Class I: Model behavior is obtained by alternating between the simulation and the analytical model
Class II: Simulation and analytical model operate parallel with interactions
Class III: Simulation model is used in a subordinate way for an analytical model
Class IV: Simulation model is used as an overall model and requires analytical solutions as input.

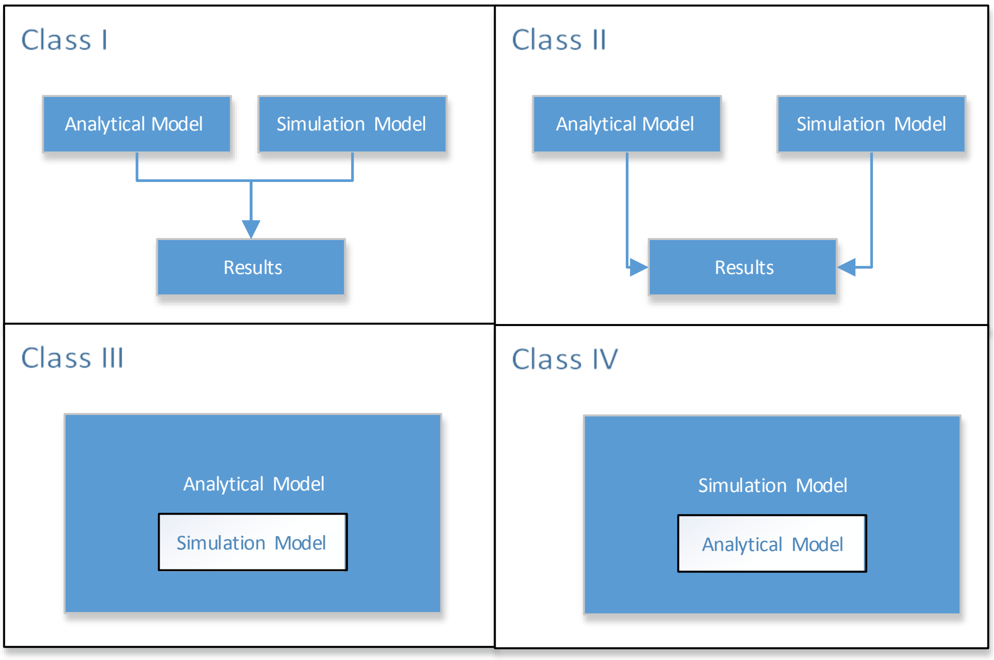


*Figure 3-2. Different classes of hybrid approaches*

Because the production line for the thermoplastic skin panel is relative simple, an analytical model is preferred. The production line is also in design phase which makes it hard to retrieve reliable data. Therefore, a simulation approach might be useful for validation of the analytical model. Therefore, the Class III hybrid model suits best for this master assignment. An analytical model is made to answer the research questions because it is less complex and time-consuming. A simulation model is made for validating the analytical model so that the outcome is reliable.

## 3.3 Analytical model

A manufacturing system with uncertain processing times can be analytically modeled as a network of queues (Zijm, 2012). A network can be open- or closed. As explained in section 3.1, the production line is an example of an open network with an internal closed network. The mold dependent processes must be modelled as a closed network. According to Zijm (2012), the closed network is an example of a Workload Controlled Manufacturing System. By controlling the Work in Process or WIP of these systems, the time a job is in the system can be reduced. A Flexible Manufacturing system is an example where the number of pallets limits the number of jobs in the system. Therefore, Closed Queuing Networks (CQN) do not imply statistical independence of the number of jobs in the system. The number of jobs is dependent on the number of pallets available. In the mold dependent processes, the mold can be seen as a pallet which limits the number of skin panels in the production line.

There are several direct methods to find the mean performance measures of a CQN. These methods are the Mean Value Analysis algorithm (MVA) and the Marginal Distribution Analysis algorithm (MDA). MVA is only applicable for single-machine stations and MDA for multi-machine stations. In both models expected cycle time is found on the Arrival Theorem. This theorem roughly states that an arriving job at any workstation observes the whole system as being a system in a steady-state with one less job (Zijm, 2012). Both algorithms assume exponential processing times (Zijm, 2012). Additionally, the algorithm assumes that there is an infinite buffer capacity between the stations. Because the production line of the skin panels is not running yet, the probability distribution of the processing times is unknown. Therefore, the assumption of exponential processing times cannot be applied and a general distribution is used instead. In most real-world manufacturing systems, processing times are not-exponential distributed. Therefore, Zijm (2012) proposes an Approximation of the Marginal Distribution Analysis algorithm (AMDA). This algorithm uses general distributed processing times and is for single-class systems. The AMDA algorithm can be used for multi-machine systems. Since the number of machines is a decision variable in our optimization model (see chapter 5), this algorithm is chosen.

The AMDA algorithm uses the following parameters:

| | |
|---|---|
| $n$ = | Number of molds in the system. |
| $N$ = | Maximum number of molds. |
| $C_j$ = | Number of machines at station j. |
| $SCV_j$ = | Squared Coefficient of Variation of the processing times of station j. |
| $EP_j$ = | Expected processing time of station j. |
| $EP_{rem,j}$ = | Expected time between arrival and first departure given that all servers are busy or expected remaining time. |
| $EL_j(n)$ = | Expected number of molds at station j. |
| $ETCQ_j(n)$ = | Expected time to clear the queue of station j. |
| $EW_j(n)$ = | Expected cycle time at station j (including processing times) |
| $TH_j(n)$ = | The throughput of station j. |
| $TH_0(n)$ = | The throughput of the network |
| $V_i$ = | Visit ratio of |
| $p_j(l\|n)$ = | The stationary probability of having l molds at station j with n molds in the network. |

The AMDA algorithm is a recursive procedure to calculate the performance measures of the CQN. Each iteration a mold is added to the network. This process continues till N molds are in the network. Because the production line is unidirectional and serial, the visit ratios for all stations are 1. Each iteration 5 key performance indicators are calculated:

1. The expected cycle time at each station (EWj (n))
2. The throughput of the network ($TH_0$ (n))
3. The throughput per station ($TH_j$ (n))
4. The expected number of molds at each station ($EL_j$ (n))
5. The marginal probabilities ($p_j(l|n)$)

The expected time at a station depends on expected remaining time when a mold has to wait in the queue. The remaining time at each station can be formulated as follows (see Zijm (2012) section 3.2.):

��₍₍₍,₍ = (1 − ���₍) ��ⱼ / (� +1) + ���₍ ��ⱼ / � �

jj

Where the squared coefficient of variation is calculated as follows and has a different value for each different probability distribution:

��� = �²ⱼ / 2 j

=

The expected time at a station also depends on the expected number of molds in the queue. This number can be calculated by the following formula:

��₍₍(� − 1) = Σ^{�−1}_{�=}(� − ��)�₍(�|� − 1)

Where the stationary probability of having l molds at station j with n molds in the network can be calculated as follows:

�₍(�|�) = ��₍��₍(�) / min(�, �) �₍(� − 1|� − 1)

=

�₍(0|�) = 1 − Σ_{�=1} �₍(�|�)

The time it takes to clear the queue before a station is given by the product of the expected number of molds in the network and the mean processing time divided by the number of machines. This is can be calculated as follows:

����₍(�) = �� (� − 1) ��ⱼ / �ⱼ

The expected time at a station is given by the following formula:

��₍(�) = �₍(�|� − 1) ∗ ��₍₍₍,₍ + ��₍,₍(� − 1) ��ⱼ / �ⱼ + ��₍

The throughput time of respectively the network and the station is calculated as follows:

��₀(�) = Σ^M

� �� (�)

�

�=0 � �

��� (�) = ��0(�)

Because the production line is serial, the visit ratios ($V_i$) are one.

The algorithm consists of the following steps:

1. Initialization (j=1,...,M, n=0, $p_j(0|0) = 1$)

2. n = n + 1
3. Calculate $EW_j(n) j = 1,\ldots, M$
4. Calculate $TH_0(n)$
5. Calculate $TH_j(n)$ $j = 1,\ldots, M$
6. Calculate $EL_j(n)$ $j = 1,\ldots, M$
7. Calculate $p_j(l|n)$ $l = 0,1,2,\ldots, n$
8. Go back to step 2, if n = N then stop

The implementation of this model is further described in chapter 4. This chapter includes the assumptions made, a description of each parameter and the validation of the model.

## 3.4 Optimization method

The AMDA algorithm can model the production line. When properly applied, it represents a realistic performance of the production line. The implementation of the AMDA algorithm is further explained in chapter 4. Assuming the model is properly implemented, it must be optimized to get the best production settings. The yearly TCO is minimized for a predetermined throughput. The decision variables (number of resources, shifts and molds) are bounded by a maximum number. This is described more detailed in chapter 5. This section describes the way how the model is optimized. The results of this optimization process are further described in chapter 5.

### 3.4.1 The Excel SOLVER

The AMDA algorithm can easily be programmed in Microsoft Excel 2013. The built-in VBA programming language can support this model including optimization methods. Another interesting feature is the Excel SOLVER. This feature is user-friendly an ideally suited for non-linear functions via an interactive algorithm. Therefore, it comes with the Excel software and is relatively cheap compared to other programs (Brown, 2001). The Excel SOLVER begins with a spreadsheet which might even contain discontinuous functions. Through the GUI of the Excel SOLVER, the user can specify the objective and constraints. The Excel SOLVER employs several methods e.g. simplex method, generalized reduced gradient (GRG) and the Evolutionary method. The disadvantage of the Excel SOLVER is that it supports only 200 decision variables (Fylstra, Lasdon, Watson, & Waren, 1998). But this disadvantage does not become a problem for optimizing the AMDA algorithm because it contains far fewer decision variables. These decision variables are integers and are further explained in chapter 4.

The AMDA model is an example of a nonlinear integer problem (see section 3.3). The Excel SOLVER uses a Branch & Bound method to give an idea of the solution for this kind of problems. The sub-problems are solved by the Simplex, the GRG method or the Evolutionary method. The Simplex can solve a problem to optimality while the GRG and the Evolutionary methods are heuristics. Since the AMDA model contains nonlinear expressions, the GRG or Evolutionary method must be used. The Evolutionary method is able to give an idea of the solution of problems which contains discrete variables. These discrete variables are characterized by e.g. IF-statements. To calculate the costs for this production line, discrete variables must be used (see section 4.2.3). Therefore, the Evolutionary method is the only method within the Excel SOLVER which is applicable for this research.

The Evolutionary method relies in part on random sampling which makes it a stochastic method. This method needs parameters e.g. mutation rate (diversity), population size (values for decision variables) and random seed (Frontline Systems Inc., 2015). The stopping condition for the evolutionary method is satisfied if 99% of the population members all have fitness values that are within the convergence tolerance of each other (Frontline Systems, 2010).

Because the AMDA algorithm is modelled in Excel, the Excel SOLVER is an interesting tool for optimizing the model. Additionally, it does not take much time to compile, it is user-friendly and iterations can easily be programmed in VBA. All features required are available in excel and can easily interact with each other.

### 3.4.2 Simulated Annealing

However, the Evolutionary method in the Excel solver is a relatively new and a developing technique to give an idea of the solution of a problem. Therefore, it has not been used much in scientific research before. Therefore, another optimization method is proposed in order to validate the outcome of the Excel SOLVER. Many optimization methods can be chosen e.g. Tabu search and Simulated Annealing. The Simulated Annealing algorithm is chosen to validate the Excel SOLVER results because it has the ability to escape from a local optimum. The comparison of the performance of the AMDA and the Simulated Annealing model is further described in appendix H.

The Simulated Annealing algorithm is a method which can give a solution to a combinatorial optimization problem (CO-problem). A CO problem consists of a finite number of alternatives (Hans, DOBP lecture slides part 1, 2002). These are measured by a criterion or objective. In this research, the objective is the minimization of the TCO. As described in chapter 5, the problem is considered NP-hard.

The idea behind this algorithm is that it starts with a random initial solution (AS). Every iteration a neighbor solution is produced (BS). If this neighbor solution is better than the current solution, the neighbor solution is accepted as the new current solution. If not, the neighbor solution is accepted with a certain probability. This probability is calculated as follows (see Hans (2002) sheet 58):

$$P_{accept}(BS) = \begin{cases} 1 & \text{if } BS \leq AS \\ e^{\frac{-(BS - AS)}{c}} & \text{else} \end{cases}$$

The variable c is the cooling parameter. The cooling parameter starts at a predetermined number and decreases every iteration when the Markov chain length is reached. The algorithm stops when cp > $cp_{stop}$. Then the best-found solution is given. The probability is high at the beginning, but it decreases as the number of iterations increases. (Hans, DOBP lecture slides part 2, 2002).

In appendix H, both models are compared. The Excel SOLVER came up with the most stable solutions which are also closer to the optimum. Therefore, the Excel SOLVER is chosen as optimization method for this research.

Additionally, the Excel SOLVER is better accessible for Fokker employees while the Simulated Annealing model is harder to understand. Therefore, the Simulated Annealing model is only used for validation.

## 3.5 Design improvements

Because the production line is still in the design phase, some design improvements should be suggested based on the outcome of the AMDA model. This is further described in chapter 5. Chapter 6 shows some pictures of these improvements. This section describes some interesting ideas from the literature concerning the design of a production line.

### 3.5.1 Lean manufacturing

Lean manufacturing is based on eliminating waste through the efficient use of space, people, machine tools and material handling elements. According to Shingo, the reduction of variation is the key to continuous improvement (Shingo, 1988). Black (2007) describes 4 design rules for implementing lean manufacturing. The first rule is that the takt-time must be based on the daily demand. The second rule is that the production system must be based on a single piece flow. This means one product can be processed at a time per station. Single piece flow can be obtained by designing a production line using parallel lines or a U-shape. The third rule states that each station must have a processing time which is lower than the necessary cycle time. This necessary cycle time is based on the takt-time and also includes some safety. Finally, the last rule concerns the minimization of the total inventory. Inventory can be analogized to water in a river. When the water is high, it covers all the rocks on the bottom of the river. These rocks are equivalent to problems. When the water level is lower, the rocks become exposed (Black, 2007). Minimizing inventory means exposing problems so they can be solved.

Another example of designing a production line according to lean principles comes from Airbus Hamburg. This production facility of Airbus went through a production system development project for fuselages for several aircraft types of Airbus. This project is called the 'New Factory' program. Mr. E. Frankenberger participated in this process and wrote an article about it. The main goal of their project was to create a manufacturing system with a continuous flow of products and materials. Mr. E. Frankenberger divided this 'New Factory' program into 3 phases: requirement analysis, solution search and decision making. They started with analyzing the whole production line and collect a list of requirements. This way the workload was balanced over the stations of the production line to optimize the throughput time. Besides, several solutions of the layout were designed, as well as new jigs, tools, machinery and logistic equipment. The designs are such that the walking distance of the operators is minimized. Additionally, the material must be distributed as close to the stations as possible. Since factory development has no prototypes, it must be right the first time (Frankenberger, 2007). Finally, a decision must be made what solution should be used. Methods used for these phases are e.g. a checklist which captures all requirements.

Things like the factors, leading to success or failure, adjustments of systematic design methods and social conflicts and disturbances are presented in this article. These lessons learned becomes interesting when designing a production factory for the thermoplastic skin panels for the G650. However, this thesis does not focus on a complex design of the production line. It only focuses on the optimization of the production line, including some improving design possibilities. These possibilities are further described in chapter 6. Therefore, the methods used in the 'New Factory' Program of Airbus are interesting for the actual design project but not further elaborated in this thesis.

### 3.5.2 Poka Yoke

Most assembly issues are analyzed after they have happened. However, it is much better to prevent these issues in advance, which saves costs and trouble. Poka Yoke or Error-proof is a useful technique to prevent failures. Poka Yoke is a method widely used when applying lean principles. The main idea of this technique is that it prevents the failures from happening. A simple example of this technique is the USB-stick. The stick can be connected one way only. Estrada et al. (2008) have come up with an interesting method to prevent assembly quality issues (aq-issues). The method can be used to design for Poka Yoke assembly. This method uses three parameters: Ax (the aq-issue), Rx (the assembly requirements), and Cx (the design characteristics). The method begins with identifying the aq-issues (or Ax). While the assembly characteristics (Cx) are known, the right requirements can be determined (Rx) (Estrada, Lloveras, & Riba, 2008). This method is not fully executed in this thesis but is only used to generate ideas on how to implement Poka Yoke assembly systems.

### 3.5.3 Theory of Constraints

The theory of constraints sees processes as chains which are only as strong as its weakest link according to Pegels and Watrous (2005). The purpose is to identify this weakest link which is called the constraint. The percept of Theory of Constraints is to identify and focus on the bottleneck because they are the source of most interferences. When this bottleneck is eliminated, improvement will follow automatically (Pegels & Watrous, 2005). Goldratt wrote a book about this theory which is called 'The Goal'. In this book he identifies 5 steps (Goldratt & Cox, 2012):

1. Identify the system constraint
2. Decide how to exploit the system constraint
3. Subordinate everything else to the above decision
4. Elevate the system constraints
5. If in any of the previous steps a constraint is broken, go back to step 1. Do not let inertia become the next constraint.

## 3.6 Summary

Literature is consulted in order to find an appropriate model and optimization method for the production line of the skin panels. Some ideas and methods concerning future state factory design are described as well.

The production line is classified as serial, discrete, unidirectional multistage with a 'Make-to-Order' policy. Additionally, it contains an inner closed loop which is a single class system. The model, used for this thesis, only represent the closed network of the whole production line. This closed network represents all mold-dependent processes. Since these processes determine the throughput, the model only takes this part of the production line into account. Additionally, the processing times are variable and they include failures and repair times as well. This is elaborated in chapter 4.

A hybrid approach is chosen to model the production line. This approach involves the AMDA algorithm and a simulation study. This simulation study is used to validate the AMDA algorithm. This model is then be optimized by using the Excel SOLVER and VBA is used as a supportive tool. The optimization includes the minimization of the Total Costs of Ownership for a predetermined throughput. Modelling and optimization are both performed in Excel.

Finally, this chapter presented some ideas on lean manufacturing like the Theory of Constraints or the "New Factory" program of Airbus. These ideas are helpful for the production facility design, given in chapter 6.

The next chapter explains how the model is implemented and validated for the production line of thermoplastic skin panels.

# 4 Modeling the production line

The AMDA algorithm is used for modelling the production line as described in chapter 3. This model only represents the mold-dependent processes of the production line because these processes determine the total throughput of the production line. Figure 4-1 gives an overview of the production processes, divided into mold-dependent and mold-independent processes. The green arrows represent the closed loop. Chapter 4 gives an answer to research question 4. The results and the model optimization are given in chapter 5.

Section 4.1 gives the assumptions for the model. Section 4.2 gives the parameters of the model. After that, the model is validated. This validation is described in section 4.3. Finally, a summary of this chapter is given in section 4.4.

The focus on this chapter is to describe the implementation and the validation of the model based on the AMDA algorithm.

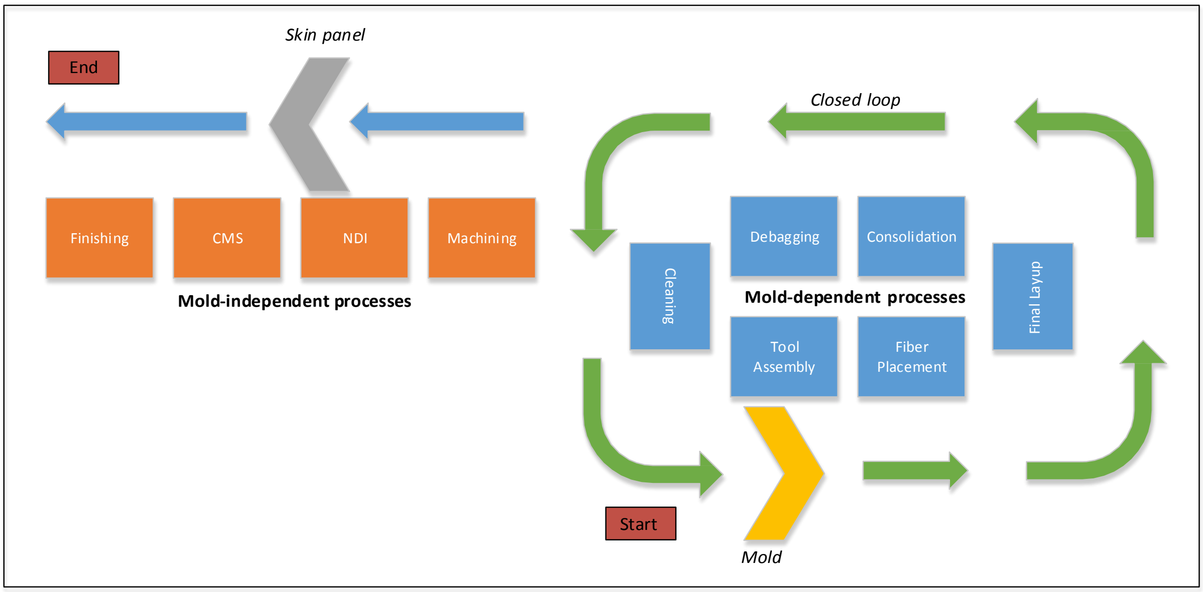


*Figure 4-1. Overview of mold-dependent and mold-independent processes*

## 4.1 Assumptions

In this section, the assumptions are described. In section 4.1.1 the project assumptions are mentioned which emanate from the TAPAS specifications. The model itself is also based on several assumptions which are described in section 4.1.2.

### 4.1.1 Project assumptions

In chapter 2 it was stated that the manufacturing concept for the TAPAS HTP is used as starting point for this master thesis. Therefore, the assumptions used in this concept are also applicable to this model. The production line is modelled in a green field scenario. The initial production rate target is 50 sets per year. However, an increase of the production target rate to a maximum of 350 sets per year is included in the scope. Further, it is assumed that the production line is in a steady state. In practice, there is a ramp-up period which means that the number of orders increases in the starting period. For this model, the ramp-up period is excluded. Another assumption is that the upper and lower skin panel have similar processing times for mold-dependent production processes. In practice, the difference in the processing time of the upper and the lower skin panels is also negligible. Therefore, the number of panels is measured, instead of the number of sets. Finally, it is assumed that the materials like webs, caps and fillers are always on stock.

### 4.1.2 Model assumptions

In chapter 3 the AMDA algorithm is proposed. The algorithm is only applicable for closed networks. The AMDA algorithm assumes that there is an infinite amount of raw materials available so that there is no stock-out. The model is based on the fact that the number of jobs in the network depends on the number of pallets in the same network. This fact is also applicable to the mold-dependent processes where the number of molds determines the number of jobs in the closed network of the production line. Another assumption is that there is always an unprocessed job available to enter the network when a finished job leaves. This assumption is applicable because the production target is on a yearly basis. This means that there are always orders waiting to be processed. The final assumption of the AMDA algorithm is that the buffers between the stations have an infinite capacity.

The approximate version of the MDA algorithm (AMDA) assumes general distributed processing times. These processing times do have a squared coefficient of variation (SCV) which determines, e.g., the probability distribution of the processing time. Since there is no data available to determine the values of the SCV's, it is estimated together with an Industrial Engineer of Fokker. More information about the variation of the processes is given in section 4.2.1. The AMDA algorithm has a single- and a multi-class variant. For this production line, the single-class variant is used since the skins can be seen as similar products for the mold-dependent processes. The model can make an approximation of the performance measures by assuming that a product-form solution and the arrival theorem are still valid (Zijm, 2012). Finally, the failure and repair times of the stations are assumed to be exponentially distributed

## 4.2 Parameters

This section describes the decision variables, input and output parameters which are necessary for modelling a thermoplastic production process. The input parameters take care for a realistic modelling of the production line. The decision variables are used to optimize the production line. The output parameters represent the performance indicators of the production line. The yearly throughput of the production line determines the key performance indicator. These parameters are graphically shown in Figure 4-2.

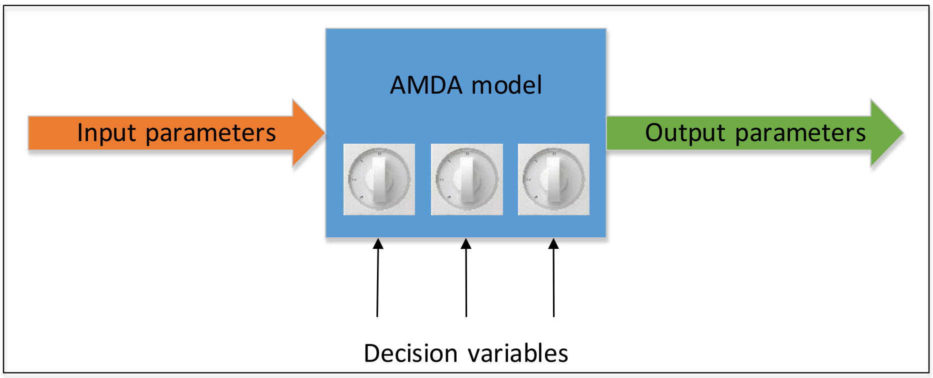


*Figure 4-2. Different parameters*

### 4.2.1 Input parameters

The input parameters influence the model such that it gives a realistic result. The main input for the AMDA model are the processing times per station. The input parameters are predefined and estimated by Fokker experts. These input parameters are as follows:

*Processing times*

A single point estimation is made on the processing times of each individual production step for the production of a thermoplastic skin panel. These estimates come from several experts like cost-estimators, process specialists and from the production of the prototype of the thermoplastic skin panel. Together they came to the estimated processing time, shown in Table 4-1.

The processing times are based on cost drivers. A cost driver can be the number of tooling blocks. Together with the time it takes to place one block, a processing time for placing all blocks is calculated. Besides, the estimations are expected processing times for the 100th skin panel. This means that the estimations are based on a steady state production line.

These data are also used for the business case of this work package. Table 4-1 gives an overview of each process including their processing times. Note that the debagging station is split into a mold dependent process (station 6a) and a mold independent process (station 6b). This is because the skin is released from the mold in an early stage of station 6.

*Table 4-1. Number of machines and processing times in hours*

In Figure 4-3 the data are graphically displayed. Station 1 to station 6a belongs to the closed network. These processes together form the bottleneck of the total production line because they depend on the number of molds in the network. Especially AFP has a high processing time.

The AMDA algorithm only represents the closed network of the production line. To calculate the time it takes to produce a skin panel, the processing times of the mold-independent processes are added to the cycle times of the mold dependent processes. This is because the waiting time of the mold independent processes can be neglected. Note that the cycle time consists of the processing time and the waiting time.

*Figure 4-3. Processing times in hours*

The total cycle time for the production line is then calculated as follows:

$$Total\ cycle\ time = \sum Cycle\ time_{mold\ dependent} + \sum Processing\ times_{mold\ independent}$$

This formula only applies when the total throughput time of the closed loop is larger than the throughput of any mold-independent process. The maximum processing time of all mold-independent processes is 12 hours (NDI). So the total cycle time of the closed loop value determines the throughput of the total production line when it remains higher than 12.

### *Availability*

A model without process interruptions, e.g. due to station failures, would not give a realistic result. Therefore, the model uses the availability per station which influences the effective processing time per station. The availability per station (A) is the fraction of time in which this station is capable of doing its job. The availability depends on the mean time to failure (MTTF) and the mean time to repair (MTTR). These two parameters are estimated by a senior manufacturing engineer of Fokker, specialized in composites. How these parameters are calculated is described in appendix B.

Outages like rework and scrap are hard to estimate because data of these outages does not exist yet. However, an assumption of the percentage of rejects is taken into account. A reject rate of 2% is taken into account, based on actual thermoplastic skin panels of other products. This percentage influences the number of skin panels produced per year. The availability is formulated as follows (see Zijm (2012) section 1.11.):

$$A = \frac{MTTF}{MTTF+MTTR}$$

The impact of the availability per station on the processing time is defined by the effective processing time which is given by the following formula:

$$t_{e,j} = \frac{t_{nom,j}}{A}$$

Beside the processing times, the variation and SCV of the processing time are also affected by the availability per station. The effective SCV of the processing times can be formulated as follows:

$$SCV_{e,j} = SCV_{nom,j} + 2A(1-A)\frac{MTTR}{t_{nom,j}}$$

Where the $SCV_{nom,\,j}$ is the nominal SCV of the processing time and the Time to Failure and the Time to repair are assumed to be exponentially distributed.

### *Squared Coefficient of Variation*

The variability of the processing time only affects the throughput. Therefore, the SCV is only calculated for the processing times and not for the inter-arrival times. The formula for the squared coefficient of variation for the processing times is given in section 3.3. The processing times distribution is unknown and therefore the SCV for the processing times is estimated by an Industrial Engineer of Fokker, specialized in lead time studies. This expert has an idea of how much variation the processes involve in practice. The result of this discussion is shown in Table 4-2. According to Hopp and Spearman (2000) the SCV of processing time in a manufacturing environment can be divided into 3 classes, low, moderate and high. (Hopp & Spearman, 2000). A low SCV has a value lower than 0.75. A moderate SCV has a value between 0.75 and 1.33 and a high SCV has a value higher than 1.33. For this model the average of these ranges is used, as shown in Table 4-2.

*Table 4-2. Variation classes and SCV per station*

| | Process per panel | Variation class | SCV |
|---|---|---|---|
| 1 | Drying of stiffeners | | |
| 2 | Extensive cleaning | Content | |
| 3 | Cleaning | not shown | |
| 4 | Tool Assembly | | |
| 5 | Automatic Fiber placement | | |
| 6 | Final layup and bagging | | |
| 7 | Consolidation | | |
| 8 | Debagging and Demolding | | |
| 9 | Machining | | |
| 10 | NDI | | |
| 11 | CMS | | |
| 12 | Finishing | | |

*Number of hours available per year*

Currently, the effectivity of the operators is on average 85% of the nominal time available per day. The other 15% are non-value adding activities like breaks and meetings. But since the estimated processing times do already contain these wastes, the model still uses 40 hours per week. If holidays are included, the total available number of weeks becomes 47 instead of 52. This results in 1880 available working hours per year. Besides, the holidays can be used for preemptive maintenance of the equipment.

*Takt-time*

The takt-time can be defined as the time required by each station for one product such that it satisfies the demand of the customer. The production target is to make 100 skin panels (or 50 sets) per year. Assuming that the production line is operational for 40 hours per week 47 weeks per year with 85% effectivity, the takt-time is 15.98 hours.

### 4.2.2 Decision variables

The decision variables are parameters which can vary per experiment. Changing these parameters results in a different model outcome. Therefore, these parameters are used to find the most effective and efficient setting of the production line.

*Number of resources*

The number of resources is a broad term. In this case, the operators and machines are together mentioned as resources. Some stations do not involve machines but only contain manual operations. Therefore, the processing times at these stations can be reduced by adding more operators. Other stations which do involve machines cannot be improved by adding operators only. At those stations, machines including operators must be added to reduce its processing time. Adding a resource to a station with machines, the number of machines for that station ($c_j$) also increases.

Some steps in a process cannot be improved by adding resources e.g. transport of the product to another location. The processing time of these stations is not reduced when an operator is added.

Only processing times which depend on the number of resources are reduced. This dependency on the number of operators is also taken into account in the model.

### *Number of shifts*

The number of shifts per station can vary from 1 shift to 3 shifts per working day, 8 hours per shift. An extra option is to include weekends. This option is then called the 5th shift. This means that the available time per day increases. The number of skin panels produced per year per station j is related to the number of shifts per station j. Riis (1995) presented a way to calculated the number of shifts (Riis, 1995). He uses this calculation for a Flexible Manufacturing System (FMS) production process. This process is also a closed network and the throughput depends on the number of pallets in the network. He calculated the number of shifts as follows:

$$\#\ \text{shifts} = \frac{\text{Processing time} * [\text{illegible}]}{\text{Available hours per year per shift}}$$

The number of shifts increases the available time per year, to produce the product. Therefore, the formula could be rewritten as follows:

$$[\text{illegible}] = \frac{\text{Available hours per year per shift} \times \#\ \text{shifts}}{\text{Processing time}}$$

The available time per station is 1880 hours, excluding the holidays. To simplify this calculation, the available time per year per shift is kept constant. The reason for this simplification is that shifts can vary per station. It is hard to change the available time per station since the stations depend on each other. In reality, the available time increases when a shift is added. To calculate the number of panels produced per year per station correctly, processing time must be divided by the number of shifts. This is also used in the model where the processing time is divided by the number of shifts for each station.

Note that when producing 5 shifts, the available time cannot be multiplied with 5. A 24/7 work week has 168 available hours so the available hours is multiplied with 4.2. A numerical example of the shift calculation is given in appendix A.

To proof the abovementioned calculation is right, a simulation study is performed. The AMDA and the simulation model both simulates the production line with 3 shifts. It can be concluded that the throughput of both models is very similar. Therefore, it can be concluded that the abovementioned calculation is right. This proof is given in appendix A.

### *Mold dependency*

All stations are classified as mold-dependent or not. If a station depends on the number of molds in the network, its cycle time influences the total cycle time of the closed network and the total throughput. In the model, each station gets a value for mold dependency. This mold dependency has a binary value (0 when mold independent and 1 when mold dependent). If a station can be improved such that it becomes independent of the mold, the total cycle time of the closed network decreases. In that case, the cycle time of that station is neglected in the total cycle time of the closed network. Like stated in section 3.3, the AMDA model only represents the closed network of the production line.

### *Number of molds*

At each iteration of the AMDA algorithm, an extra mold is added to the closed network. The molds have an impact on the output. This impact on output is further explained in section 5.1 and graphically displayed in Figure 5-1.

| |
|---|
| *SIDESTEP 5: The mold for the upper and lower panel have their own specific shape. It is made of Invar steel which has a low thermal expansion coefficient. This makes the mold very complex and expensive. The expected price of a mold for the HTP skin panels is approximately 1, 6 million euros.* |

### 4.2.3 Output parameters

The output parameters indicate how well the production line is performing, based on the decision variables. The most effective and efficient settings result in a total throughput which satisfies the yearly throughput target at minimum costs. The calculated output parameters are the following:

### *Total cycle time of closed network*

The cycle time per station is calculated as described in section 3.3. Adding all processing times and waiting times per station results in a total cycle time for the closed network. Since the skins move in one direction through the production line, the visit ratios are 1 and therefore neglected. All mold-dependent stations are included in this calculation. However, mold requires non-preemptive maintenance and repairs. Therefore, the total cycle time of the closed loop is divided by the availability of the mold. Additionally, the reject rate is also taken into account. The total cycle time for the closed network is calculated as follows:

$$CT_0 = \frac{\sum_i CT_i}{Mold\ availability * (1 - reject\ rate)}$$

The percentage of rejects of an average product, produced at Fokker, is taken into account. In this case, a reject percentage of 2% is assumed (see section 4.2.1). A numerical example of this calculation is given in appendix A.

### *Throughput*

The hourly throughput of the closed network can be calculated as follows:

$$TH_0 = \frac{n}{CT_0} \quad \text{(Little's law)}$$

Note that the work in process (WIP) equals the number of molds (n). The result of this formula gives the throughput per hour. Multiplying this value with the number of available hours per year gives the number of skin panels per year.

$$\#\ panels\ per\ year = TH_0 * number\ of\ available\ hours\ per\ year$$

The number of available hours per year is calculated as described in section 4.2.1. Like described in section 4.3.2, this number remains constant.

### *Utilization*

The utilization per station is the fraction of time in which the station is working. The utilization is calculated with the following formula:

$$\rho = \frac{TH_0(n)\, t_i}{m_i}$$

## Total Cost of Ownership

The Total costs of Ownership per panel is divided into three groups and calculated as follows:

$$[illegible] = [illegible] + [illegible] +$$

$$[illegible]$$

The first group contains the hour rates of the operators. These costs are based on current operations at Fokker but also apply to a green field scenario. These costs are calculated per panel, per station (j):

$$\sum_{[illegible]} [illegible]_{[illegible]} = [illegible]_{[illegible]} \times \# [illegible]_{[illegible]} \times [illegible]_{[illegible]} \times [illegible]$$

The shift percentage is a predetermined percentage which increases when another shift is added. This is a discrete increase and therefore the resource costs calculation also becomes discrete. This is also the reason why the evolutionary method is the only option to use within the Excel SOLVER (see section 3.4.1).

The second group of costs are the production costs. These costs contain the operation costs e.g. maintenance of a station. These costs are also calculated per panel, per station (j):

$$\sum_{[illegible]} [illegible]_{[illegible]} = [illegible]_{[illegible]} * \# [illegible]_{[illegible]} * [illegible]_{[illegible]}$$

In both costs formulas, the processing time is used. This is because the waiting time is not included in the calculation of the resources and the production costs.

The third group of costs contains the investments costs. These investment costs include machines, tools, molds and support fixtures. To represent a green field scenario, the yearly pay-off costs of the investments must be taken into account. Normally at Fokker, the pay-off time for all resources (machines molds, etc.) are set to 10 years. Therefore, this research also takes a pay-off time of 10 years into account. All costs are increased with 10% for contingency costs.

The investment costs are also calculated per panel and depend on the number of molds (n):

$$[illegible]\,([illegible]) = \frac{[illegible]}{[illegible] * \# [illegible]\,([illegible])}$$

For the mold investments, the investment costs are multiplied by the number of molds. For the machines, the investment costs are multiplied with the number of machines.

With these formulas, a cost estimation can be made for each experiment in the model. All costs are influenced by the input parameters of the AMDA model. The TCO per panel is multiplied by the number of skin panels produced so that the yearly TCO is calculated. This way a specific production setting and its yearly total costs can be optimized.

It is important to remark that some costs are not taken into account e.g. material costs, warranty, interest, engineering and quality. These costs are not directly related to the decision variables for this research problem.

## 4.3 Model validation

To make sure the model gives a realistic view of the production performance, the model needs to be validated. As the component is still in its design phase, the validation of the data is done by consulting Fokker experts. As described in Chapter 3, a simulation model is also used for validation of the model. The first section of this chapter describes the findings of two Fokker experts and the second section gives the result of the simulation model. The model is shown in appendix E.

### 4.3.1 Validation by Fokker experts

Two Fokker experts have been interviewed separately. Both experts are Industrial Engineers specialized in lead time studies of production processes. Both are relative close at the workshop and have practical experience. They stated that the model would work for a green field scenario since the production line is dedicated to one product type namely the skin panels of the HTP. Finally, the mold should also be considered as a 'machine' which might fail sometimes. According to a Tool Engineer of Fokker, these failures happen once per year. The repair time of such a failure is in some cases 2 weeks. Therefore, the availability of the mold is calculated the same way as the machine availability is calculated (see appendix B). The planned maintenance is once per year. Because the model calculates for 47 weeks, this maintenance can be done during the holidays. Finally, one of the Engineers stated that operators can shift between workstations in practice. This is not taken into account into this research. It is assumed that the operators are dedicated to one station to keep the model simple. However, it will result in higher resource costs.

Since the production line does not exist yet, the experts could not say anything about the performance of the production line, given by the AMDA model. A simulation study is done to validate the model.

### 4.3.2 Validation by simulation

A simulation model is built in Plant Simulation provided by Siemens PLM software. The purpose of this validation is to make sure that the AMDA model is correctly applied. Additionally, it gives an insight how the production line performs according to a dynamic and a static model. An overview of the simulation model can be seen in appendix E.

*Simulation assumptions*

To compare both models, a buffer with infinite capacity has been placed in front of all stations. This way the WIP is constant and equals the number of molds released.

The settings were also synchronized with the AMDA model. This means that the SCV of the processing times in the model is set to 0.5 or 1. In the simulation model, the SCV is then translated to an erlang (SCV of 0.5) or exponential (SCV of 1) distribution. The failure and repair times are also taken into account. The initial situation is used for this comparison. This means that all decision variables are one. It is assumed that there are always jobs waiting to be processed and each run contained 1880 hours.

With these settings, 1000 runs were performed and each run a different random number stream is used to model the stochastic effect. Each run the number of skin panels produced and the cycle time were monitored. The averages of these parameters were compared with the output of the AMDA model.

Finally, the simulation model is a dynamic model. This means that it actually simulates the failure and repair times. Thereby the processing times are distributed according to a specific distribution (erlang or exponential. On the other hand, the AMDA model is a static model. The influences of the failure and repair time on the throughput are mathematically estimated. This influence also applies to the cycle time which depends on the SCV. The results are shown in the next subsection.

### *Simulation results*

In this subsection, the results of both models are shown. In Figure 4-4 it is shown that the number of panels produced per year of both models is almost equal.

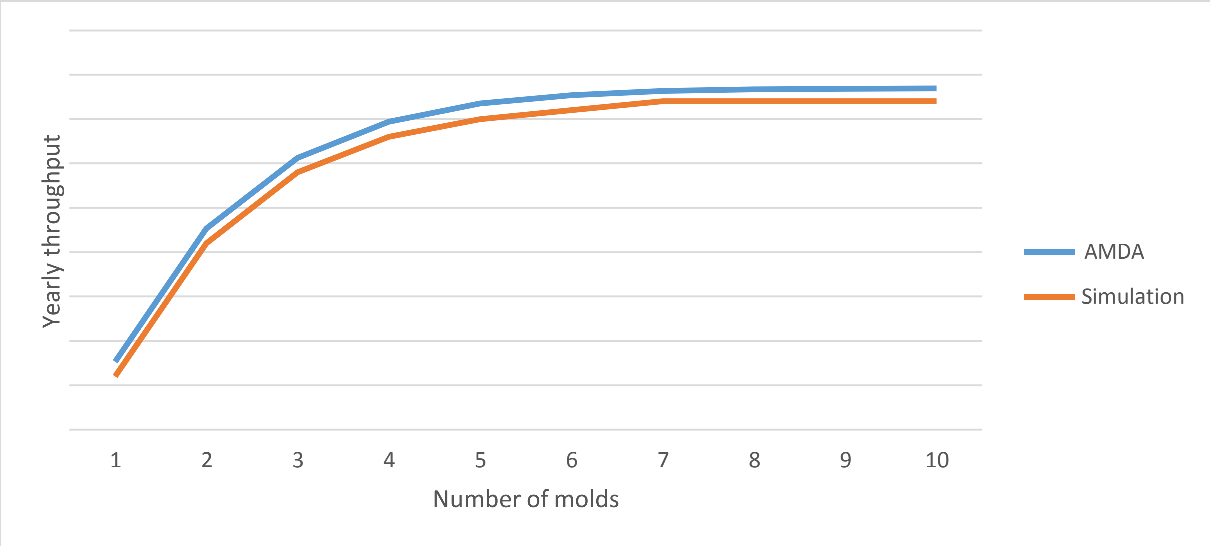


*Figure 4-4. Yearly throughput comparison between both models using 1 shift*

In Figure 4-5 the cycle time of both models is shown. The simulation model gives a slightly lower cycle time for a high number of molds.

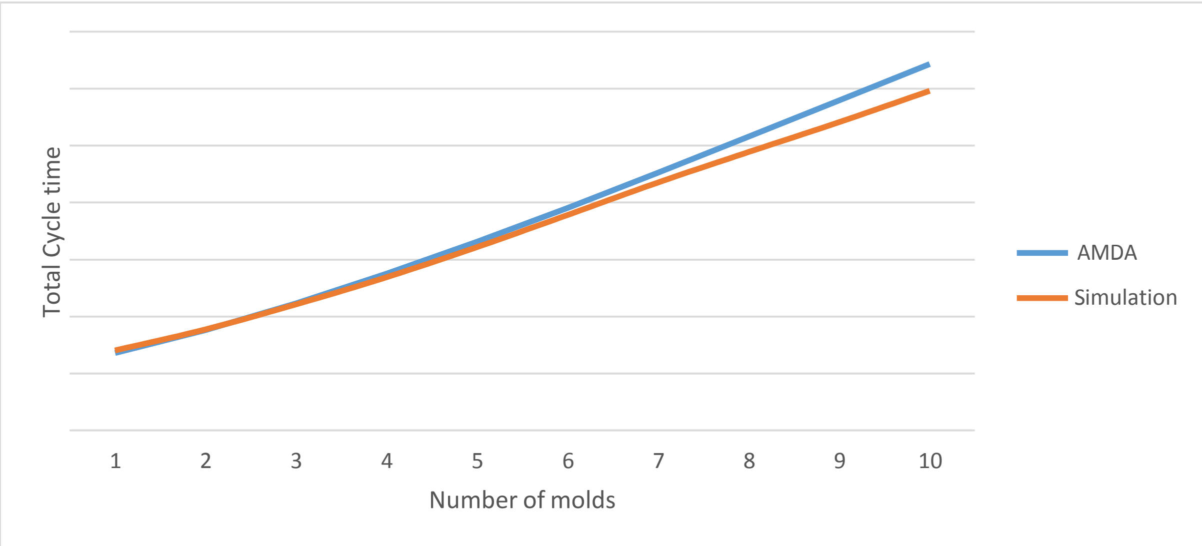


*Figure 4-5. Average cycle time comparison between both models using 1 shift.*

This effect can also be noticed in Figure 4-6. the throughput per hour does show the same effect as presented in Figure 4-5 which is caused by little's law. Since the WIP equals the number of molds released, the throughput stabilizes eventually.

Note that the results deviate as the number of molds in the network increases. At the end of each run (year), a number of unfinished products are still in the production line. The more WIP (or number of molds), the more this remaining number of unfinished products is. The cycle times for these remaining products are taken into account in the AMDA model since this model is static. The simulation model, which is dynamic, only takes into account the cycle times of the finished products. This causes the deviation in cycle times and throughput which can be seen in Figure 4-5 and Figure 4-6.

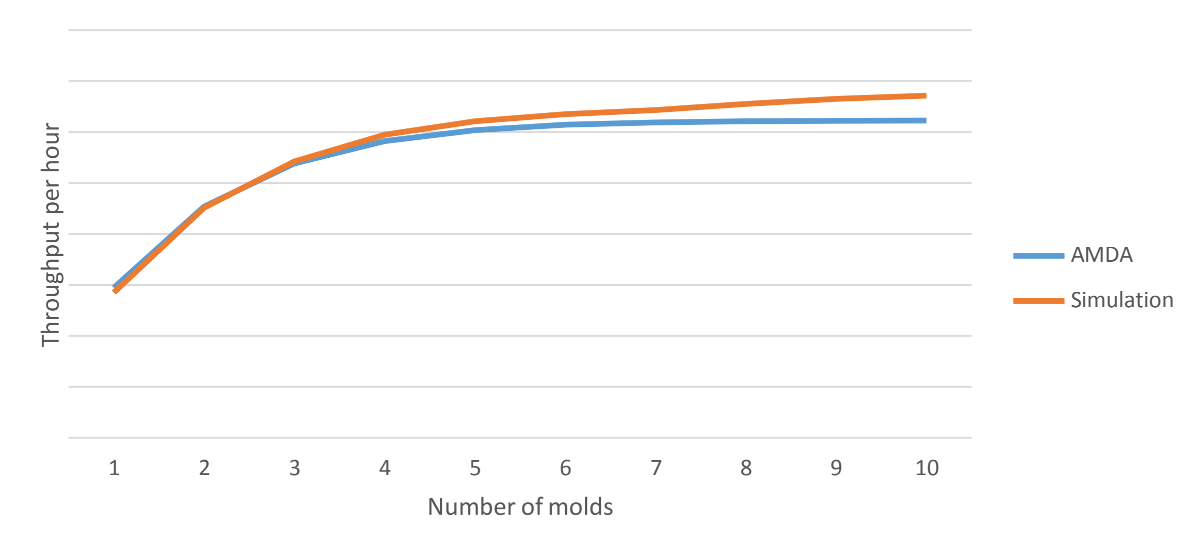


*Figure 4-6. Average throughput comparison between both models using 1 shift.*

It can be concluded that both models do have a similar result. Both models calculate with the same input but both in a different way. This means that the calculations in the AMDA model are correct. It also means that the AMDA model is able to represent the production line realistically. For this production line, a static model is not inferior to a dynamic model.

The AMDA model is used for this research project. The reasons are mentioned in the literature study in chapter 3. Beside these reasons, the simulation model is a black box for Fokker employees because they have no access to the software. The AMDA model is made in Excel which makes it accessible and transparent for them and changes can be made. This makes the model also suitable to use it in the future by Fokker employees.

An additional comparison between the two models is done. This analysis has the purpose to verify the artificial processing time calculations which is used to model the effect of the number of shifts on the throughput (see section 4.2.2). The result of this analysis can be seen in appendix A.

## 4.4 Summary

This chapter presents how the AMDA algorithm is used to model the production line. Additionally, the assumptions are given. Therefore, it has given an answer to research question 3 and 4.

After that, the input, output parameters and decision variables were explained. An even number of molds is required because a set consists of two skin panels which are mutually different.

In section 4.4 the AMDA model is validated by Fokker experts and by comparing it to a simulation model. The AMDA model is able to represent the production line. The AMDA model is transparent, and easy use because it's programmed in Excel. A simulation study is a 'black box' and not convenient to use by Fokker employees. Furthermore, the simulation model is used to verify the artificial processing time, used in the AMDA model. Both models show a very similar result considering the yearly throughput.

The AMDA model is capable of modelling a production line which does not exist yet, in a realistic way. Beside the advantages of this model, it is also easier to optimize the results in Excel. The results and optimization of the model are further described in chapter 5.

# 5 Result and Improvement

This chapter describes the result of the model, explained in chapter 4, and gives an answer to research question 5. The first part of this chapter describes the experiments and the results (section 5.1 – 5.6). The second part describes some of the improvement potential (section 5.7). This second part therefore deviates from the current state as described in section 2.3.3.

In section 5.1 the first results of the AMDA model are shown. The optimization problem and method are mentioned in section 5.2. Section 5.3 gives the most effective and efficient production process for a production rate of 50 sets per year. This section provides an answer to research question 5a. After that, the sensitivity of the input parameters and the decision variables are described in section 5.4 and 5.5. Section 5.6 gives the cost efficient frontier for different throughput targets. These sections give an answer to research question 5b. Section 5.7 describes some process improvements and answers research question 5c. Based on these improvements the yearly throughput of the production line is changed which is described in chapter 6. Finally, the conclusion is described in section 5.8.

The purpose of this chapter is to present the experimental results of the AMDA model and to give suggestions where process improvements are most effective and efficient. This chapter gives therefore suggestions for the future state based on the AMDA model results. How this future state looks like is described in chapter 6.

## 5.1 Initial results

In Figure 5-1 the throughput per year can be seen for different iterations in the initial setting. This initial setting includes 1 machine and 1 shift per station. Table 5-1 gives an indication of the utilization of the closed network. Each iteration of the algorithm an extra mold is added to the closed network. The more molds in the closed network, the more waiting time. At a certain number of molds, the throughput does not increase anymore. The maximum throughput of the system has been reached and the production line becomes saturated. Since the molds for this production line are expensive (approximately M€ 1,6. - per mold incl. 10% for contingency costs), adding extra molds also becomes an expensive improvement.

*Table 5-1. Utilization of all mold dependent processes*

| Stations | Utilization |
|---|---|
| Cleaning | Content not shown |
| Tool Assembly | |
| Automatic Fiber placement | |
| Final layup and bagging | |
| Consolidation | |
| Debagging and Demolding | |

Since a set consists of two types of skin panels which differ in shape, the total number of molds in the closed network must be even. In Figure 5-1 the graph shows that when having 6 molds in the process, the throughput does not improve much. Adding more molds would be inefficient since the throughput does increase a little. The minimum number of molds is set to 2.

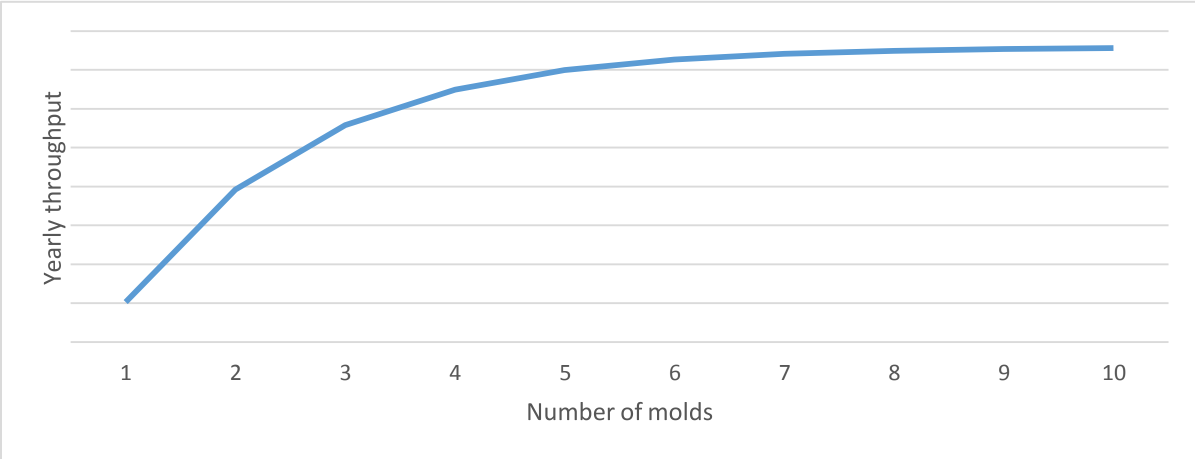


*Figure 5-1. Number of skin panels produced per year per iteration*

The number of molds has a big influence on the throughput but stabilize which can be seen in Figure 5-1. It shows a different graph than shown in Figure 5-2. The differences between those figures are explained in section 5.3.

The takt-time as described in section 4.2.1 must be minimal 15.98 hours for 100 produced skin panels per year. With the initial settings, the production line can produce maximal 58 skin panels per year. This results in a takt-time of X (value not shown) hours which is higher than 15.98. The most effective and efficient setting of decision variables must be found which can produce 100 skin panels per year. This optimization is described in the next section where the optimization of the model is shown. The optimization result is described in section 5.3.

## 5.2 Optimization

The AMDA model is used to minimize the TCO for a predefined throughput target. To minimize the Total Costs of Ownership, a nonlinear integer programming model is formulated. The total costs formulas in section 4.2.3 make the model nonlinear. As described in chapter 3, the Excel SOLVER is used. The Excel SOLVER first needs the objective function. This objective function can be stated as follows:

$$\min \ \text{Total Costs of Ownership per year} \ (€)$$

The Total Costs of Ownership must be minimized. These costs are determined by several decision variables. These are the number of resources ($R_j$), the number of shifts ($S_j$), the number of molds (n) and the mold-dependency ($MD_j$) where j represents the stations. How these decision variables are related to the TCO calculation is explained in section 4.2.3. Changing the decision variables results in a different model output. To make sure the objective value is realistic several constraints are needed:

$$1 \leq R_j \leq \text{maximum number of resources}$$

$$1 \leq S_j \leq \text{maximum number of shifts}$$

$$\text{Yearly throughput} \ (n) \geq \text{throughput target}$$

$$MD_j = \text{binary}$$

�,� = �������

Non-linear problems with integer decision variables are typically NP-hard. Therefore the problem, described in this section is considered NP-hard.

These constraints provide a solution space in which the Excel SOLVER must find a minimum TCO which is feasible. The Excel SOLVER cannot guarantee an optimal solution. Therefore, it runs each experiment several times and picks the best solution from all these experiments. This way the solution is expected to be very close to the optimum. The Excel SOLVER must calculate the output separately for 2, 4 and 6 molds. A VBA code is written to run the SOLVER for all three scenarios. After that, the best solution for each yearly throughput target is determined.

As described in chapter 3 the Excel SOLVER contains several optimization methods. For this optimization problem, the Evolutionary method can only be used because some calculations are discrete (see section 4.2.3).

The results of the Evolutionary method are compared with the results of a Simulated Annealing algorithm, written for this optimization problem (see appendix D). These differences are described in appendix H. From this comparison it can be concluded that the Evolutionary method is a better method to optimize in this case. This method is also much more user-friendly and very simple to use. This makes the model able to become suitable to be used by Fokker employees.

## 5.3 Results for 50 sets per year

The business proposal, made for the production of G650 HTP panels, is based on a production rate of 100 panels (50 sets) per year. This is also the starting point of this research. This section provides a best-found solution for this production rate, based on the current state (see section 2.3.3).

This section gives the settings for this production process for 50 sets per year and its performance. It provides an answer to research question 5a.

### 5.3.1 Settings and performance

The Excel SOLVER has been executed 100 times. Each time the new solution did not improve the current best solution anymore, the decision variables are set back to their initial value. This way the solution is close to the global optimum. The results of this optimization can be seen in Table 5-2. Note that the number of shifts is different per station. This is currently used at Fokker. The autoclave station has a high processing time while the processing time of debagging station is much lower. This difference is then captured by a different number of shifts for these stations.

*Table 5-2. Production settings for a yearly throughput target of 50 sets*

| Production stations | Number of resources | Number of shifts |
|---|---|---|
| Cleaning | 5 | 1 |
| Tool assembly | 2 | 1 |
| Automatic Fiber placement | 1 | 3 |
| Layup and bagging | 1 | 1 |
| Consolidation | 1 | 2 |
| Debagging | 1 | 2 |
| Number of Molds | 2 | |
| ***Yearly TCO*** | | |
| ***Yearly throughput*** | ***100*** | |

Table 5-2 shows a feasible solution which is best-found solution so far for all mold dependent stations. The most labor intensive stations require a lot of resources (cleaning and tool assembly). The machine intensive stations require more shifts. From this perspective, an extra AFP robot is not required for a yearly throughput target of 50 sets.

In Figure 5-2 the throughput is shown for a different number of molds but with the same number of resources and shifts as in Table 5-2. Note that the stabilizing effect is much less, compared to Figure 5-1. This is caused by the increase of resources and shifts per station. When the throughput stabilizes, it becomes important to move the mold through the mold dependent processes, as quickly as possible. The decision variables (number of resources and shifts per station) reduce the processing time which result in a faster throughput per station and prevents the stabilizing effect of the total throughput.

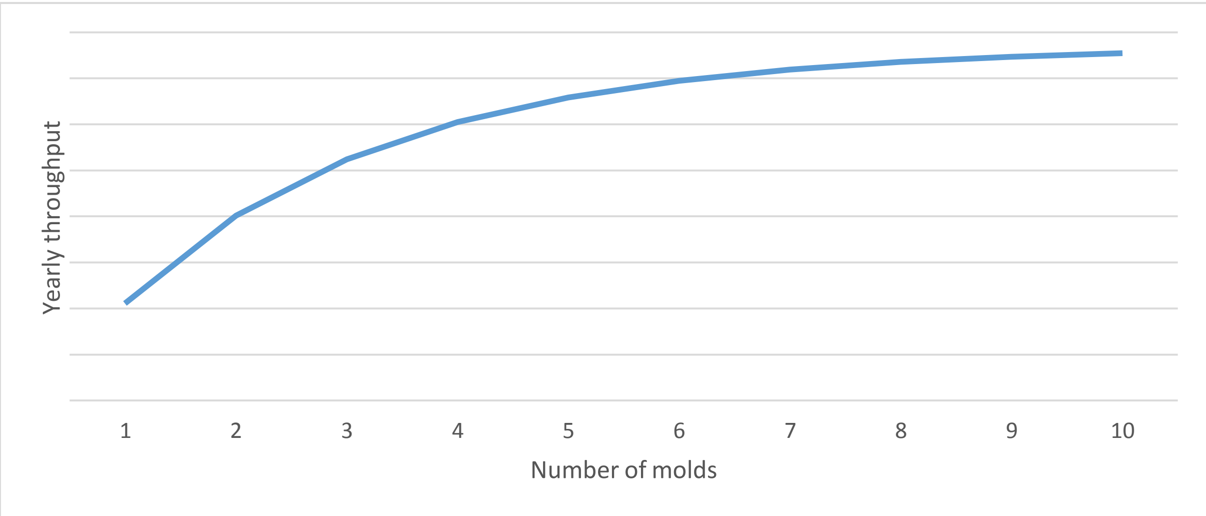


*Figure 5-2. Number of skin panels produced per year per iteration for 50 sets with 2 molds*

The investment costs are divided over the number of skin panels per year. This results in an optimum considering the number of molds, looking at the TCO per panel. The more molds, the more investment costs. More molds also result in a higher throughput. However, this stabilizes eventually (see Figure 5-2) so from there, the costs will increase as well. This can be seen in Figure 5-3. The optimal number of molds is 2 for a throughput target of 100 and considering the TCO per panel.

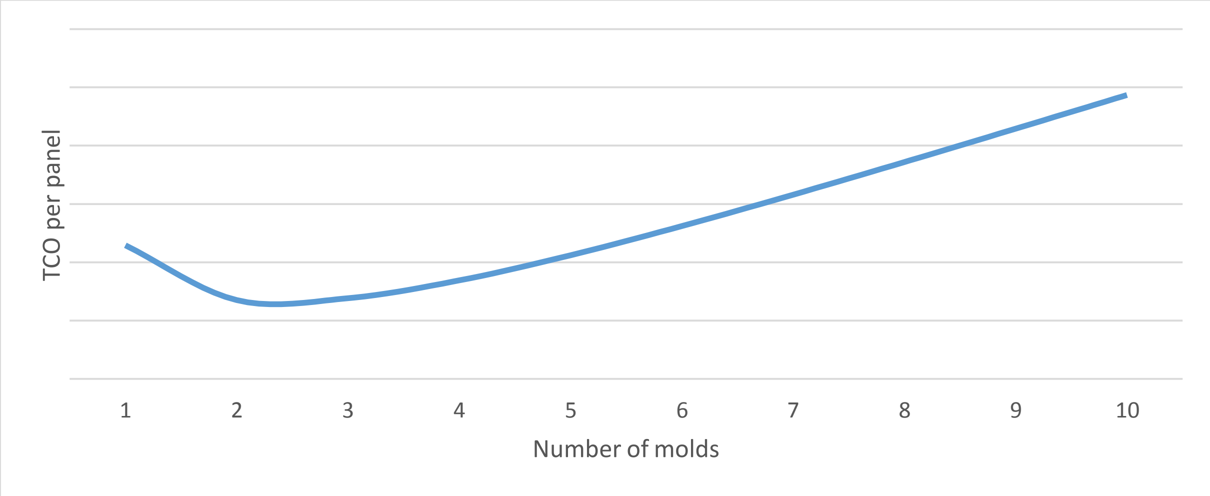


*Figure 5-3. TCO per panel for different number of molds*

## 5.4 Sensitivity of the input parameters

A way to improve a manufacturing system is by reducing the variation. The SCV has an influence on the yearly throughput of the production line. Two analyses show the impact of this influence. The throughput and costs are measured for both analyses separately. The calculated costs are the TCO per panel. The yearly TCO cannot be used because the input parameters influence the throughput. Therefore, the yearly TCO would give a wrong representation of the costs involved. Section 5.4, 5.5 and 5.6 both provide an answer to research question 5b. These sections show the robustness of the production line.

First the impact on the closed network is analyzed. This is shown in Figure 5-4. After that, the impact on each station is analyzed as is shown in Figure C-1 in appendix C.

### 5.4.1 Sensitivity of the Closed Network throughput

The graph in Figure 5-4 shows how the throughput changes when the SCV of the processing time is changed. This graph gives an indication how sensitive the model is to the SCV change. A certain value station is added to the current SCV of each station simultaneously. This way the characteristics of each station stays the same. The range for these values varied from 0.3 to 5. This range is chosen especially to get realistic values by preventing negative variation. An SCV of 5 is also not realistic, but this is for scientific reasons to see how the model acts. The analysis is on process level which means that all stations together are analyzed. The number of skin panels per year is computed for each SCV value. In Figure 5-4 the results are presented for a different number of molds.

The graph shows an increasing descend for all situations, but especially for a low number of molds. This difference in descending can be explained because a closed network with a high number of molds has e.g. less number of idle stations. A closed network with a higher number of molds is more stable or robust. This means that it becomes less sensitive to variations. The SCV has therefore less effect on the throughput and the decrease is smaller for 6 molds than for 2 molds.

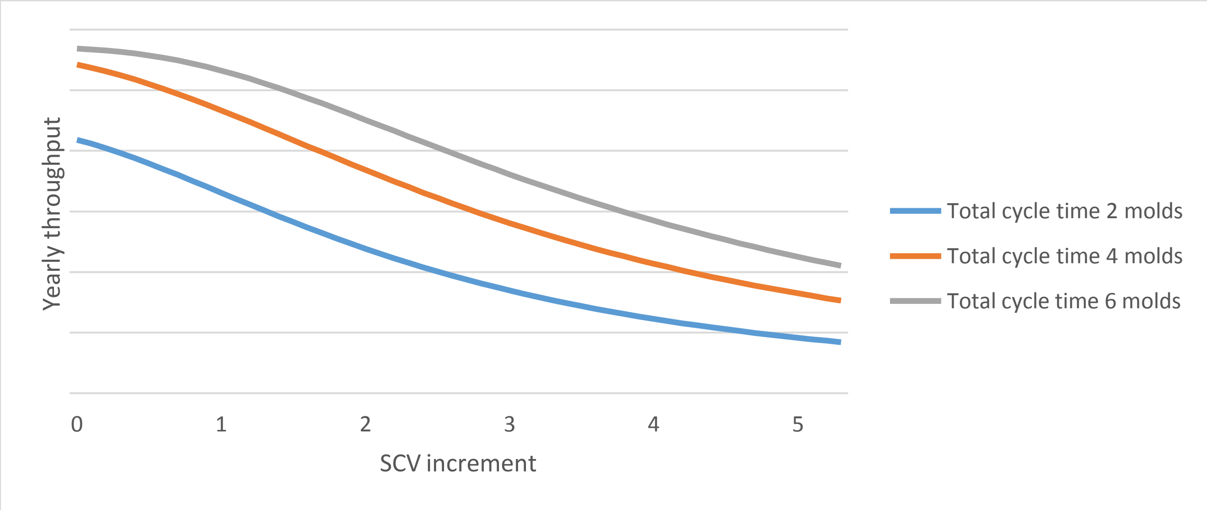


*Figure 5-4 Number of skin panels yearly produced for different SCV of stations in the total closed network*

This also means that the SCV has the highest impact in a closed network with 2 molds. Note that the throughput stabilizes at a higher SCV value. This is because the throughput rate is equal to the number of jobs divided by the total cycle time (littles law). The cycle time does increase exponentially which makes the throughput rate (and throughput) decrease negative exponentially.

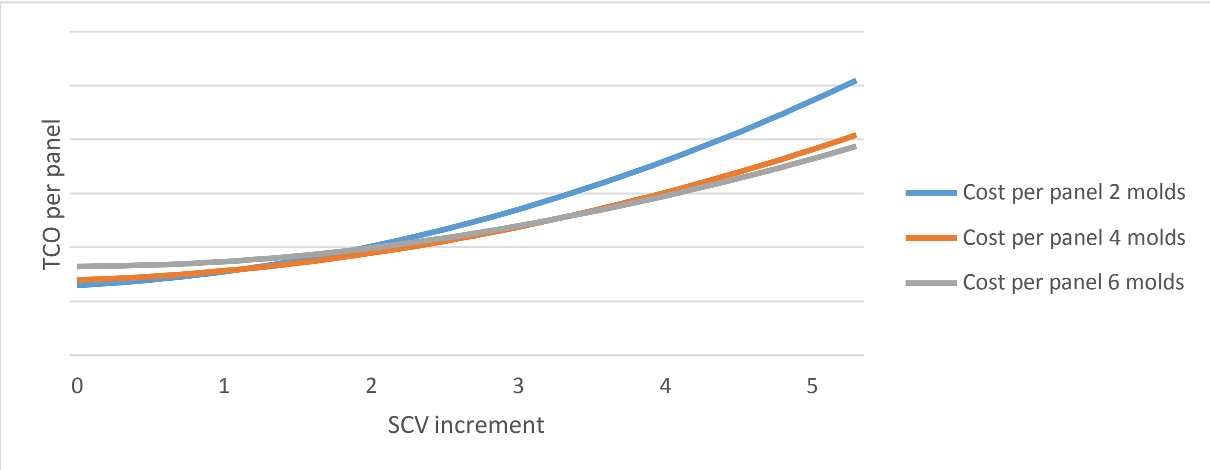


*Figure 5-5. TCO per panel for different SCV of stations in the total closed network*

In Figure 5-5 the increase in costs per panel is shown for different SCV changes. Note that the y-axis shows the TCO per panel. With a high SCV, a station takes more time to complete one panel. The total cycle time for a panel is therefore longer. The total cycle time has a relation with the costs and results in an increasing TCO per panel. The costs per panel are calculated as described in section 4.2.3.

The increase in costs for 2 molds is much more than for 6 molds. The costs of 2 molds even exceed the costs for 4 and even for 6 molds eventually. The more molds there are in the process, the more financial stability is created. The TCO per panel is therefore less influenced by the variation. This causes a higher costs increase for a low number of molds.

### 5.4.2 Sensitivity of the station throughput

This analysis focuses on how the stations independently react on variation. The analysis is on station level. This means that every station is analyzed separately. The SCV at each station is added number varying from -0.3 to 2. In this analysis, the number of molds in the closed network is 2. This number is chosen because the SCV for the processing times has the highest influence on a network with a low number of molds. The AFP station is most sensitive to the SCV. This can be seen in Figure C-1 in appendix C where the AFP station shows a negative exponential decrease.

The AFP station stands out. This is due to its high cycle time. This results in a high utilization (see section 5.1 and 4.2.1) and therefore its sensitivity when the variation is increased. An increase of variation also results in higher costs. This can be seen in Figure C-2 in appendix C where the AFP station shows an exponential increase. The more variation the AFP station has, the higher the cycle time. Therefore, it will take more time to finish a skin panel. Therefore, the costs per panel increases.

The analysis is also done for 4 and 6 molds. Comparing these three, it is noticed that the decrease in throughput becomes less. This is caused by the increasing stability of the network when more molds are available in the network.

A reduction of variation for the AFP station has the highest effect on costs per panels. The skin panels have the highest probability of waiting when arriving at this station because it has the highest processing time. Therefore, a change in variation has a higher impact on the AFP station compared to the other stations.

## 5.5 Sensitivity of the decision variables

This section gives the effect of the decision variables on the throughput per year. This analysis is performed at station level. This means that the performance of each station is independently analyzed. The results of that analysis are given in appendix C. However, the most effective and efficient value of the decision variables is determined when optimizing the problem.

First the effect of the number of resources on the throughput is analyzed and shown in Figure C-3. In this analysis, 2 molds are in the process. The AFP station has the largest linearly increasing effect on the throughput but stabilizes when adding more than 2 resources. This is because there are 2 molds in the process. In appendix G, an extended analysis is shown to see the effect when having more molds in the network. This analysis shows an increase in throughput when adding resources to the AFP. The effect from the other stations is relatively small. The explanation for this is explained in section 5.7.2, where the similar effect appears.

The resource costs increase steadily when adding more resources (see Figure C-4). Note that resources are defined as the number of operators (for manual stations) or the number of machines including operators (for station involving machines). For the AFP and consolidation stations, the investment costs are linearly increasing. This is because these stations include machines which do effect the investment costs. Comparing both figures, the AFP station would be a costly but effective station to improve by adding more resources.

The other decision variable is the number of shifts. Since an extra shift increases the available hours per year, the effect is expected to be large (see section 4.2.2). The result of this analysis can be seen in Figure C-5. The increase of throughput for the AFP station is significant.

The number of shifts also influence the resource costs. Therefore, the change in resource costs has been monitored. The result can be seen in Figure C-6. The effect on the resource costs, in general, is relatively small. Therefore, adding a shift is a cheap and effective option.

Both parameters (number of resources and number of shifts) reduce the cycle times in the AMDA model in their own way. The number of shifts the most effective parameter to change because the costs are relative low and throughput increase is relative high. Additionally, the AFP robot is the best station to improve.

## 5.6 Cost efficient frontier

This section describes the most effective option and the capabilities of the production line. The output for different targets is analyzed in this section. This analysis is on process level which means that the yearly throughput of the mold dependent stations together is taken into account. Note that some costs, not related to the decision variables, are not taken into account. This is explained in section 4.2.3.

Considering the throughput of the production line, the starting point is 100 skin panels (50 sets) per year, as described in chapter 2. But it is interesting to see what happens when the yearly throughput target is increased. A VBA code is written to calculate the costs for a multiple predetermined targets. Since the Evolutionary method is stochastic, each target is analyzed 5 times by the Excel SOLVER. Each time the best solution so far is saved. This way the result is very close to the optimum. The result of this is shown in appendix F. Note that this analysis is based on the current state (see section 2.3.3).

The result is graphically displayed in Figure 5-6. The dotted line represents the cost efficient frontier. In Figure 5-6 it can easily be seen when to add two extra molds. The graph also shows the moments when an extra AFP robot or autoclave is added. These moments are marked in the graph by the discontinuous increase. The required number of machines for each throughput target is graphically shown in appendix I.

Note the change of molds between throughput targets 180 and 240 panels at the "Cost e*fficient frontier"* in Figure 5-6*.* This change is because 2 molds in the process require another AFP robot is sooner than 4 molds. Therefore, at a throughput target of 220, 4 molds would be cheaper since it continues with 1 AFP robot. With 2 molds and a target of 220 panels, an extra AFP robot is required and has increased the TCO.

With 2 molds in the process, the production line is capable of producing 260 panels per year. There are only one autoclave and one AFP robot necessary till 180 panels per year. After that, another AFP is required. The maximum throughput target of 700 panels per year can be reached in the current state.

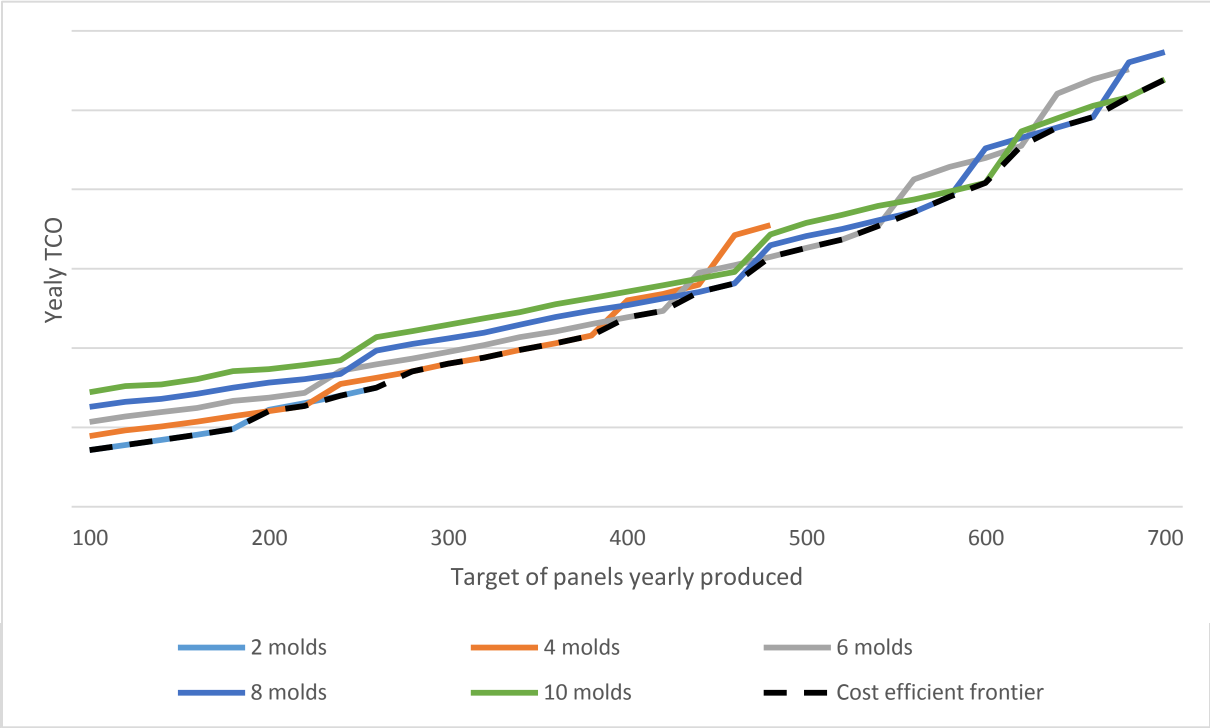


*Figure 5-6. Yearly costs based per mold for different target of skin panels to be produced yearly*

Finally, the yearly TCO is analyzed and not the costs per panel. The TCO gives the costs for a factory which is capable of producing a certain throughput target. Take for instance a throughput target of 200 panels per year. The best option is to use 2 molds. Suppose Gulfstream only wants 160 panels now and 200 next year. It would be wise to anticipate and design the factory for 200 panels already. This will costs almost M€ 2 despite the fact 160 panels are sold this year. The TCO is therefore relevant for decision making. However, there is an optimal amount of panels to produce per year. This can be seen in appendix F.

Note that the current production of thermoset skin panels requires 4 molds to reach a throughput target of 140 panels (see section 2.3.1). This is also due to the green field approach of this research project.

Note the instability in Figure 5-6 from 400 panels per year. From this point adding resources becomes less efficient. The investments are faster increasing than the throughput. Therefore, it can be concluded that the current state becomes less efficient after 400 panels per year. If the throughput target becomes higher than 400, process improvements are needed. This is further described in the next section and chapter 6.

*SIDESTEP 6: Like described before the Excel SOLVER finds the minimum costs for a given target. Let's call this a run. For this sensitivity analysis, the Excel SOLVER performed each run 5 times for one target to be sure it is close to the optimum. It had to calculate the minimum TCO for 124 different targets (for 2,4,6,8 and 10 molds). This resulted in a total computation time of approximately 9 hours (for 5x124 = 620 scenarios).*

## 5.7 Improvement potential

Changing the decision variables improves the throughput of the production line. But these improvements have their limits as described in section 5.5. Therefore, the production line requires some more effective improvements. These improvements are described in section 5.7.1 while section 5.7.2 describes the effect of these improvements. This section provides an answer to research question 5c.

Section 5.5 describes what the effect on the yearly throughput is when changing the decision variables. The Excel SOLVER makes this decision for a predetermined throughput target and the lowest Total Costs of Ownership. This section describes what input parameters to change in order to improve the closed network. The target of this section is first to identify the network constraint. How to exploit and elevate this constraint is described in chapter 6. Chapter 6 also describes how the stations subordinate to the network constraint (Theory of Constraints).

Note that this section deviates from this current state like described in chapter 2 (see section 2.3.3). It gives the effects of improvements for the future state based on the results of the AMDA model. This future state is further described in chapter 6.

### 5.7.1 Possible improvements

Changing the decision variables can be done at relatively low costs. When the yearly throughput of the production line must be further improved, the input parameters have to change. The most effective ways to improve the production line are: first to reduce the processing times and second by making processes mold-independent. How this can be done in practice is described in chapter 6.

As described before, the closed loop determines the total throughput. Reducing the processing time results in a lower total cycle time of the closed network and a higher throughput. Also when a process is made independent of the mold and from the closed loop, the total cycle time decreases and the total throughput increases.

Both input parameters (processing time and mold-dependency) do influence the yearly throughput of the production line. However, they both require large design changes like automation of process and extra materials and tools. These design changes increase the total costs which are therefore hard to estimate. The analyses in the next sub-section therefore only describe the effect on the yearly throughput. These design changes are further elaborated in chapter 6.

### 5.7.2 Effects of improvements

By improving the production line like described previous in this section, the input parameters must change. This sub-section gives an insight in the effects of different improvements.

#### *Reducing the processing time*

To see what effect the processing time has on the yearly throughput of the production line the processing time per station is changed and analyzed. The result can be seen in the graph in Figure 5-7. From this graph the conclusion can be made that the most effective improvement can be made on the AFP robot. How this can be done in practice is described in chapter 6.

This analysis is only performed for a network with 2 molds since the effect when having more molds in the network is similar.

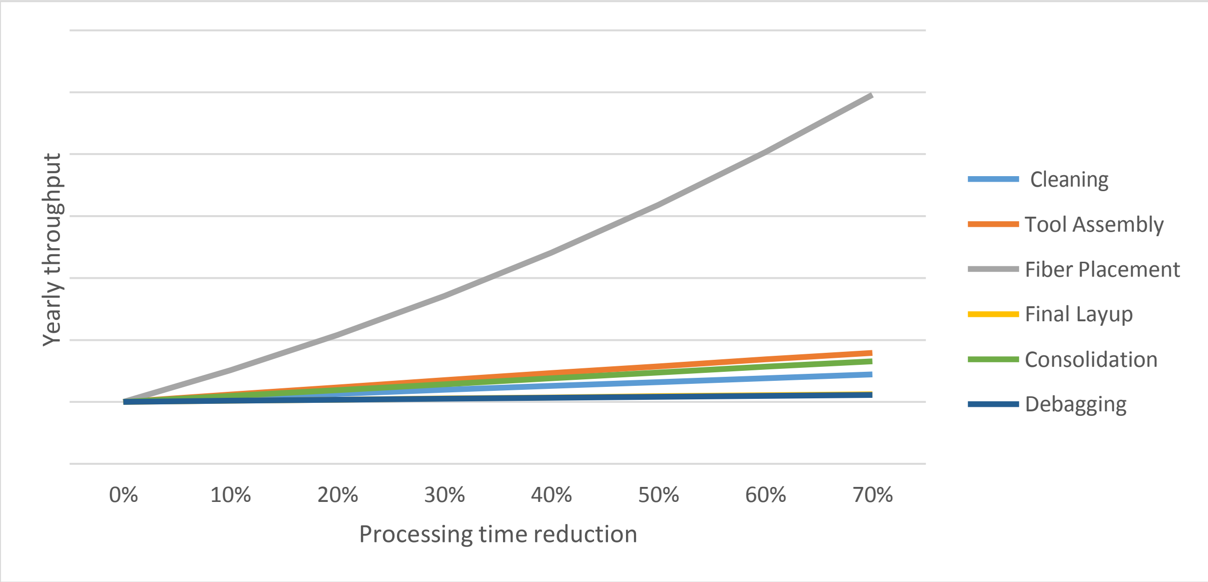


*Figure 5-7. Throughput increase for different reduction of processing time*

## *Decoupling of process*

To see how the throughput of the production line changes when a process is made independent of the mold, another analysis is done. In this analysis, the processes in the closed network are consecutively made mold-independent. This change is modelled by excluding the cycle times of the decoupled station from the total cycle time of the closed network.

The throughput is retrieved for a different number of molds in the process. The effect on the throughput can be seen in Figure 5-8. Currently, the R&D department is looking for a way to decouple the AFP station. An option is to produce the skin panels on another, much cheaper, mold. For the other stations decoupling from the mold has a less potential effect.

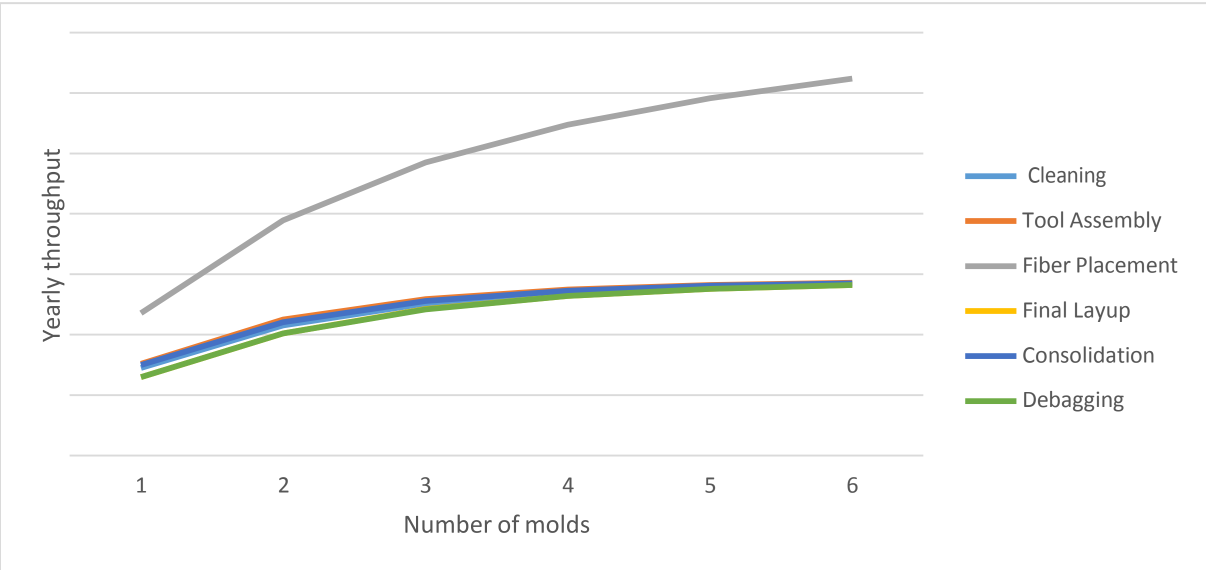


*Figure 5-8. Throughput increase when making processes mold-independent*

In both analyses, the AFP station has the highest effect of the yearly throughput of the production line when improved. Because this station has the highest cycle time, the effect on the throughput is also the largest. How this can be done in practice is described in chapter 6.

Figure 5-8 shows that the AFP has a different effect on throughput than the other stations. This is because this station can be seen as the bottleneck of the closed loop. The AFP station prevents further improvement when it still depends on the mold. Therefore, the other stations do not increase the throughput per year when decoupled. After reducing the total cycle time of the closed loop, balancing the stations becomes important. This is further described in chapter 6.

In this chapter, the sensitivity of the decision variables is described. This also gives an indication how robust the production line is. But the robustness is also influenced by factors which cannot be addressed by the AMDA model. If a certain station runs in 3 shifts, the 4$^{th}$ and 5$^{th}$ shift can be used for maintenance or repair activities. This increases the robustness of the production line. A stations which runs for 5 shifts (24/7) is more sensitive for failures and maintenance. In practice, another set of molds is purchased which result in higher investment costs. Another solution might be to keep stock products which can be delivered to the customer immediately. This way the service level is not influenced by the mold dependent processes. This will increase the robustness, the service level and is much cheaper than purchasing an extra set molds. Extra storage is not LEAN and must be avoided. However, a production line with 'anorexia' (or without buffers) makes processes very sensitive for interruptions. This is a tradeoff between the storage costs versus the increase of service level.

## 5.8 Conclusion

This chapter started with the initial results and gives an indication how the model works. This initial situation has a maximum throughput of 58 panels (24 sets) per year. By changing the decision variables, the production line is capable of a throughput to 100 panels (50 sets) per year. The Excel SOLVER came up with a total yearly TCO of M€ 1,5. This is k€ 15 per panel. Furthermore the scenario with 2 molds is most optimal for a throughput target of 100, considering the TCO per panel.

Furthermore, this chapter has shown how the production line behaves for different output parameters. It became clear that more than 6 molds in the process do not result in better performance. Adding more than 6 molds, the production line becomes saturated. Improving the stations can prevent saturation by e.g. reducing the processing time.

The output parameters are measured for different yearly throughput targets and a different number of molds. A network with 2 molds is capable of producing 300 panels (150 sets). The TCO of this target is M€ 3,3 which is k€ 11 per panel. Besides, an extra AFP robot is required from 220 panels (110 sets) onwards. The maximum throughput of 700 panels (350 sets) per year can easily be made. However, the current state production line is efficient till a throughput of 400 panels per year. The optimum number of panels to produce with 2 molds is 220 panels (see appendix F).

Finally, two improvement options were given. These options are reducing the processing times and making processes mold-independent. They were tested for a different number of molds. The AFP station can improve the throughput with almost 40% when the processing time is halved. When the

AFP robot can produce independently of the mold, the throughput is improved with 65%, with 2 molds in the network.

This chapter gave the optimization results and has indicated where improvement is most efficient. The best station to improve is the AFP station. The best way to improve this station is to let it operate (partly) independent of the mold. This way the cycle time decreases and the workload over the closed network will be better balanced.

The next chapter describes the future state of the production line. It explains how some improvements can be implemented. Additionally, it provides an indication on how big the influence of this future state is on the yearly throughput of the production line, in comparison with the current state.

# 6 Facility layout

This chapter describes the future state while the current state is described in section 2.3.3.

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# 7 Conclusions and Recommendations

This chapter finalizes this master thesis. In section 7.1 the conclusions are described. Furthermore the research questions, stated in chapter 1, are answered. Section 7.2 describes the recommendations for Fokker. In Section 7.3 the limitations are described. Additionally, some areas for further research are given in this section.

## 7.1 Conclusions

When this research project started, a lot of research is done, concerning production methods, the material properties and applications. However, the insight in the capabilities of a thermoplastic skin production facility was lacking. Therefore, this research project is established to answer the following research question:

*'What is the most effective and efficient production process for the production of skin panels for horizontal tail plane of the Gulfstream G650, from a green field scenario, which satisfies the requirements and what should such a facility layout look like?'*

To answer this question, several sub-research questions are stated and answered in this master thesis.

- First information about thermoplastic production processes is gathered. The processing times of each production step, including its variability and availability, are important for this research project.
- Second the literature is consulted to see how the problem could be tackled.
- Third an analytical modelling approach (AMDA) is found and applied to model the production line. The required information about the thermoplastic production process for the HTP skin panels is implemented in the AMDA model. Since this production process includes a closed loop and depends on the number of molds in this loop, the AMDA algorithm is applicable.
- Fourth the throughput and the TCO are analyzed.
- Fifth the AMDA model is optimized by minimizing the TCO for a given throughput target. Several conclusions are made based on the analyses of these performance indicators. The Excel SOLVER is used to optimize the AMDA model.
- Finally, a proposal of the future state is given and compared with the current state. The future state indicates where the production process can be improved, what the effects of the improvements are and how they relate to the current state calculated results.

This research project delivers a model, which is able to determine the yearly throughput and the TCO. The model uses the number of resources and the number of shifts to minimize the TCO for a predetermined throughput target. Furthermore, several analyses are done to find the most effective and efficient production frontier (see Error! Reference source not found.). Based on these results, a future state is visualized (see Error! Reference source not found.)

Some additional analyses are performed to verify the methods which are used to answer the research question. First the AMDA model is validated by a simulation study. Second the Excel SOLVER is validated by the Simulated Annealing algorithm. Both validations provide similar results. Finally, the influence of the number of shifts per station was hard to calculate. It is not clearly described in the literature. Therefore, the influence of the number of shifts is verified by the simulation study as well.

The sensitivity analyses give an indication how and when the production line respond when decision variables are changed. These analyses show that capital intensive stations can better be improved by adding shifts. The other stations, which mostly include manual operations, can better be improved by adding operators. Based on the results of this research project the following main conclusions can be made:

- The number of molds has a significant effect on the throughput of the production line. Especially in the current state, the mold must be seen as the bottleneck. Together with the cycle time of the mold dependent processes, they mainly determine the throughput of the total production line.
- The AFP station is the most critical station of the mold dependent processes. Its processing time represents 42% of the total processing time of the mold dependent processes in the current state. Eventually, this high processing time results in a high waiting time as well.
- With the current state and 2 molds, a maximum throughput of 260 panels per year can be reached. An extra AFP robot is necessary when producing more than 180 panels per year. The future state is capable of producing 560 panels per year with 2 molds.
- The maximum throughput target of this research of 700 panels (or 350 sets) can be reached in the current and the future state.
- The current state production line is efficient till a throughput of 400 panels per year.
- The yearly TCO for the current state, considering 100 panels per year is M€ 1,5. The yearly TCO for the future state for the same target is M€ 1,4. Note that some costs are not taken into account, as described in section 4.2.3. The maximum improvement in TCO is 60%, compared to the current state. The maximum improvement in throughput is 176%, compared to the current state.
- The future state performs better than the current state, despite the additional investment costs. The throughput is almost twice as high considering 2 molds. The TCO of the future state is lower for all researched throughput targets.
- This research project shows that a static model provides similar results as a dynamic model, considering this production process. Additionally, the model and the optimization application is built in Excel. This results in an accessible, and transparent model.

## 7.2 Recommendations

From the conclusions, made in section 7.1, several recommendations are made.

First the number of parts, used in the closed network, must be reduced. The production line is restricted by the design of the skin panel. This design is mainly based on the function of the skin panels. The shape, for instance, is determined by the weight and strength performance. This results in a high amount of unique parts. From an industrialization point of view, such a design results in high production costs. This is at the expense of the manufacturability and affordability of the skin panels. This can be prevented by standardizing the stringers. The tooling blocks will then also be more standardized. This will make the production line more robust and eliminates errors. Another work package within TAPAS2 can be created to find the most efficient stringer design, with the same capabilities as the current stringer. This will improve the manufacturability and affordability of all TAPAS products.

It is also recommended to focus more on Design to Costs in the early stages of a design project. A focus on costs in an early design phase might come up with smart, affordable techniques which will reduce the production costs. It should be a balance of performance and costs. For instance, the number of parts had to be reduced in an early stage.

The proposed design of the future state should be further developed. Additionally, it is recommended to focus on the technical parts as well. Like described before, AFP might be further improved (see section 6.2.4)

This research project shows that the AMDA model is validated and can provide reliable results. The AMDA model can therefore be applied to multiple other Fokker (future) production lines. However, the model is not validated by real data. It is therefore recommended to use data from practice to validate the model first.

This research project also shows that the process improvements, stated in chapter 6, are very effective and efficient. Therefore, these improvements should be considered when designing the production line. The additional investment costs are not proportional to the increased throughput. Therefore, the yearly TCO becomes less than the yearly TCO of the current state. The total costs for the current state are also not proportional to the assumed additional investment for process improvements. Therefore, it is recommended to invest in process improvements.

## 7.3 Limitations and Future Research

This research project has several limitations.

- The conclusions, based on the model, are meant for long term decisions. It cannot be used for e.g. a workforce planning. It only determines the expected average throughput and the TCO.
- The model is applicable for closed production networks. The throughput of the network is then based on the number of pallets (in this case molds) in the network.
- The starting point of this research project is a green field scenario. This means that all production stations are dedicated to the production of thermoplastic HTP skin panels. Therefore, the investment costs are relatively high, compared to a 'brown' field scenario.
- The data which is used as input for the AMDA model are estimations by several Fokker experts. Therefore, the results also include some uncertainty. When decisions are based on this research project, one should be aware of this uncertainty. To eliminate this uncertainty, the model can be validated by using real data. The results can then be compared with the realistic performance of that production line.
- The model assumes a steady-state production line. The 'warm-up' period of the processes is not taken into account.
- Some costs are not taken into account, as described in section 4.2.3. This is because they were less relevant to this research problem since they are not directly related to the decision variables. Therefore, the Return on Investment is not calculated.

This research project is mainly focused on modelling and optimizing the production line. How the production facility should look like requires a more elaborated research study. The design described in chapter 6 is a very simplistic view of the future state. There are a lot of technical aspects included which require more research. However, they are validated by several engineers at Fokker which means they are technically feasible.

Beside the technical aspects of the production line, one should take the design of the panels into account as well. The design of the current panels is complex because of the large quantity of identical parts involved. This is at the expense of the manufacturability and indirectly influences the affordability. When the number of parts is reduced the production processes become more standardized.

Like stated in section 1.4, the lead time of the new equipment is kept out of the scope for this assignment. However, it is important to take the lead times into account, especially for the molds.

Finally, the AMDA model is applied for the HTP skin panels of the Gulfstream G650. However, many other production lines within Fokker consist of closed networks and are determined by the number of molds. Therefore, this model should be standardized so it can be used for these production lines as well. However, it would require extra time in order to make the model applicable for other production lines and make it user-friendly.

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# A. Example and validation of the number of shifts calculations

In this section an example is given of how the cycle time is calculated. In this example the production line consists of 4 stations (see Table A-1). Each station has its own processing time and number of shifts. The number of shifts influence the available time per station. But as described in section 4.2.2, the processing time is divided by the number of shifts. This results in a 'modified processing time' per station. After that, the total cycle time is calculated by adding the modified processing time with the expected waiting time. Finally the total cycle time of each station is summed and results in a total cycle time of the total network.

This way the processing time is calculated in the AMDA model, used for this research project. The costs calculations use the processing time instead of the modified processing time. This modified processing time is only used to calculate the throughput of the network.

Note that when operating 5 shifts, the available time cannot be multiplied with 5. A 24/7 work week has 168 available hours so the available hours is multiplied with 4.2.

*Table A-1. Numerical example of processing time calculation, using fictive numbers*

| Stations | Processing time (h) | Shifts | Modified processing time (h) | Expected waiting time (h) | Total cycle time (h) |
|---|---|---|---|---|---|
| 1 | 6 | 1 | 6 | 5 | 11 |
| 2 | 8 | 2 | 4 | 4 | 8 |
| 3 | 10 | 5 | 2.38 | 2 | 4.38 |
| 4 | 8 | 1 | 8 | 7 | 15 |
| **Total cycle time** | | | | | ***38.38*** |

To verify this calculation, a simulation study is done. A 3 shift production is simulated. This means that the simulation model runs for 24 hours, 5 days per week, 47 weeks. The AMDA model uses the artificial processing time calculation, as described above and in section 4.2.2. The simulation model is able to simulate the shifts in real-time. The result can be seen in Figure A-1.

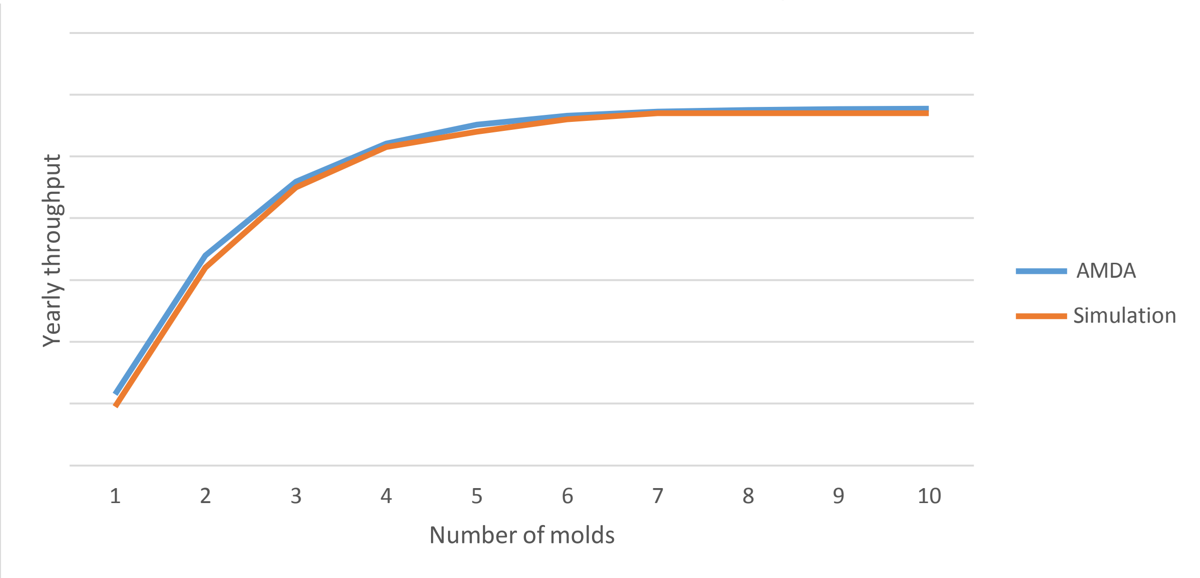



*Figure A-1. Yearly throughput comparison between both models using 3 shifts*

# B. Availability of the stations

The availability per station is determined by the following formula:

$$A = \frac{MTTF}{MTTF+MTTR}$$

The MTTF and MTTR are determined by together with input a Senior Manufacturing Engineer of Fokker, specialized in composite materials. Since the production line is in the design phase, the numbers are still estimations based on current production of other thermoplastic products. In Table B-1 the data are given to calculate the MTTF and MTTR.

*Table B-1. The aggregate availability per station is calculated by multiplying the availabilities of the disturbances.*

| **Station** | **Disturbance** | **MTTF (hrs.)** | **MTTR (hrs.)** | **Availability** |
|---|---|---|---|---|
| *Cleaning* | | | | |
| | | | | |
| *Tool Assembly* | | | | |
| | | | | |
| *Automatic Fiber placement* | | | | |
| | | | | |
| *Final layup and bagging* | | | | |
| | | | | |
| *Consolidation* | | | | |
| | | | | |
| *Debagging and Demolding* | | | | |
| | | | | |
| *Mold* | | | | |
| | | | | |

# C. Sensitivity Analyses on SCV and decision variables

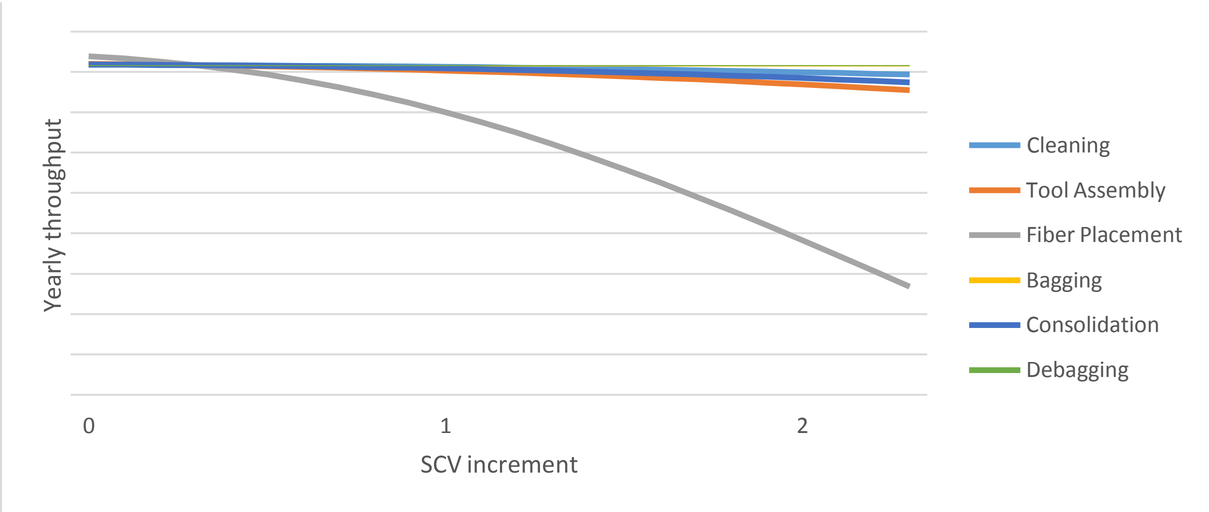



*Figure C-1. Number of skin panels yearly produced when changing the predetermined SCV per station for 2 molds*

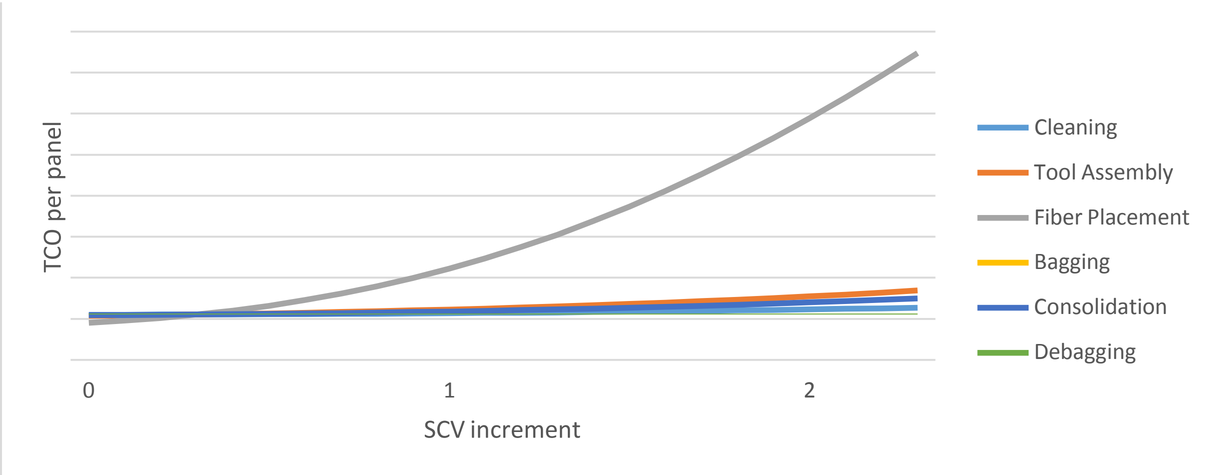



*Figure C-2. TCO per panel when changing the predetermined SCV per station for 2 molds*

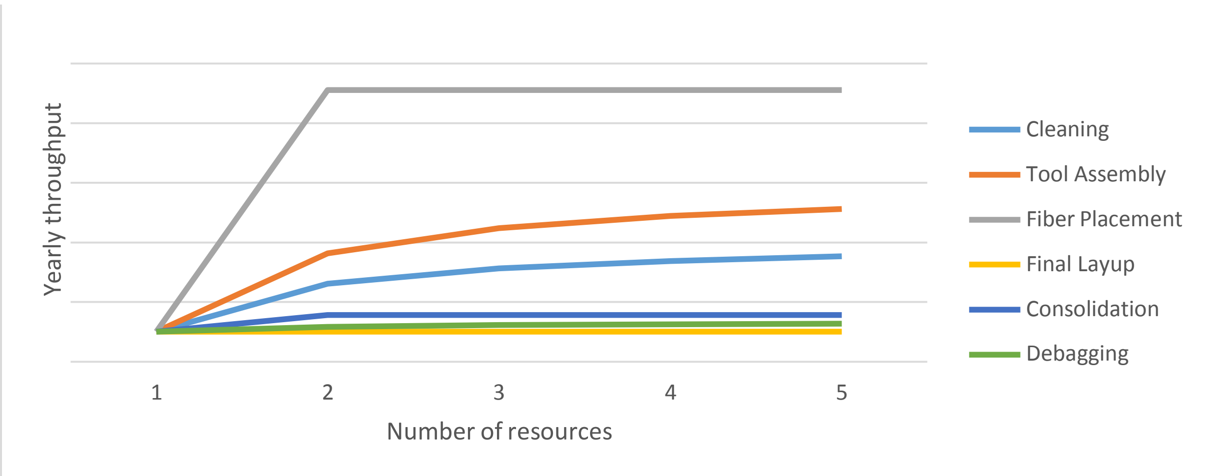



*Figure C-3. Effect on throughput when changing the number of resources per individual station*

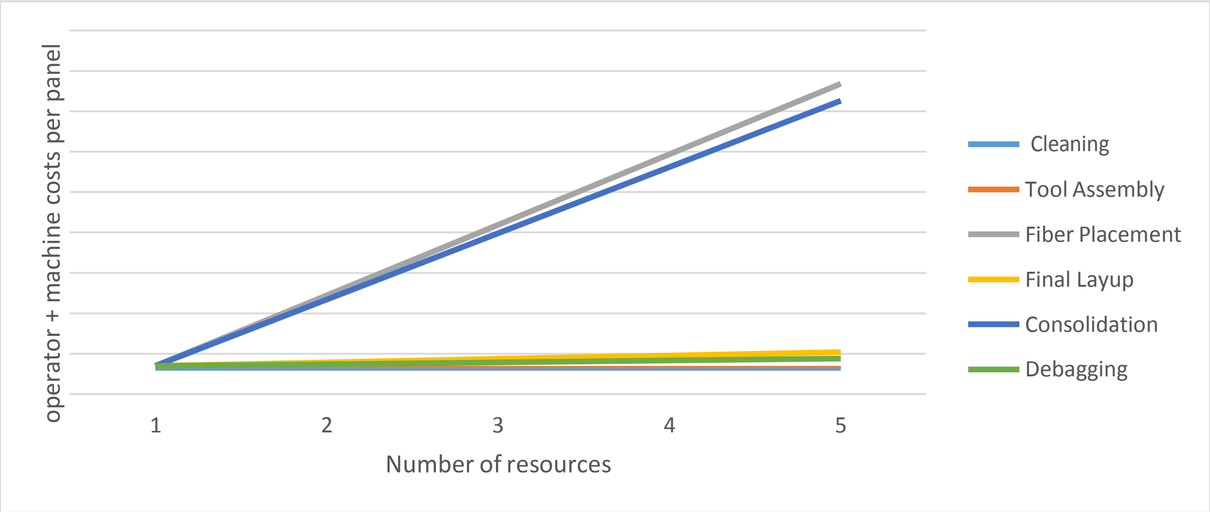



*Figure C-4. Effect in resource costs when changing the number of shifts*

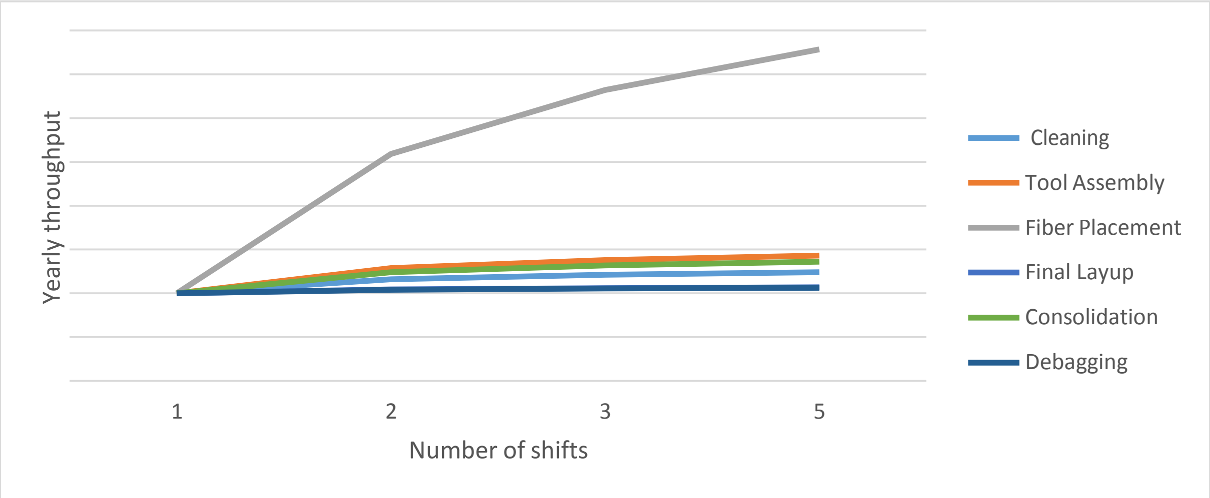



*Figure C-5. Effect on throughput when changing the number of shifts*

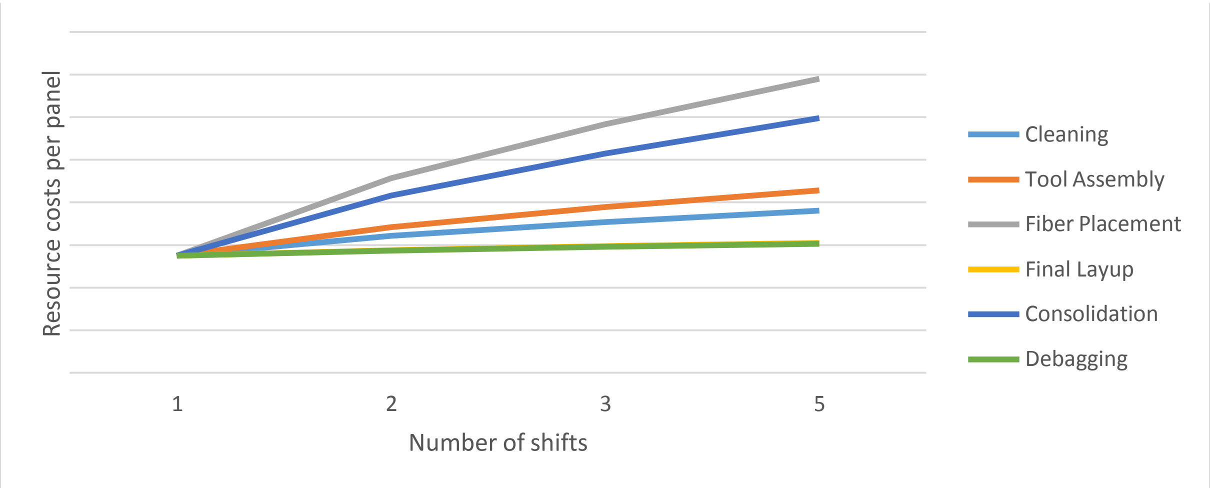



*Figure C-6. Effect in resource costs when changing the number of shifts*

# D. VBA programs

This section give the pseudo codes for the optimization methods. Both methods are programmed in VBA.

## Pseudocode for optimization using Excel SOLVER

```
For 2, 4 and 6 molds do
    For all different yearly throughput targets do
        Initialize current TCO
        Initialize current throughput
        For 1 to 3 do
            Run Evolutionary method of Excel SOLVER
            Save new solution
            If new TCO = current TCO then
                Reset all decision variables
            End if
            If current TCO > new TCO then
                Current TCO = new TCO
                Current throughput = new throughput
            End if
        Next
        Save current solution
        If throughput cannot reach yearly throughput target then
            Exit for loop
        End if
    Next
Next

For each throughput target
    Find best solution
Next

End sub
```

## Pseudocode for Simulated Annealing

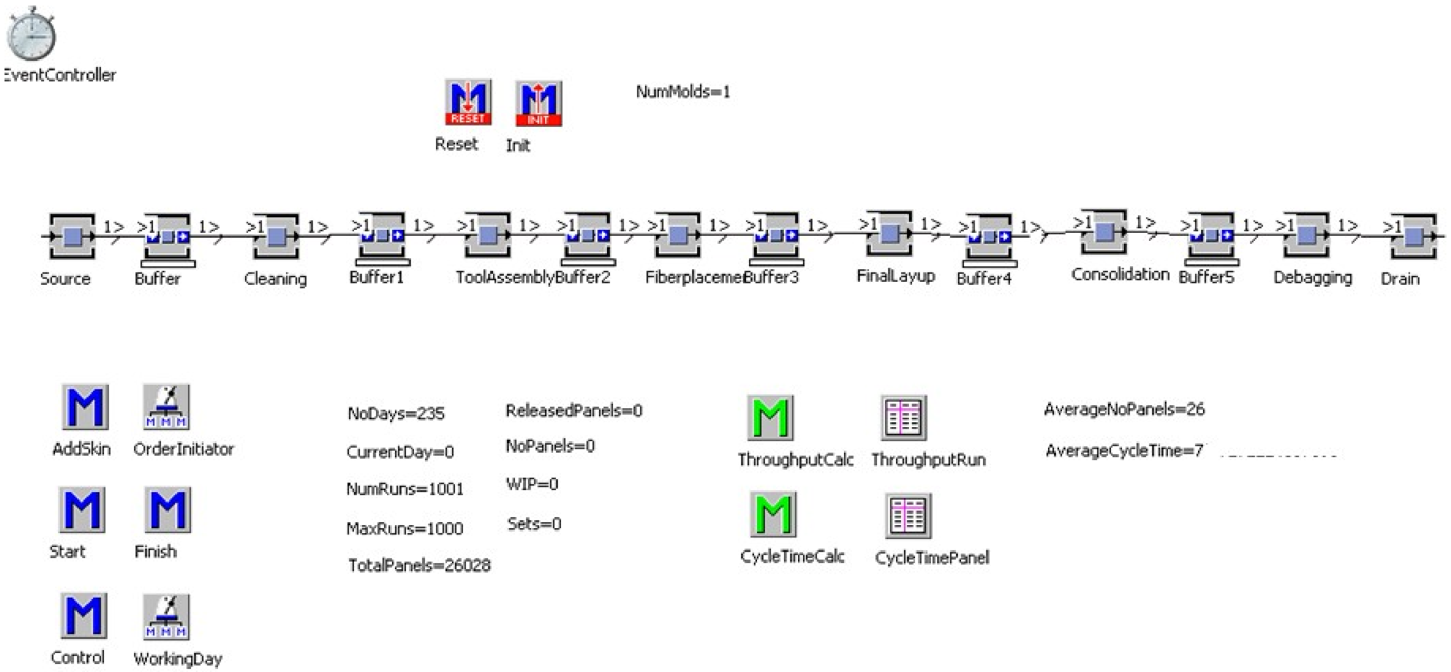
```
Create initial solution
Initialize (Current, Neighbor, Best, BestSoFar)

Do while Ck > C0
    For k = 1 to MarkovChainLength
        Create random decision variable = random value If
        NeighborThroughput >= TargetThroughput then
            If CurrentTCO >= NeighborTCO then
                Current solution = Neighbor solution
            Elseif exp((CurrentTCO – NewTCO)/Ck) = random (0,1) then
                Current solution = Neighbor solution
            Endif

            If BestTCO>= NeighborTCO then
                Best solution = Neighbor solution
            Endif
        Endif
    Next
    If BestSoFarTCO >= BestTCO then
        BestSoFar solution = Best solution
    endif
    Ck = Ck * Alpha
Loop

Save BestSoFar solution
```

# E. Simulation model



# F. Yearly TCO for different number of molds

*Table F-1. Yearly costs per mold for different yearly target of skin panels capable of producing*

| **Constraints** | *Maximum number of resources* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Maximum number of shifts* | | | | | | | | | | | |
| | **2 molds** | | **4 molds** | | **6 molds** | | **8 molds** | | **10 molds** | | ***Cost efficient frontier*** | |
| **Throughput Target** | **Yearly TCO** | **# panels** | **Yearly TCO** | **# panels** | **Yearly TCO** | **# panels** | **Yearly TCO** | **# panels** | **Yearly TCO** | **# panels** | ***Molds*** | **Yearly TCO** |
| 100 | | | | | | | | | | | | |
| 120 | | | | | | | | | | | | |
| 140 | | | | | | | | | | | | |
| 160 | | | | | | | | | | | | |
| 180 | | | | | | | | | | | | |
| 200 | | | | | | | | | | | | |
| 220 | | | | | | | | | | | | |
| 240 | | | | | | | | | | | | |
| 260 | | | | | | | | | | | | |
| 280 | | | | | | | | | | | | |
| 300 | | | | | | | | | | | | |
| 320 | | | | | | | | | | | | |
| 340 | | | | | | | | | | | | |
| 360 | | | | | | | | | | | | |
| 380 | | | | | | | | | | | | |
| 400 | | | | | | | | | | | | |
| 420 | | | | | | | | | | | | |
| 440 | | | | | | | | | | | | |
| 460 | | | | | | | | | | | | |
| 480 | | | | | | | | | | | | |
| 500 | | | | | | | | | | | | |
| 520 | | | | | | | | | | | | |
| 540 | | | | | | | | | | | | |
| 560 | | | | | | | | | | | | |
| 580 | | | | | | | | | | | | |
| 600 | | | | | | | | | | | | |
| 620 | | | | | | | | | | | | |
| 640 | | | | | | | | | | | | |
| 660 | | | | | | | | | | | | |
| 680 | | | | | | | | | | | | |
| 700 | | | | | | | | | | | | |

The maximum number of resources and number of shifts for this analysis is 5 (see *"Constraints"*). The solver performs each experiment five times. When current solution is not improved anymore, the decision variables are initialized (like described in section 5.3). This way the solution gets closer to the global optimum since the Evolutionary method is a stochastic solver like explained in chapter 3.

The first column *"Yearly throughput target"* of Table F-1 give the targets for the number of skin panels to produce. The columns *"2 molds, "4 molds"* and *"6 molds"* give the TCO and throughput for these targets for different number of molds in the closed network. The results in column "Cost e*fficient frontier"* give the best option for each yearly throughput target. Additionally, it also gives the maximum capability for 2, 4 or 6 molds in the production line.

In Figure F-1 gives an overview of the costs per panel. The optimum number of panels to produce for 2, 4, 6, 8 and 10 molds is respectively 180, 220, 420, 460 and 460 panels per year. Note the increase between 220 and 240 panels when having 2 molds in the network. This increase is caused by an increase in investment costs. These costs emanate from another AFP robot which is required.

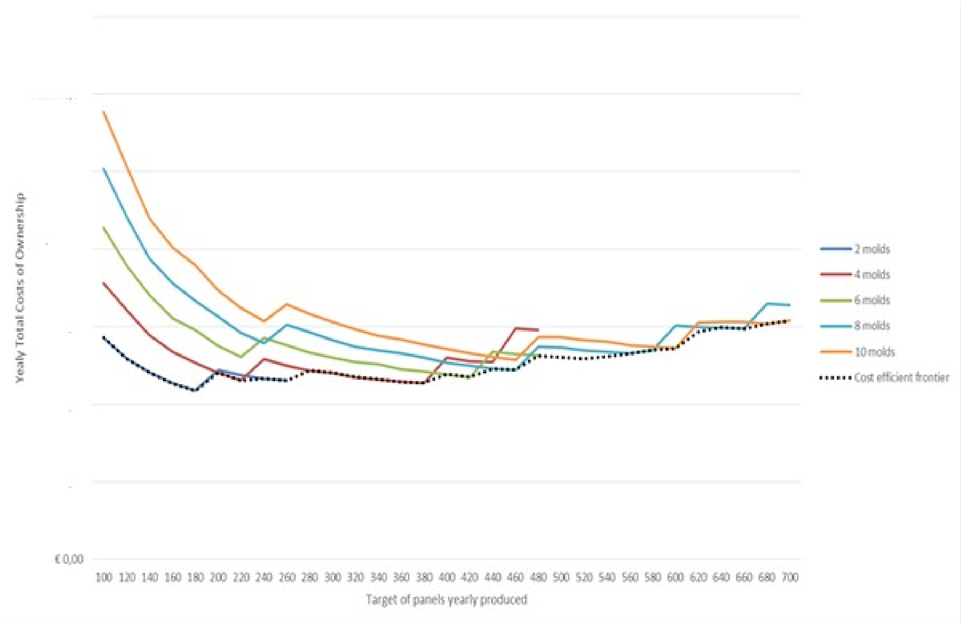



*Figure F-1 Costs per panel for different number of molds and for different targets*

# G. Sensitivity of decision variables with 6 molds in the network.

This sections shows an extension of the analysis described in section 5.5. This analysis shows the effect on the throughput when changing the number of resources. Like it can be seen in the Figure G-1, the AFP still shows positive effect on the throughput.

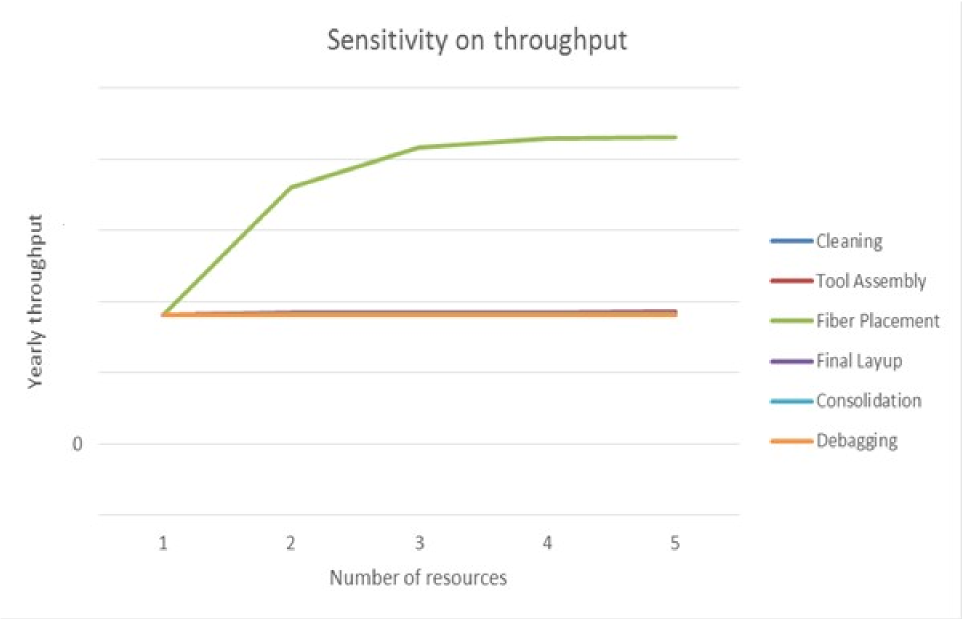



*Figure G-1. Effect when changing the number of resources per individual station for 6 molds in the closed network*

# H. Validation of the Excel SOLVER

The Excel SOLVER is a relative new optimizing tool which is not frequently used in scientific research yet. Therefore, its results had to be validated. This has been done by comparing it with the solution of a Simulated Annealing algorithm. The code of the SA algorithm is given in appendix D.

Both models have executed a deep search with the same settings. Both models had a computation time of approximately an hour per experiment. The throughput target is set to 100 for the scenario with 2 molds in the process. The results of this experiment is given in Table H-1.

*Table H-1. Best solution for both optimization methods after a deep search*

| | **SA** | **Excel Solver** |
|---|---|---|
| Best solution | € X | € X - € 2,700 |
| Throughput | 100 | 100 |

Both models give the exact same result. Therefore, it can be concluded that both reached the optimum. Additionally, both models are capable to reach the optimum. But what would happen when the computation time is normal (approximately 30 seconds per experiment). The answer can be seen in the following analysis. In Figure H-1 the difference in solution can be seen for both models. It is clear that the Excel SOLVER performs better for low and moderate throughput targets. At high throughput targets the Simulated Annealing algorithm provides a better solution. But when executing the Excel SOLVER several times and save the best solution (like described in section 5.3), it is able to reach a lower value compared to the Simulated Annealing solution.

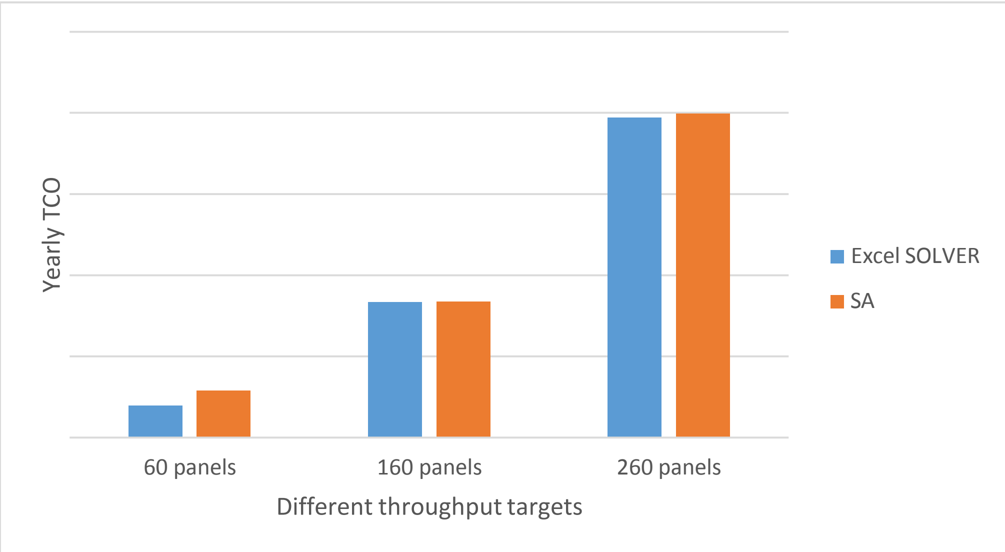



*Figure H-1. Performance of both optimization methods for different targets*

The third analysis is performed to see how both model can improve each other. First the Excel SOLVER is executed for 30 seconds. After that, the Simulated Annealing algorithm is executed to see if it can improve the solution given by the Excel SOLVER. This is also performed also the other way around. The result can be seen in Figure H-2. The table also gives the expected optimum of this experiment. This is obtained by executing both models for a long time (computation time of approximately 1 hour.)

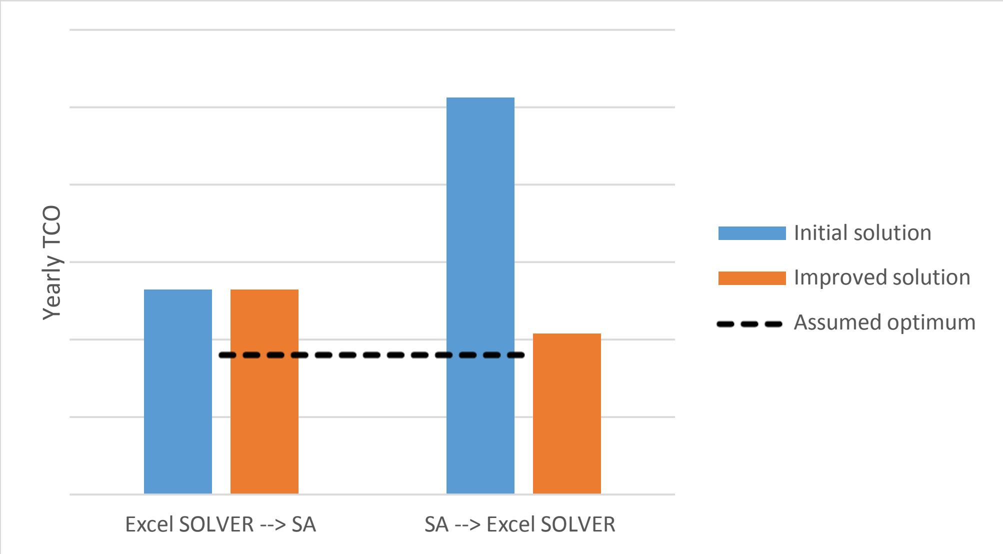



*Figure H-2. Results of methods improving each other with yearly throughput target of 100*

From these analyses it can be concluded that the Excel SOLVER and the Simulated Annealing algorithm show very similar solutions. The Excel SOLVER performs slightly better. The computation time of the Excel SOLVER is also less in general. For this reason this optimization tool is used for this research project.

# I. Number of machines required for the current state

content not shown