- Master Thesis -

"Lead time reduction at Fokker Aerostructures B.V."

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"Design of a logistical concept to reduce the lead time of the chemical treatment process and the paint shop at Fokker Aerostructures B.V"

Master Thesis
Industrial Engineering and Management
Production and Logistic Management

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Management summary

Stork Fokker Aerostructures B.V. is facing the problem that the lead time at the Sheet Metal department is too long and unreliable. The objective of this research is to design a logistical concept that reduces the lead time of the production orders that need a chemical treatment and (mostly) a paint job.

After analyzing the current situation, we conclude that the waiting time at the batching zone of the chemical treatment installation mainly determines the total lead time of the orders that need a chemical treatment and (mostly) a paint job. The available literature contains a model that is able to optimize the planning of jobs comparable with the orders available at the batching zone. This model is also able to incorporate the differences in batches between two consecutive departments comparable with the chemical department and the paint shop. The complexity of the practical situation in number of orders, flows, programs, and restrictions results in an unacceptable long computation time to optimize the problem with a mathematical model. To improve the performances at the chemical line and the paint shop in terms of lead time and service level, we have to design a logistical concept that incorporates clear working instructions for the operators at the chemical line.

To be able to construct a schedule that results in a shorter and more reliable lead time, we analyze the product mix that is offered to the chemical line in terms of orders per flow number and program. Based on the historical data of the chemical line, we conclude that the product mix is too diversified and the arrival process is too unpredictable to construct a fixed schedule that can guarantee an acceptable and reliable lead time. To improve the lead time, we have to develop a schedule that is able to react on the available orders at the batching zone. We decide to develop a number of alternative schedules that contains fixed time windows for each type of chemical treatment. This cuts the initial problem into smaller problems. To determine the right flow number during these time windows, we make use of the FIFO concept.

To compare the alternative schedules, we develop a simulation model that simulates the stochastic arrival process and makes it able to analyse how well the schedules react on the unpredictable arrival process. Based on the quantitative results of the simulation runs, we conclude that the use of a structured way of working according to a schedule results in the following improvements without decreasing the efficiency at the chemical line:

- Increase in service level from 65-70% to 90-99%
- Reduction of average lead time from 3,5 days to 1,5 – 2 days
- A more reliable lead time with a decrease of the standard deviation of the average lead time from more than 4 days to 1 day.

We consider multiple schedules that are based on a one-cycle schedule or a two-cycle schedule. With a one-cycle schedule, every type of chemical treatment has one time window during the day that it is performed. With a two-cycle schedule we use two time windows per type of chemical treatment. Based on a multi-criteria analysis of the alternative schedules, we conclude that the one-cycle schedule has the most promising results. To test the schedule in practice, we execute a test pilot of one week with the one-cycle schedule. After evaluating the pilot, we recommend the following actions to be taken in the forthcoming period:

- Match the workforce with the requirements of the schedule, in number of operators and their capabilities.

- Reorganize the batching zone to visualize the available work.
- Perform a time study at the chemical line and the paint shop to find the most disturbing effects and eliminate them.

Our main conclusion is that implementing a structured way of working at the chemical line, results in significant better performances in terms of lead time and service level. The performances are less independent of a specific schedule, but the one-cycle schedule has the most promising results.

Preface

In the context of the Master Industrial Engineering & Management at the University of Twente, I did my graduation project on designing a logistical concept to control the lead time of the production process within the Sheet Metal department at Fokker Aerostructures B.V. at Papendrecht.

During my project I have seen, heard, and learned a lot of the world of Fokker. The complex (high-tech) products, the rich history, and the diversity of processes really triggered my interest for this company.

The realisation of this thesis would not have been possible without the support of several people. I am really grateful for them and I want to express my gratitude to some of them in particular. First of all, I thank Marco Schutten and Martijn Mes, my supervisors from the University of Twente. The regular meetings and discussions were really useful and kept me on the right track. Furthermore, I thank my supervisors of Fokker Aerostructures B.V. The first months of my graduation project, Jantien Kemperman helped me to get access to the necessary data and made sure I could talk with the right people. After she moved to another company, Rutger van Galen was always available to give his opinion about my ideas and evaluate my progress. His practical comments were of high value to the quality of this thesis. Finally, I thank the people at the chemical treatment line and the paint shop. The team leaders and their operators really helped me to get more insight into the problem and were really excited to turn the theoretical solutions into practice.

Papendrecht, 26 February 2010

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1 Introduction

This chapter gives an introduction to the problem setting at the Sheet Metal department within Fokker Aerostructures B.V. Section 1.1 gives the background of the problem to understand the reasons to start this research. Section 1.2 formulates the problem statement and introduces the production processes that are subject to this research.. Based on the problem statement, Section 1.3 gives the main research objective. Finally, Section 1.4 gives the research questions and the corresponding thesis outline.

1.1 Background

As part of the Stork B.V. concern (see Section 2.1.2), Fokker Aerostructures B.V. is responsible for the design, development, and production of complex lightweight structures for the aviation, aerospace, and defence industries. Since 2006, Fokker Aerostructures B.V. focuses on lean manufacturing. This company-wide project is called Lean Enterprise Fokker (LEF). The Sheet Metal department within Fokker Aerostructures B.V. is responsible for the production of parts of aircrafts, helicopters, and space rockets that are assembled by the assembly department or are directly sent to the customer. With value stream mapping, the LEF project team of the Sheet Metal department analyzed the flow of materials and information currently required to deliver the products to the customer. Almost all the parts produced by this department need a chemical treatment and a paint job before they are ready to use. By reducing the lead time at these two processes, the overall performance of the Sheet Metal department is improved directly.

1.2 Problem statement

Figure 1 gives a general process overview of the problem situation where this research is about. At the beginning of the chemical treatment line there is a batching zone. This area is used to temporally store the items and make batches before the chemical treatment process is executed. These items arrive from three different independent sources, namely:

- Tthe Sheet Metal department (internal).
- The other factory location in Hoogeveen (machining), see also Section 2.2.2.
- External suppliers from different (international) locations (outsourced work).

Due to these different sources, the point in time at which the items arrive and the amount of items that arrive are (completely) unknown for the operators at the chemical treatment line until they actually arrive at the batching zone.

The chemical treatment is an (almost completely) automated process. The items are put on a carrier by hand. A carrier is automatically transported to multiple predefined positions in the line by one of the two cranes. At each position, an activity is performed in a specified fixed time. A specific sequence of these activities is called a flow. Currently, there are 36 different predefined flows available at the chemical treatment line. A batch is a combination of production orders that need the same flow. When the treatment is done, the items are transported to the paint shop. The paint shop is located at another section of the factory site. The paint job should be done within 16, 24, or 72 hours after the chemical treatment, depending on the kind of item. When the paint job is done, the items are sent to the assembly department, to the general warehouse, or directly to the customer.

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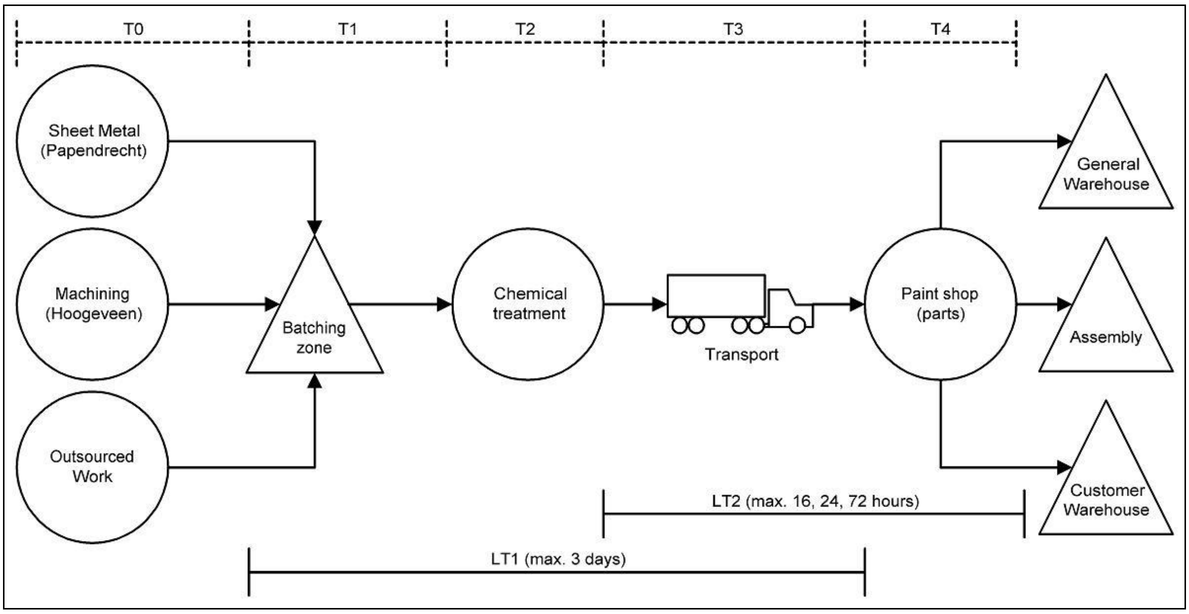


Batching zone


Chemical line


Transport


Paint shop

Figure 1: General Process Overview

To get more insight in the total lead time of the two processes, we divide the total lead time into five parts (see Figure 1):

T0: Processes before the orders arrive at the chemical line
T1: The time the item is at the batching zone before it starts the chemical treatment
T2: The chemical treatment
T3: The time between the end of the chemical treatment and the start of the paint job
T4: The paint job

In the current situation, the operators at the chemical treatment line have the objective to realise a lead time (LT1) of at most three days. So, a maximum lead time of three days from the moment the items arrive at the batching zone until they arrive at the paint shop (T1 + T2 + T3). The lead time (LT2) is defined by the production requirements for every item and may not be exceeded or else the chemical treatment should be done again.

Based on this problem situation the main problem statement is:

How can we reduce the total lead time (T1-T4) of the orders that need a chemical treatment and (mostly) a paint job?

1.3 Research objective

When we zoom in on the five partial lead times, we see that T2 is (almost) deterministic because of the automated process. T3 depends on the distance between the chemical line and the paint shop. The only way to reduce this transport time is to move one of the two processes. Because of the high costs involved, this is not to be changed in the near future. For this research we assume that this transport time cannot be changed. The process time at the paint shop (T4) depends on a number of variables and are described in Section (2.2.4). For this research, we focus on one aspect of the paint shop. When orders of the same program are at the paint shop at the same time, the paint shop can make larger batches and work more efficiently. So, to reduce the total lead time of the orders that need a chemical treatment and a paint job, we have to focus on the batching process at the batching zone.

The decisions made at the batching zone determine the efficiency at the chemical line and the paint shop. So, they have an effect on the total lead time (T1 to T4) of the orders. The time an order is at the batching zone (T1) is mainly consists of waiting time and does not add any value to the products. The lead time T0 is not taken into account within this research. Although the lead time before the batching zone is out of scope of this research, the planning of the processes before the chemical treatment determines the arrival process at the batching zone. The arrival process may have a huge impact on the batching possibilities. Based on this problem situation, we formulate the following main research objective:

To design a logistical model aimed at reducing the lead time (T1), such that the chemical treatment and paint job can be done efficiently

This objective focuses on the batching zone at the chemical treatment line. As already pointed out in Section 1.2, this is the point where different product routings come together and need a specific chemical treatment. For the production of parts, the paint shop is the last step in the process before they are actually assembled or directly sent to the customer. So, the reduction of the lead time at the chemical treatment line and the paint shop directly results in improvement of the overall performance of the Sheet Metal department.

1.4 Research questions

By using the intervention cycle of Verschuren and Doorewaard (2007), we translate the problem statement into different partial questions. The first step in the intervention cycle is the problem analysis. By identifying the different process routings and quantifying the product mix, we get more insight in the current situation. Chapter 2 covers the problem analysis by answering the first research question:

1. *What are the different flows of the products from the moment they arrive at the batching zone and how can we quantify the product mix at the chemical treatment line?*

To get more insight in the production process, we need some practical working experience. Next to this practical experience, we do some desk research. We make use of the available historical data of the production orders handled by the chemical treatment line. To get more insight in the product mix, we make use of the master item data from the ERP system. To get the details clear and to verify the acquired data, we do some interviews with the operators, their team leaders, and the chemical specialist.

By using the available literature we do the actual diagnose. We need to know which aspects of the problem are important for us and which of these aspects are already covered by the literature. Then, we need to know which of the available models can be used and whether they have to be extended. The research question involved is (Chapter 3):

2. *What is known about the aspects of the problem that are already encountered in the available literature?*

When we know the important aspects of the problem. we need to design a model to optimize the batching process at the start of the chemical treatment process. This should result in a reduction of the total lead time. The batching process involves the decisions of the operators whether to do a specific flow and if so, at which moment in time. This is the so-called design phase, covered in Chapter 4. The research question involved is:

3. *How can we optimize the batching process in order to reduce the lead time (T1)?*

To optimize the batching processes, we develop a number of scheduling alternatives based on the characteristics of the product mix and the available literature. The idea is to start with a simple situation and then gradually introduce more complexity to finally come up with a suitable model for the real situation. We may need some iterative steps to test and evaluate the proposed schedules. To be able to evaluate different schedules for large amount of orders we make use of simulation. By using simulation, we are able to simulate the arrival process of production orders in the batching zone and to visualize the movement of the products through the production process. By incorporating the decision rules from the proposed schedules into a simulation model, we are able to measure the performances of the different decision rules. The research question involved is (Chapter 5 and 6):

4. *How can we evaluate the performance of different decision rules?*

After finding the best schedule, we have to translate it into the real situation and find a way to implement this schedule. This is the so-called intervention/change phase (Chapter 7). The question to answer is:

5. *How can the proposed batching model be implemented?*

Figure 2 displays the relationships between the different research questions and the different phases of the intervention cycle of Verschuren and Doorewaard (2007).

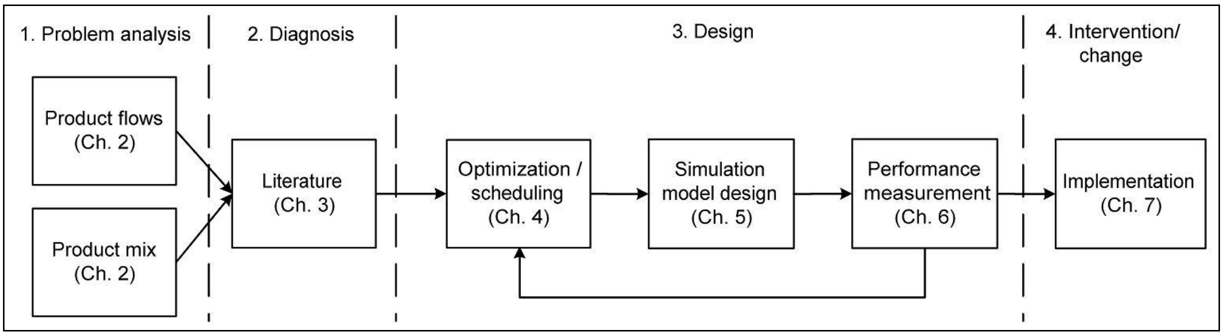

Figure 2: Research design and thesis outline

2 Problem analysis

Now we have more information about the problem setting, this chapter describes the current situation in more detail. Section 2.1 provides a brief description of the company and shows where this research is positioned within Stork B.V. Section 2.2 gives a more detailed description of the processes within the chemical treatment line and the paint shop. Section 2.3 gives an analysis of the historically offered workload at the chemical treatment. Section 2.4 discusses the impact of rush orders. Finally, Section 2.5 provides an overview of the problems within the current situation.

2.1 Company description

For those who are likely to know more about the interesting history of Stork Fokker, Section 2.1.1 describes the brief history. Others can directly go to Section 2.1.2, where the current organization structure is described. Section 2.1.3 gives an overview of the products currently produced by Fokker Aerostructures B.V. Finally, Section 2.1.4 describes the position of Fokker Aerostructures B.V. within the supply chain.

2.1.1 History

Between 1911 and 1928, Anthony Fokker developed his company to, what once was the largest aircraft manufacturer in the world, with factories in Europe and America. Even in those years, Stork (then Werkspoor) already supplied Fokker. Moreover, Fokker and Stork developed the first Dutch helicopter in cooperation with the Dutch Airforce and in 1927 KLM gave an order for the construction of a special freight aircraft.

From 1919, Fokker is active in civil aviation. By 1930, 172 out of the 596 aircrafts operated by European airlines were Fokkers; worldwide 54 airlines had Fokker planes and in 22 countries Fokker aircraft were manufactured under license.

After WWII, Fokker restarted its activities and the relationship with Stork was being formalized as Stork took a seat in the Advisory Board of Fokker. In this period, Fokker built 786 Fokker F27s and Fokker assembled 300 of the famous F16 fighter aircraft for the Dutch Airforce. Also Fokker became an associated manufacturer for the Airbus A300.

In the period 1980-1996, Fokker developed and manufactured the Fokker 50, 60, 70, and 100. Due the worldwide airline crisis in the 1990s and a wobbly dollar, Fokker went bankrupt in 1996. By then, Stork acquired Fokker and the company successfully changed from aircraft integrator into a specialist for structures, wiring, and services with an impressive portfolio. In 2003, Stork Aerospace opens a new facility for producing Glare, which is a revolutionary new Fibre Metal Laminate (FML) of which 500 m^2 is present in each Airbus A380.

The Stork Group structure changed considerably in 2008. A public bid by a consortium, led by Candover Partners Ltd., on the shares of Stork N.V. resulted in the delisting of Stork N.V. from Euronext Stock Exchange on 20 February 2008. This last change resulted in the company Stork B.V. of today. Section 2.1.2 describes the organization in more detail.

2.1.2 Organization

To get clear where this research is positioned in the organization of Stork B.V., Figure 3 provides a simplified overview of the organizational structure. It contains two main divisions, namely Stork Technical Services and Stork Fokker Aerospace. Stork Technical Services provides its customers with a total package of services such as assembly, installation, (preventive) maintenance, repairing, modification, relocation, and extension for a wide-range of technical installations. Stork Fokker Aerospace provides its customers in the aerospace industry with a wide range of products such as landing gears, wing parts, and wiring systems. Table 1 displays the key figures of these divisions.

	Stork Technical Services	Stork Fokker Aerospace
Net turnover (in € million)	1.185	597
EBITDA (in € million)	112	62
Number of Employees	10.611	3.700

Table 1: Key figures (Annual Report 2008)

The division Stork Fokker Aerospace is divided in three business units. One of these business units is Fokker Aerostructures B.V., which consists of two main factory locations: one in Hoogeveen and one in Papendrecht. The other facility in Helmond is specialized in the production of landing gears. The core activities of this business unit are:

- Design, development, and production of complex lightweight structures for the aviation, aerospace, and defence industries;
- Component supply for operators of commercial and defence aircraft.

The production facility in Papendrecht consists of the four departments: Engineering, Sheet Metal, Metal Bonding Glare & Composites, and Assembly. This research is performed in the Sheet Metal department which is highlighted in Figure 3.

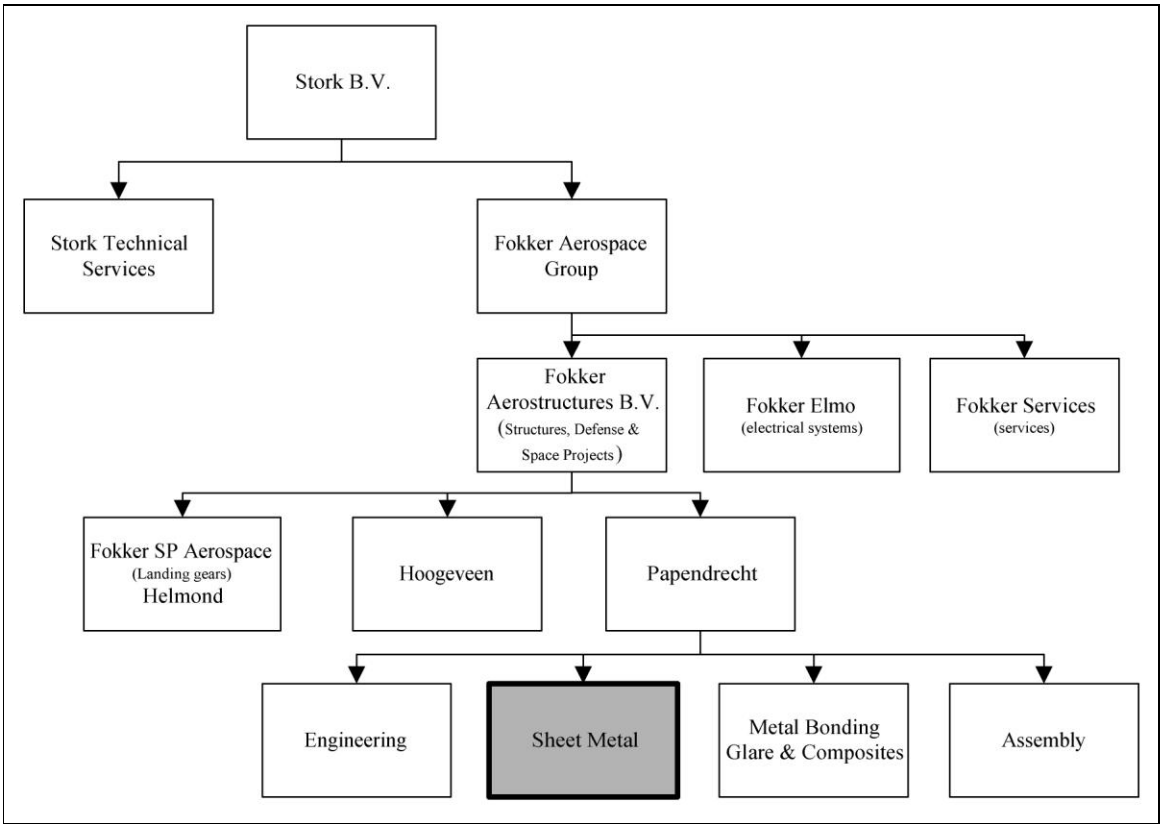

Figure 3: Simplified overview of organization structure of Stork B.V.

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2.1.3 Product portfolio

Now we have a global overview of the organization of Stork B.V. and the position of Fokker Aerostructures B.V., we zoom in on the core activities of this business unit. Table 2 gives an overview of the programs where the chemical treatment line and the parts paint shop of Fokker Aerostructures B.V. are involved. A program is the project name for a specific customer and can contain one or more components. The first column of Table 2 shows the main customers. These customers all have their specific requirements in terms of traceability, controllability, quality, and production methods. Stork does not specialize on a small set of components but is able to provide their customers with a wide-range of different components of an aircraft, a helicopter, or even a space rocket such as the Ariane. In Sections 2.3 and 2.5, we discuss the effects of all these different products on the production process.

Customer	Program	Component
Airbus	A300/A310	Wingparts
	A340	Pressure bulkhead
NHIndustries	NH-90	Tail section
		Doors
Boeing	Apache	IEFAB
		Vertical Sparbox
	C-17	Troop Door Air Deflector (TDAD)
		Ramp Attach Torque Box (RATB)
	747-8	Inboard Flaps
Gulfstream	Gulfstream IV/V	Tail
		Rudder
		MLG Door
	Gulfstream GGB	Tail
Dassault	Falcon 7X	Wing movables
Lockheed Martin	F-16	Flaperon
		ML Update
		Off load
Fokker	Full Fleet	Fokker Spares
Dutch Space	Ariane	Panels

Table 2: Overview of current programs

2.1.4 Supply chain

Figure 4 illustrates the productive pyramid in the civil aeronautical industry according to Ferreri (2003). To get an idea of the position of Fokker Aerostructures B.V. within the supply chain of aircraft manufacturers, we discuss this pyramid in more detail. The firm leader is located at the top of the pyramid, which designs, develops, and organizes the complete program. The firm leader is responsible not only for the activities of planning and final assembly, but also for marketing and product support. In addition, the firm leader carries out the role of collecting the flow parts, in the form of components or finished products, coming from lower levels. Examples of those firms are Boeing and Airbus.

The old Fokker-company designed, built, delivered, and serviced her own fleet (1st and/or 2nd level). The current Fokker Aerostructures B.V. is best described as a first tier supplier of these prime manufacturers (3rd level). For major parts such as inboard flaps, tails, and pressure bulkheads, Stork is also strongly involved in the design phase. For other parts, Stork just delivers the parts, which are specified by the customer (7th level). Besides this, Stork Fokker is still responsible for the delivery of spare parts of the Fokker fleet, which normally is the responsibility of the prime manufacturer.

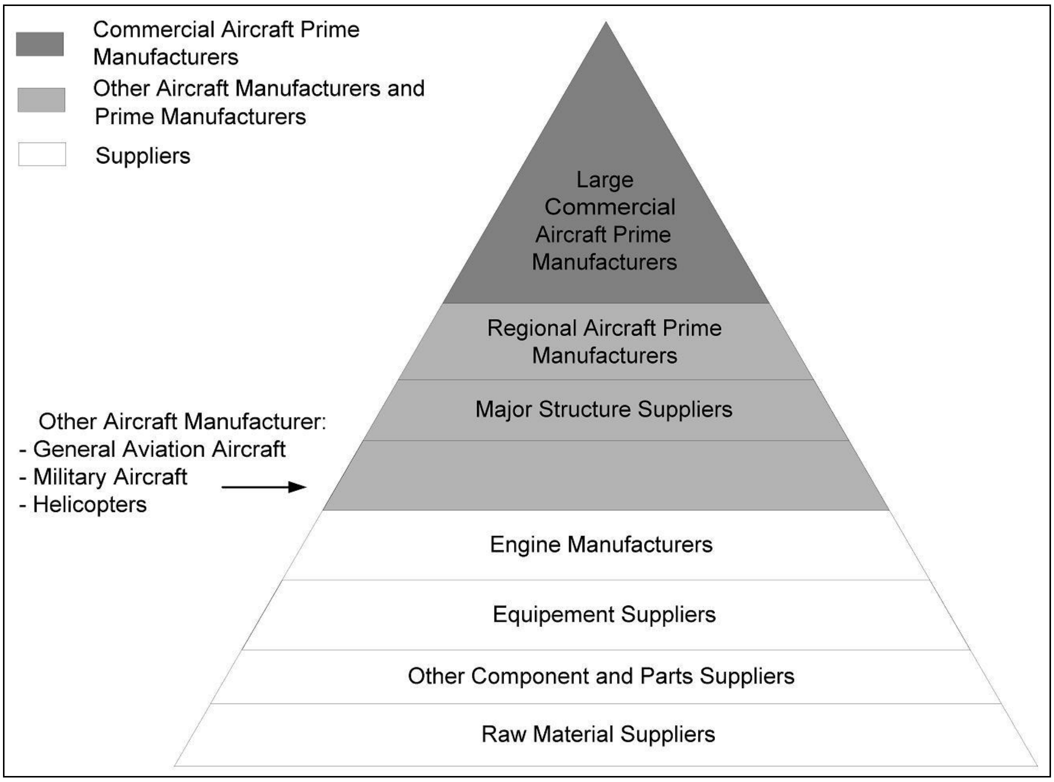


Figure 4: Productive pyramid (Ferreri 2003)

2.2 Product routings

To get more insight in the product routing, Section 2.2.1 gives a classification of the processes. Section 2.2.2 zooms in on the chemical treatment process and Section 2.2.3 describes the individual flows. Finally, Section 2.2.4 describes the paint shop in more detail.

2.2.1 Process classification

To get more information about the process structure, we zoom out from the chemical treatment process and the paint shop and look at the characteristics of the general process. These characteristics are clarified by the Product-Process matrix of Hayes and Wheelwright (1979), see Figure 5. Based on history, the traditional aircraft manufacturers organize their process structure as a job shop.

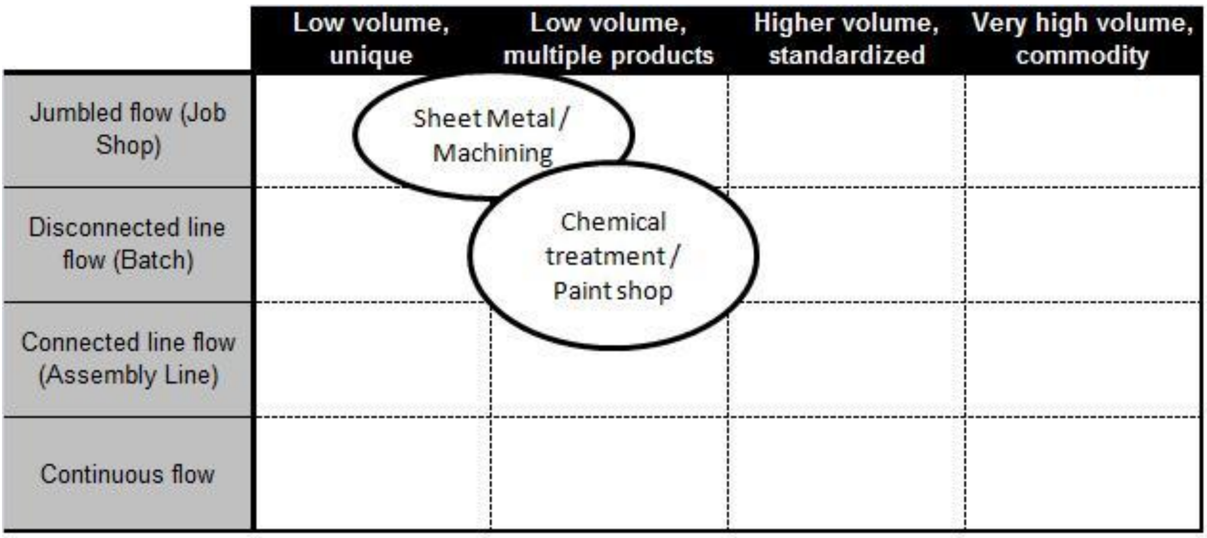


Figure 5: Product-Process Matrix

Within a job shop, unique products are produced. The organization interprets the customer specific design and specifications. This requires a relatively high level of skills and experience. Generally, resources for processing have limited availability. In a job shop, the outputs differ significantly in form, structure, materials, and processing required. Each unique job travels from one machine cluster to another, according to its own unique routing, requiring different operations, using different inputs, and requiring varying amounts of time. This causes the flow of the product through the shop to be jumbled, following no repetitive pattern.

Nowadays, there are a few large manufacturers that produce larger quantities of the same product (aircraft or helicopter). This makes it possible to organize the processes more as a batch process. A batch process is defined by Barker and Rawtani (2005) as follows: "*The output of the process appears in quantities of materials or lots. A batch process has, unlike a continuous flow, a beginning and an end. Batch processes are neither continuous nor discrete but have the characteristics of both. Firms utilizing batch processes provide similar items on a periodic basis, usually in larger volumes than that associated with job shops. Products are accumulated until a lot can be processed together. Since the volume is higher than that of the job shop, many processes can be utilized in repetition, creating a much smoother flow of work-in-process throughout the shop. While the flow is smoother, the work-in-process still moves around to the various machine clusters throughout the factory in a somewhat jumbled fashion*".

When we now look at the actual process structure within Fokker Aerostructures B.V., we see that the departments Sheet Metal (Papendrecht) and Machining (Hoogeveen) are designed for a job shop environment with functionally clustered machines. The chemical treatment process and paint shop are at the end of the process and can handle multiple (accumulated) products at one time. These are typical batch processes.

Now that we have a general overview of the different process characteristics, we are able to identify the different product routings within the chemical treatment process and the paint shop.

2.2.2 Chemical treatment process

Figure 6 displays the five main flow types within the chemical treatment process. A flow type is a group of predefined flows with comparable chemical treatments that can vary in temperature and duration. Every single flow of the 36 predefined flows is a member of one of these five flow types, as can be seen in Table 3. The specifications of these five flow types are:

1. penetrant inspection (PT): inspection of material on cracks or deep scratches with penetrant liquid;
2. chromic-acid anodizing (AN): applying a corrosion protection layer on the material by electrolysis;
3. chromate "iridite" (IR): applying a corrosion protection layer that covers the blank material;
4. alodine (AL): applying a corrosion protection layer that covers the blank material;
5. passivation for chemical milling (PS): cleaning process to be able to perform a chemical milling treatment at the chemical milling department next to the chemical line.

The product routing can be one of these flows types or a combination of two or three flow types. For example, an order can arrive at the batching zone for a passivation treatment. After passivation, the order goes to the chemical milling department. When it is ready, it comes back to the batching zone for penetrant inspection. When all the products of the order are confirmed by the inspection, they get a chromic-acid anodizing treatment. After that, the order is transported to the paint shop. In this situation, the items can stay on the same carrier after the penetrant inspection and are sent back to the beginning of the chemical treatment line for the next treatment. When a part failed the penetrant inspection, it is rejected and the engineering department has to make a decision what to do with that part. It is possible that the item can be repaired. Otherwise, it has to be scrapped.

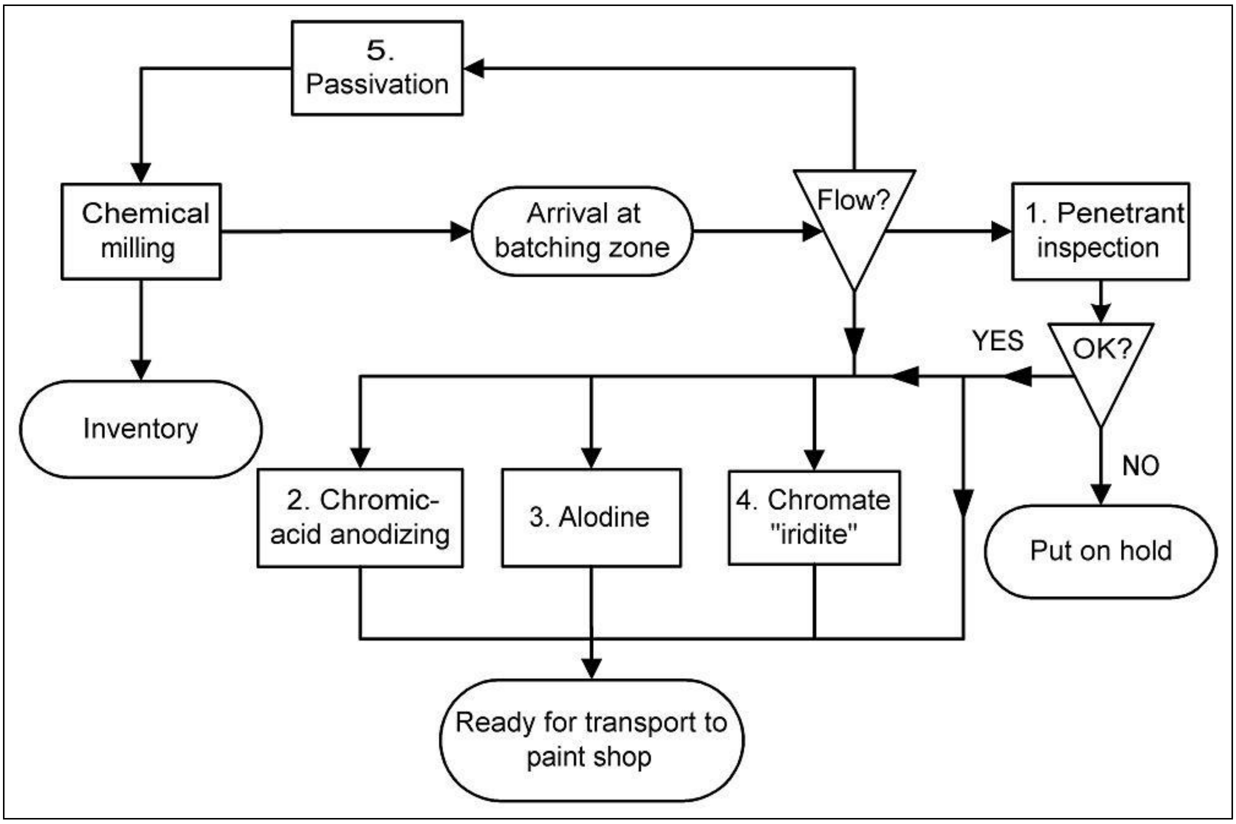


Figure 6: Flowchart of chemical treatment process

The flowchart starts with the arrival of the orders at the batching zone. The upper triangle in Figure 6 displays the actual batching process. This is the moment in the production process were the operators constantly have to make a trade-off between:

- Maximizing the occupation of carriers of the chemical treatment line by waiting for more incoming orders.
- Staying within the lead time of three days.
- Maximizing output of the operators (OWE).
- Taking care of rush orders that arrive.
- Offering the paint shop and chemical milling department a constant amount of work that can be completed on time and as efficiently as possible.

The last point is a result from the parts that have had a chemical treatment and have to be painted in the paint shop within 16, 24, or 72 hours (mostly within 24 hours). The paint shop can handle multiple orders of the same program in one batch. Another complicating factor is the distance between the chemical treatment line and the paint shop, located at the other end of the factory site. This distance results in bad communication between the chemical line and paint shop, additional material handling, and waste of time. According to the operators at the paint shop, they do not know what kind of orders arrive next and at which time they arrive.

Next to the regular orders, there are rush orders. Rush orders should be handled as soon as possible. This has a disturbing effect on the process flow. The impact of these orders and the way they are handled now, are covered by Section 2.4.

Besides these main product routings at the chemical line, the operators have a number of other tasks (e.g. magnaflux, s-line, k-line, and unscheduled penetrant inspection for Assembly department) We do not consider the scheduling of these other tasks within our simulation model, because they have no direct involvement of the regular processes at the chemical line.

2.2.3 Chemical treatment flows

Within the chemical treatment installation there are 36 unique flows possible. For the current programs, only 18 of these flows are actually used. The other flows are currently not in use, because they are replaced by another flow or there are simply no orders that need this chemical treatment. Furthermore there are 3 flows to clean materials or tools and to de-anodize parts. These flows are flow numbers 2, 3, and 28. Table 3 shows the active flows with their number, codes, and the kind of chemical treatment that is involved.

Flow no.	Code	Flow type	Flow no.	Code	Flow type
4	P010	Passivation	26	CN340	Anodizing
6	C130	Anodizing	27	A010	Alodine
7	C140	Anodizing	29	CN120	Anodizing
11	A020	Alodine	31	C121	Anodizing
12	I010	Iridite	32	CN331	Anodizing
14	CN330	Anodizing	33	CN341	Anodizing
15	B040	Penetrant	34	PT01	Penetrant
16	B030	Penetrant	35	I030	Iridite
17	B020	Penetrant	36	B015	Penetrant

Table 3: Active flows

All of these flows from Table 3 should be incorporated in our logistical model, except for flow 27, which we show in Section 2.3. For most of the flow types there are multiple flows. The treatments can differ in temperature, amount of time the carrier has to stay in a tank, and electric power.

2.2.4 Paint shop process

After the parts have had their chemical treatment, the primer coating and top paint have to be applied within a certain amount of time. Table 4 shows the paint requirements, the so-called FP, for every program according to the official FP handbook. For the primer coating, it is the amount of time between the end of the chemical treatment and applying the primer. For the top paint, it is the amount of time between applying the primer and applying the top paint. For some programs the parts do not need a top paint. After anodizing flow 6 and 33, it is possible that an order needs a 'bleeding' time of at least eight hours. This time is included in the time window. During these eight hours, the chemicals mark deep scratches or cracks, because it 'bleeds out' of the material. This process is in alternative inspection for the penetrant inspection. However, a penetrant inspection is more advanced. The choice between a penetrant inspection, 'bleeding' time, or just a visual inspection, depends on the criticality of the part, the production process, and the requirements of the customer.

Program	Primer	Top paint
Airbus A300/A310 Wingparts	<(16 or) 24 hours	N/A
Airbus Pressure Bulkhead	<16 or 24 hours	4-72 hours
Boeing 747-8 Inboard Flaps	< 16 hours	2-48 hours
Boeing Apache	< 72 hours	N/A
Boeing C17	< 24 hours	1-24 hours
Dassault	< 24 hours	< 48, 72 hours
F16	< 72 hours	1-24 hours
Fokker Spares	< 24 hours	2-48 or 4-72 hours
Gulfstream IV/V	< 24 hours	N/A
Gulfstream GGB Tail	< 24 hours	N/A
NH-90	< 24 hours	1-24 hours
Dutch Space Ariane	< 24 hours	N/A

Table 4: Paint requirements

Within the paint shop we identify 4 different groups of paint jobs with a specific lead time:

1. primer only LT: 2 - 2,5 hours
2. primer, top paint LT: 6 - 7 hours
3. masking/taping, primer LT: 2,5 + max. 2 hours
4. (masking/taping), primer, masking/taping, top paint LT: 7 + max. 2 hours

Every order that arrives at the paint shop from the chemical line can be put in one of these groups. The lead time of these paint jobs is the time that is needed to finish the whole paint job, so including drying, stamping and packaging. The indicated lead times assume that the different process steps are done directly after each other. Because the operators do more paint jobs at the same time, the orders are waiting for the next process step and the actual lead time becomes longer.

When doing the actual paint job, the products are heated and turned to paint both sides of the products. Figure 7 displays the different routings and also the heating loops. After the chemical treatment the orders are transported to the paint shop by the operators of the chemical line. The flowchart in Figure 7 starts with the arrival of the orders at the paint shop. The triangle displays the batching process at the paint shop. When the orders arrive from the chemical line, the operators have to make the decision which products to paint first. This depends on the amount of products, the requirement for these products, and the amount of time needed to finish these products.

When products are produced for the first time or are reproduced after more than two years, these products get a First Article Inspection (FAI). The means that the products, processes, and paperwork should be checked at every production step. When the parts are stamped, Quality Control (QC) does an overall check. The order can only be reported as finished when QC has approved the order. In the current situation, this step in the process can take an relatively huge amount of time and most of the problems are discovered at the paint shop, when every process step is ready. This happens not only with orders with FAI but also with the regular orders. The delay can be days but in some cases weeks or even months. At this point in the production process, all the process steps are finished and it takes a lot of time to verify all these steps. This causes a lot of delay of these orders and the lead time becomes unpredictable. Without any problems or FAI, the maximum lead time of the paint shop could be 24 hours, according to the employees at the paint shop. This means that every product that arrives at the paint shop can be ready for transport within 24 hours.

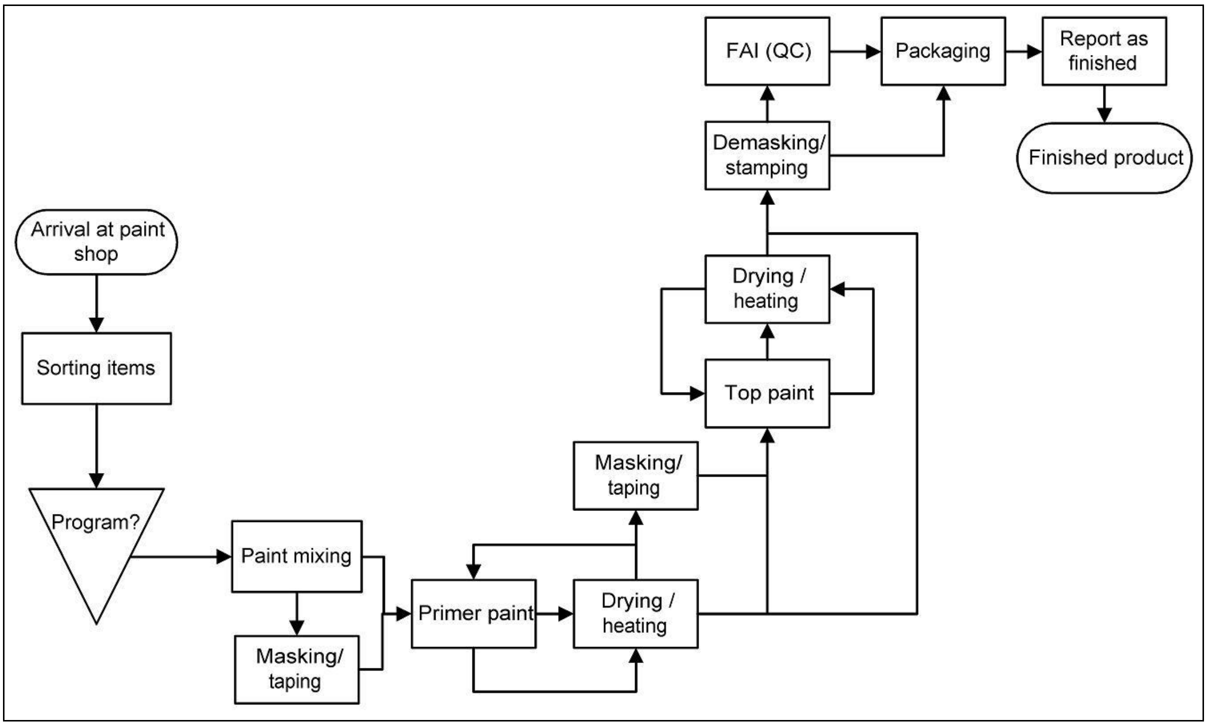


Figure 7: Flowchart of paint shop process

Now we know the different processes in more detail, we are able to analyze the historical data of the chemical line to get more insight in the product mix.

2.3 Product mix

When we analyse the paint shop processes in more detail, we see that this process becomes more efficient if more parts of the same program arrive at the paint shop at the same time. In other words, larger batches of the same program are more efficient at the paint shop. This means that the batches at the chemical line differ from the batches at the paint shop. The chemical line makes batches of the same flow. At the paint shop, it depends on the program. To get more insight in the product mix, we analyzed the historical data of all the charges that have been done since 2007. We analyze the product mix in two ways. First, we show the division of orders per chemical treatment flow (flow mix). Secondly, we analyze the division of orders between the different programs (program mix). To use the historical data of the years 2007, 2008, and 2009, the data is corrected for the following aspects:

- Excluding the double inputs of the same flow and production order number. These are not really executed but returned from the buffer and put back into the system again.
- Excluding the lines without production order number. These are not real production orders but activities such as cleaning tools or unspecified tests.
- Excluding flow 2, 3, and 28, because these are mostly used for cleaning tools or sometimes to de-anodize when something went wrong with the products. These orders are not regular production orders.
- Excluding flow 20 (anodizing). This flow is for specific Boeing parts. When in the future these products need to be produced, Fokker Aerostructures B.V. should be able to show that they can perform this treatment and that the process is stable enough. To approve this, the treatment is tested every month. This flow is not used for production orders at this moment.

Table 5 shows the summary of the flow mix of the cleaned data. For the years 2007-2009, it shows the number of orders and charges for every active flow. Furthermore, the orders and charges are divided over the different type of flows (anodizing, penetrant, iridite, alodine, passivation) to get insight in the type of work that is offered to the chemical treatment line. The table also shows the relative amount of work that is done during every year. Based on the weeks that the line was in use during a year, the total completed work is calculated. When we look at these figures in more detail, we can make the following remarks:

- The number of orders per charge increases every year. There are several causes for this. First, the increasing amount of orders that is offered. With more orders the operators can make larger batches. Second, the focus on lean manufacturing and the reduction of the order quantities. Also when we look at the relative totals, we see that every year there are completed more orders with less charges.
- Although 2009 seems to be a difficult year for Stork, the amount of work completed at the chemical treatment line seems to be relatively good. When the first 20 weeks are representative for the rest of the year, the number of orders still increases. The number of operators is on a minimal level, so the efficiency is relatively good.
- The number of orders per charge differs a lot per flow (1 – 15.5). This is also seen in the division per flow type. For example, in 2008, the percentage of production orders that need an anodizing treatment is 60,1%, whereas the percentage of charges is just 48,7%. This means that the number of orders per charge is above the average.
- The division between the flow types seems to be stable. Only the ‘iridite’ flows are increasing significantly during the last three years.
- In 2008, the line was in use for only 42 weeks. Within this year there was a full maintenance action at the chemical treatment line, which took about 8 weeks.

Generally, the programs are long term contracts. However, the product mix may change during a year. A program may come to an end or a new program is launched. Furthermore, the planners can decide to shift work packages from Hoogeveen to Papendrecht or the other way around. Theoretically, this could change the product mix significantly and the numbers displayed in Table 5 change considerably.

The data of 2009 (until May 24) is also checked for other irregularities, such as different flows for same article number, non-logical combinations of flows, or non regular flows for a specific program. Based on these checks, we conclude that:

- For the same article the different production orders can give different flows.
- The production orders can be interpreted in different ways, because the flow is not specified.
- The operators choose another flow that is not on the production order. This should be changed on the order but this is not always done.
- The wrong flow is specified on the production order. Mostly this is discovered by the operators of the chemical treatment line.
- Flow 27 is not active anymore in 2009, so there are 17 flows left to put into the model.

Flow	Flowtype	2007 # production orders	2007 % production orders	2007 # charges	2007 % charges	2007 Average orders/charge	2008 # production orders	2008 % production orders	2008 # charges	2008 % charges	2008 Average orders/charge	2009 (until 24/5) # production orders	2009 (until 24/5) % production orders	2009 (until 24/5) # charges	2009 (until 24/5) % charges	2009 (until 24/5) Average orders/charge
4	Passivation	670	6,5%	237	14,1%	2,8	600	5,3%	207	13,4%	2,9	289	5,2%	77	11,1%	3,8
6	Anodizing	2.125	20,6%	210	12,5%	10,1	2.031	18,1%	158	10,2%	12,9	1.166	21,1%	75	10,8%	15,5
7	Anodizing	62	0,6%	35	2,1%	1,8	34	0,3%	20	1,3%	1,7	24	0,4%	12	1,7%	2,0
11	Alodine	65	0,6%	24	1,4%	2,7	63	0,6%	21	1,4%	3,0	31	0,6%	15	2,2%	2,1
12	Iridite	65	0,6%	18	1,1%	3,6	362	3,2%	49	3,2%	7,4	289	5,2%	38	5,5%	7,6
14	Anodizing	802	7,8%	75	4,5%	10,7	1.260	11,2%	93	6,0%	13,5	336	6,1%	32	4,6%	10,5
15	Penetrant	32	0,3%	25	1,5%	1,3	37	0,3%	14	0,9%	2,6	6	0,1%	4	0,6%	1,5
16	Penetrant	1.144	11,1%	202	12,0%	5,7	1.057	9,4%	181	11,7%	5,8	531	9,6%	79	11,4%	6,7
17	Penetrant	1.429	13,9%	180	10,7%	7,9	1.449	12,9%	168	10,9%	8,6	514	9,3%	67	9,7%	7,7
26	Anodizing	33	0,3%	16	1,0%	2,1	74	0,7%	20	1,3%	3,7	151	2,7%	21	3,0%	7,2
27	Alodine	95	0,9%	38	2,3%	2,5	52	0,5%	20	1,3%	2,6	2	0,0%	2	0,3%	1,0
29	Anodizing	74	0,7%	19	1,1%	3,9	76	0,7%	20	1,3%	3,8	13	0,2%	8	1,2%	1,6
31	Anodizing	50	0,5%	18	1,1%	2,8	25	0,2%	10	0,6%	2,5	8	0,1%	2	0,3%	4,0
32	Anodizing	918	8,9%	147	8,7%	6,2	946	8,4%	120	7,8%	7,9	407	7,4%	41	5,9%	9,9
33	Anodizing	1.957	19,0%	300	17,8%	6,5	2.304	20,5%	312	20,2%	7,4	1.186	21,5%	129	18,6%	9,2
34	Penetrant	734	7,1%	131	7,8%	5,6	531	4,7%	87	5,6%	6,1	183	3,3%	36	5,2%	5,1
35	Iridite	0	0,0%	0	0,0%	0,0	17	0,2%	5	0,3%	3,4	58	1,1%	19	2,7%	3,1
36	Penetrant	55	0,5%	9	0,5%	6,1	319	2,8%	42	2,7%	7,6	320	5,8%	35	5,1%	9,1
Grand Total		*10.310*	*100,0%*	*1.684*	*100,0%*		*11.237*	*100,0%*	*1.547*	*100,0%*		*5.514*	*100,0%*	692	100,0%	
Anodizing (8)			58,4%		48,7%			60,1%		48,7%			59,7%		46,2%	
Penetrant (5)			32,9%		32,5%			30,2%		31,8%			28,2%		31,9%	
Iridite (2)			0,6%		1,1%			3,4%		3,5%			6,3%		8,2%	
Alodine (2)			1,6%		3,7%			1,0%		2,7%			0,6%		2,5%	
Passivation (1)			6,5%		14,1%			5,3%		13,4%			5,2%		11,1%	
Av. orders/charge		6,1					7,3					8,0				
Operational weeks		49					42					20				

Week	20	of	48
Factor	2,40		
Prognose 2009			
# orders	13.234		
# charges	1.661		

Week	49	of	49
Factor	1,00		
Relative 2007			
# orders	10.310		
# charges	1.684		

Week	42	of	49
Factor	1,17		
Relative 2008			
# orders	13.110		
# charges	1.805		

Week	48	of	49
Factor	1,02		
Relative 2009			
# orders	13.509		
# charges	1.695		

Table 5: Chemical treatment process data 2007-2009 (flow mix)

In this research we focus on the 17 flows that are used at this moment (see Section 2.2.3, excluding flow 27). The other flows are excluded from the data. Table 6 gives the number of orders per flow and program (program mix) in 2009 until May 24. From the historical data of the chemical line, we subtracted the program of all the orders based on the item numbers. Based on this table we make the following remarks:

- For most of the programs the orders are spread out over a lot of different flows, up to 9 different flows for Gulfstream IV/V.
- Most of the flows are used for a lot of different programs, up to 9 different programs for flow 4.
- The number of orders per program differs a lot. From 21 for the NH-90 program to 1.133 for the Gulfstream IV/V
- The number of orders that need a specific flow differs a lot per flow. From 7 orders for flow 15 to 1.208 for flow 33.
- A lot of variation in the number of orders for every program/flow-combination. It differs from 1 order from Gulfseam GGB, flow 35 to 393 orders for Gulfstream IV/V, flow 33.

	Flow number																		
Program	4	6	7	11	12	14	15	16	17	26	29	31	32	33	34	35	36	*Total*	
Airbus A300/A310 Wingparts	20	169			72										10			*271*	4,9%
Airbus A340 Pressure Bulkhead		140						25						123			123	*411*	7,5%
Boeing 747-8 Inboard Flaps					15					115				136			136	*402*	7,3%
Boeing Apache	5				88			8								48	72	*221*	4,0%
Boeing C17	41					68		373					325					*807*	14,7%
Cessna	11					219			50				52				12	*344*	6,3%
Dassault	100	194	11	19					25					217	11			*577*	10,5%
F16	11				12	13	7											*43*	0,8%
Fokker Spares	2	81			9				2	4	8		3					*109*	2,0%
Gulfstream GGB Tail	23	294						32	146			17		339		1		*852*	15,5%
Gulfstream IV/V	66	214	13	2	16			84	207					393	138			*1.133*	20,6%
NH-90		21																*21*	0,4%
Dutch Space Ariane					9				91							10		*110*	2,0%
Test	10	15		11	70	33				21	4		29					*193*	3,5%
Total	*289*	*1.128*	*24*	*32*	*291*	*333*	*7*	*522*	*521*	*140*	*12*	*17*	*409*	*1.208*	*159*	*59*	*343*	*5.494*	*100,0%*

Table 6: Program mix 2009

Based on Table 6, we have more insight in the regular product mix. In the next section we describe how the rush orders are handled.

2.4 Rush orders

Besides the normal (planned) production orders, the production planner can label an order in two ways:

- A red label with PRIO on it, to give the production order high priority. These products are mostly needed for assembly on short term.
- A red label with AOG on it. AOG stands for Aircraft On Ground. This means that there is an aircraft on the ground waiting for a specific part, before it can be back in use.

For both types of high priority orders, it holds that every department has to handle the order as soon as possible, to ensure a minimal lead time. For the chemical treatment process, these orders can be disturbing. It frequently happens that a high priority order is processed instead of other orders that were at the batching zone earlier or are even on the bar already. Another effect of these rush orders, is that the bar needs a lot of scrap material to get the anodizing process done. The anodizing process needs a minimal surface of at least $6m^2$ at the bar. When there are not enough orders available the operators have to put scrap material at the bars to get the process done. Furthermore, it is possible that a bar, that was intended to be processed, is put on hold to get the high priority order done. It is also possible that the capacity required for the rush orders prevents other bars from being processed that day. The high priority orders are mostly caused by rejection of production orders, bad planning, damage at assembly, or other problems with a specific program or item.

2.5 Problems within the current situation

Now we know the processes in more detail, we can discuss the problems with the current working methods. Next to the batching difficulties, we encountered other possibilities for improvement at both departments. Section 2.5.1 focuses on the chemical line and Section 2.5.2 on the paint shop.

2.5.1 Chemical treatment line

This research focuses on the reduction of the total lead time by optimizing the batching process at the batching zone (T1), see Section 1.2. According to the interviews with different operators and their team leader and based on the observations during the practical sessions, we encounter problems with the current situation which can probably cause longer lead times. Below, we describe the most important problems we encountered:

- In the current situation the operators of the chemical treatment installation have an unstructured way of working. This unstructured way of working involves the following aspects:
  - A schedule that determines which flow number should be done at which moment in time does not exist.
  - The number of people and the combination of people working at the chemical line are constantly changing. So, the operator that decides which flow to do next is also changing. Assigning tasks to a single person becomes more difficult.
  - The offered work at the chemical treatment line is at a relatively low level according to the operators. This seems not in line with the figures in Table 5. The main reason for this is the focus on smaller production orders. So, the chemical line receives more orders but the number of items can be lower. This makes the batching process more difficult because it is harder to get a bar with a good occupation. The operators constantly look for more work for specific flows and try to wait for next delivery of new production orders. The arrival of new orders occurs 3 to 5 times a day. The operators just 'hope' they receive the right orders to make a good batch.

- The main goal at the chemical treatment line is to achieve a maximum lead time of three days. The operators do not use a systematic approach at the batching zone to track how long the items are waiting and how much orders are available for a specific flow. On the orders that are stored at the batching zone, the operators can put a stamp to track the date at which they were taken into the batching zone but this is not used as a performance measure. Besides this, they also have the opportunity to scan the orders to register them into the system. The operators do not make use of the system to see how long products are staying in the batching zone. The actual tracking of the lead time in the Management Information System (MIS) starts at the end of the process that precedes the chemical treatment line. So, in the current situation, the waiting and transport time at the preceding department is also on the account of the chemical treatment line.

- Despite the relatively low work load at the batching zone, the way of working at the batching zone is still messy. The products are put on roll tables, shelves, directly on the bar, or directly in a spring (small parts). The shelves are marked with the kind of process and some also with the program involved. One cannot directly see the required flow number or whether the parts need more than one flow, such as penetrant and chromic-acid anodizing.
- The operators at the chemical treatment line do also have problems with the tools they need to put products at the bars, such as metal racks or springs. The racks are broken often, the springs are not tight enough, and even the carriers are damaged. They constantly have to search for the right materials and so it takes a lot more time to secure the materials on the bars.

Now we know the most important problems at the chemical line, Section 2.5.2 discusses the problems at the paint shop.

2.5.2 Paint shop

As already mentioned in Section 2.3, the batches of the chemical line differ from the batches at the paint shop. Besides the batching problems, we encountered also other problems at the paint shop by interviewing the employees and by observations during the practical sessions. Again, we describe the most important problems:

- Besides the difficulties at the chemical treatment itself, the operators at the paint shop complain about the fluctuating amount of work that arrives from the chemical line. Not only the amount but also the kind of work, fluctuates heavily per day and week. In addition, the actual arrival times of jobs as well as the job characteristics are not known beforehand. Besides that, there is not a fixed working schedule at the chemical treatment line and the operators hardly communicate with each other. As a result the operators at the paint shop do not know the amount and the timing of the incoming work.
- The paint job itself does not take a lot of time. As mentioned before, when there are no problems, all the orders can be completed within 24 hours. However, there are a lot of problems with masking and taping, because drawings are not available or not clear, or there are no moulds available.
- Another big issue is the FAI. As mentioned in Section 2.2.4, this non-recurring process can take a lot of time. This depends on the amount of work QC has and the amount of problems they encounter with each order. These problems have a high impact on the actual lead time of the products. Improvement of this process can reduce the variation of the lead time a lot. However, since we focus only on the lead time of the recurring process, this issue is out of scope of this research.

2.6 Conclusions

Now we know the origin of the processes and the different factors involved in these processes, we have a base for the design of a logistical concept. Besides the operational problems at both processes, it is clear that a logistical concept to generate the working schedule of the chemical line is beneficial for the chemical treatment process, as well as the paint process. Most important characteristic is the difference in the batches between both departments. Within this research we focus on a logistical concept that, given a working package (# orders per flow and program) and historical data, constructs a working schedule that optimizes the batching processes at the chemical line such that both departments can work efficiently. When a program comes to an end or a new program is launched, this should be taken into account in the model and the schedule may be changed. The complexity of the problem is already reduced because only 17 of the 36 flows have to be taken into account.

In Chapter 3, the available literature is studied to see whether some aspects of the problem are already encountered in the available literature. We also look for available models that can be used or have to be extended to cover the characteristics of the current problem situation. This should result in a Stork-specific model that can be used for simulation.

3 Literature study

This chapter describes literature that contains problem characteristics comparable with the problem described in Chapter 2. Section 3.1 describes general literature to classify the problem. Section 3.2 describes models that can probably be used to optimize the problem. Finally, Section 3.3 introduces tools to develop a simulation model and to evaluate the performances of different alternatives.

3.1 Problem classification

To classify the problem, Section 3.1.1 describes a hierarchical planning framework. Section 3.1.2 describes the different forms of batch processing. Section 3.1.3 describes the process of the chemical line known in the literature as hoist scheduling. Finally, Section 3.1.4 describes a batching problem which involves the processing of different batches on different working stations.

3.1.1 Hierarchy of planning framework

There exist several classification schemes for planning within a production facility. Most of these schemes structure different types of organizational planning in a hierarchical way (Verbreack 1991). The classical hierarchy of Anthony (1965) distinguishes three levels of planning: Strategic, tactical, and operational planning. Boskma (1987) extended this framework and described the hierarchy in further detail and he differentiates between five levels. Table 7 displays the main features of these levels. The period defines the planning horizon and the frequency indicates the amount of time until the plans are revised. The classification is clearly hierarchical, and the different levels are dependent. The definitions of these levels are given by Boskma (1987).

Level	Period	Frequency
Strategic Planning	5-10 years	Yearly
Long-term planning	4-10 years	Yearly
Medium-term tactical planning	1-5 years	Monthly / Quarterly
Short term production planning	1-26 weeks	Weekly / Monthly
Detailed Production planning	Hours / Days	Weekly / Daily

Table 7: Hierarchy of planning, adapted from Boskma (1987)

Strategic planning: At this highest level the main goals are defined. The focus is on the development of the external position of the organization, especially the position compared with the competition. The strategic planning is always about the complete organization.

Long-term planning: The long term planning focuses on the decisions about new products, long-term product range, investments, and the global planning of the capacity of the production systems. This planning level is also applicable to the whole organization.

Medium-term tactical planning: At this planning level, the main issues for the coordination of production and sales are described. It focuses on production amounts, changes in personnel, and machine capacity.

Short-term production planning: The short-term planning is based on the medium-term planning. At this level the production level for the coming weeks or months is determined in sub periods of one week. In practice this level includes one functional unit of an organization and has relatively few relations with the rest of the organization.

Detailed production planning: At this most detailed level of production planning the decision involves the assignment of production orders to person and/or machines for a certain moment in time. The short term planning is in principle the base for the detailed planning. During the operations every disturbance results in a deviation from the detailed plan. So, the detailed planning has to be revised frequently.

3.1.2 Batching

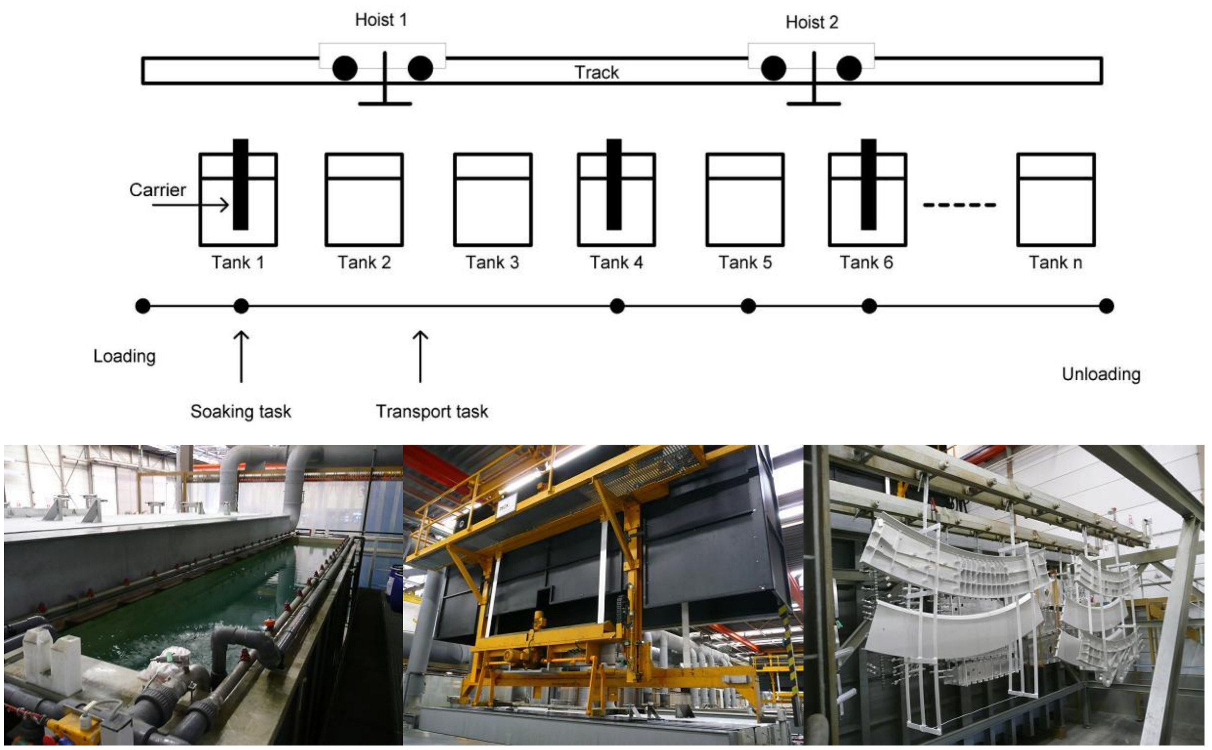
To describe the theoretical problem in a more formal way, the nature of the batching process needs to be defined. The literature defines two different types of batch processing (Potts & Kovalyov, 2000). The first one occurs when a machine requires setups if it processes jobs that have different characteristics. In this so-called family scheduling model, jobs are partitioned into families according to their similarity, such that no setup is required for a job if it belongs to the same family as the previously processed job. In this model a batch is a maximal set of jobs that are scheduled contiguously on a machine and share the setup. The second type of batch processing occurs when a batching machine is capable of processing several jobs simultaneously. In this situation, a batching machine processes a batch of jobs at the same time, where there is sometimes an upper limit on the batch size. In our problem, the two processes are both under the definition of a batching machine. This means that all the jobs in the batch have the same start and end time and have the same processing time. The chemical line does not have setup time between different batches. Obviously, the items have to be put on the carrier before the process can actually start but the chemical line can perform any flow on any moment in time without any changes on the installation itself.

3.1.3 Hoist scheduling

When we zoom in on the chemical line itself, this process is known in literature as a hoist scheduling problem (Manier and Bloch, 2003). The typical processing resources of a chemical line (Figure 8) are tanks, containing chemical liquids in which parts must be soaked according to a given processing sequence.

Each sequence is decomposed into several soaking operations that cannot be pre-empted. The duration of each operation is bounded by minimal and maximal limits, because of chemical constraints. For example, the thickness of the deposit depends on the surface to cover, the concentration of the chemical bath, and the intensity of the electrolysis process. When the duration is shorter than the minimal value, the deposit might be too thin. If the duration exceeds the maximal limit, the parts might be damaged or the production cost might increase because too much metal is deposed. Each operation is executed in a single tank. Batches of parts are first loaded on carriers. Then handling devices (hoists or cranes) move carriers from tank to tank. Generally, all hoists are identical. They move along a single track above the line, which prevents them from crossing over. A transport operation is made up of several steps. A hoist moves empty from its current location to the tank containing the carrier to be transferred. Then it grasps the carrier, raises it above the tank, and pauses to allow it to drip (to limit the pollution of the other tanks while moving). It transports the carrier to the next tank in the sequence of treatments. The hoist pauses again for stabilization and lowers the carrier to lower it in the new tank. Then the hoist becomes available to perform another transfer operation. All moving times are fixed. A scheduling procedure must take them into account, because they take a significant amount of time. In fact, while moving a carrier, pauses of the hoist are not allowed except for dripping and stabilization steps whose durations are known.

Other kinds of pauses may damage the parts (e.g., oxidation of parts remaining in the air too long). In a basic line, all of the transport operations are performed by hoists. Scheduling transport tasks in such lines is well known in the literature as the hoist scheduling problem (HSP). The model often aims for a schedule that maximizes the throughput. Other criteria may also be considered, such as maximizing the load of some resources. Whatever the goal may be, it must be reached while respecting all of the constraints of the system, namely the potential constraints involved by the processing sequence, the minimal and maximal limits on processing times, the capacity of resources (tanks, hoists, and carriers), and the time a hoist needs to move empty between two successive transport operations. This problem is a no-wait no pre-emption scheduling problem. The built-in control system of the chemical line subject to this research, can optimize the handling of the carriers, such that the total completion time is minimized. The loaded carriers and their required flow number are put into the system and the system calculates the best schedule.



Crane (hoist) Tank Carrier

Figure 8: Chemical line

3.1.4 Batching problem

For this research we have to zoom out from the chemical line itself and look at the batching process in more detail. In basic terms this problem is the same as the 'baking problem' described by Sule (2007). The problem of scheduling N jobs for processing on a batching machine with capacity of C jobs at a time. Once placed on the machine, a job must be processed continuously during B time periods. A new job cannot be added to the batch while the machine is in operation. For each job the arrival date and promised delivery date are known. To find an optimal schedule, the total tardiness (the number of time units a job is delayed) should be minimized. This 'baking problem' has the following constraints:

- The number of jobs scheduled in one batch cannot exceed the capacity of the machine.
- Once a batch starts, no new jobs can be added to the batch or any existing jobs removed from the batch until the batch is completely finished.
- Each job must be processed exactly once.
- A job cannot be scheduled for processing before the day of its arrival.

3.2 Optimization

This section describes the 'baking problem' in more detail. Section 3.2.1 describes the basic heuristic to optimize a schedule with one batching machine. Section 3.2.1 describes the extended version where there can be m machines in series.

3.2.1 Baking problem

For those who are interested. the mathematical formulation of the baking problem is described in Appendix A. To solve these equations, a substantial amount of computation time is needed, even with a small problem. The number of variables and constraints increases rapidly with an increase in:

- time periods under consideration;
- number of jobs to be scheduled;
- capacity of the machine.

To solve this problem for realistic size, an heuristic procedure is proposed by Sule (2007). The following steps for the heuristic procedure have been found to be extremely efficient in solving even large size problems, according to Sule (2007):

Step1: Rank the jobs in ascending order of their arrival dates, and within each arrival date, ascending order of their promised delivery dates.

Step 2: Schedule a job that has not yet been scheduled in a batch based on the following three conditions:

1. The job arrived before the starting time of the batch.
2. The job has the earliest promised delivery date of all jobs that are eligible for scheduling in the present batch.
3. The batch is not full.

Step 3: We have the optimal solution if one of the following two conditions is valid.

1. If the total tardiness in the schedule is zero.
2. If there is some tardiness in the schedule, then each batch, except perhaps the last one, is filled to the capacity and each batch has been scheduled to start as early as possible.

If the schedule is optimal at this stage, the procedure is terminated. If not, step 4 describes the procedure to search for improvements.

Step 4: If none of the conditions from step 3 are satisfied, then it may be possible to improve the solution by delaying the start of a batch that is not completely filled. Let us define the schedule from step 3 as the basic schedule at this point. Then, check within this schedule for a delaying possibility, one batch at a time, starting from the first batch that is not full. The batch should be delayed in such a way that more jobs can be put into the batch, so delay the batch to the point in time were the next job arrives after the start of the batch in the basic schedule. Delaying the start of a batch that is not full may not necessarily fill the machine to its capacity but would fill it with more jobs than that were scheduled earlier. Repeat the following two steps until no further improvement is possible.

1. If there is a reduction in the total tardiness, use the new schedule as the basic schedule and recheck the first unfilled batch in the new schedule for delay and so on.

2. If there is no reduction in total delay, using the original basic schedule as the base, go to the next unfilled batch and examine the possibility of delaying it, and so on.

Step 5: When no further improvements (see step 4) are possible, the procedure is terminated.

The last accepted schedule is a schedule with minimal total tardiness.

3.2.2 Extended baking problem

Sule (2007) extended this 'baking problem' by adding extra processors in sequence with varying job requirements. This extended model is comparable to the situation at the chemical line and the paint shop which also have different requirements. Sule (2007) claims that under the following additional constraints this problem can still be optimized:

- All jobs are processed in one batch have the same processing time.
- All jobs have equal importance. So, every job gets the same amount of tardiness penalty when it is delayed.
- A job cannot be processed in the succeeding machine until it is released by the previous one.

The procedure is similar to that of the basic 'baking problem'. For every machine the first three steps of the heuristic can be done. When this does not results in an optimal schedule, the next step is to delay batches at the last machine, as described in step 4, until no further improvements are possible. The next step is to delay a batch at the machine before the last machine and check all the variations possible at the last machine. This procedure can be repeated until the first machine. From all generated solutions the one with the minimal total tardiness is the optimal solution.

3.2.3 Conclusions

Although the 'baking problem' contains elements that identical with our problem, there are too many problems to use the mathematical model to optimize the scheduling of orders at the chemical line and the paint shop. Some of these problems are:

- The 'baking model' does not incorporate orders that visit the first machine more than once.
- The 'baking model' does not incorporate a maximum time between two consecutive machines.
- The capacity of a carrier depends on the size of single units.
- Orders can have a higher importance that others.

Even when we overcome these problems, the size of the problem is too large to find the optimal solution in reasonable time. The rules used in the heuristic procedure may be used to improve the scheduling of orders at the chemical line and the paint shop.

3.3 Tools

This section describes the method that we use to develop a simulation model (Section 3.3.1) and a tool to measure the performances of the proposed alternatives and to evaluate the performances of these alternatives (Section 3.3.2).

3.3.1 *Development of a simulation model*

To develop a simulation model and do a simulation study Law (2007) formulates ten steps. Figure 9 summarizes these steps and shows a number of iterative steps. We used these ten steps to structure our activities. For more details about each step, we refer to Law (2007) .

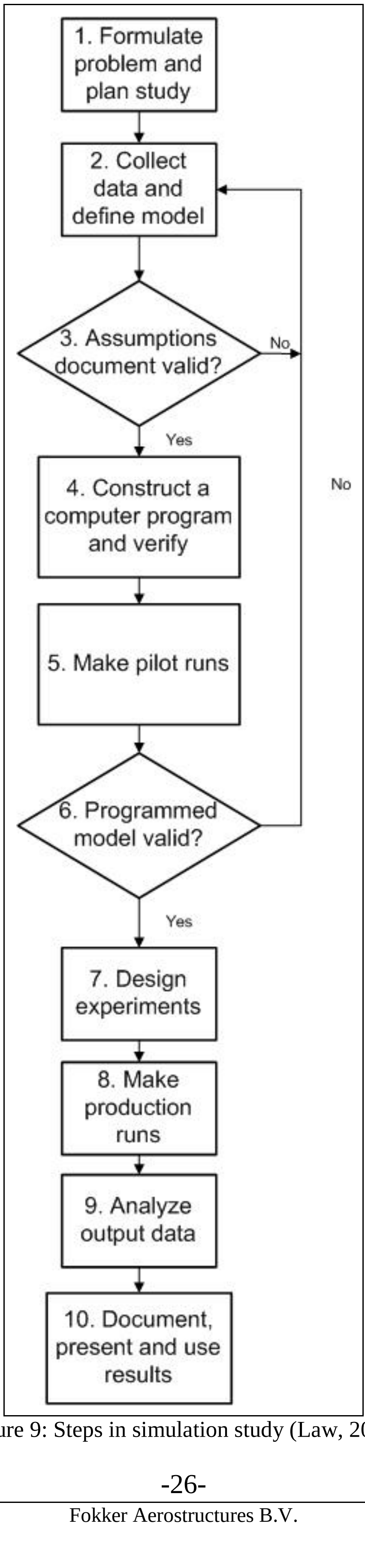


Figure 9: Steps in simulation study (Law, 2007)

3.3.2 Multi-Criteria Analysis (SMART)

During our research we develop different alternative solutions to reduce the lead time at the chemical treatment installation and the paint shop by constructing different working schedules (Chapter 4). To decide which of the alternatives is the best, we want to incorporate multiple criteria. These criteria can be quantitative or qualitative. We make use of the Simple Multi-attribute Rating Technique (SMART). In our case an attribute is called a criteria. Goodwin and Wright (1991) make the following remarks about the SMART method. *Because of the simplicity of both the responses required of the decision maker and the manner in which these responses are analyzed, SMART has been a widely applied. The analysis involved is transparent, so the method is likely to yield an enhanced understanding of the problem and be acceptable to the decision maker who is distrustful of a mathematical 'black box' approach. This, coupled with the relative speed by which the method can be applied, means that SMART has been found to be a useful vehicle for decision conferences, where groups of decision makers meet to consider a decision problem. The cost of this simplicity is that the method may not capture all the detail and complexities of the real problem. Nevertheless, in practice, the approach has been found extremely robust*.

To assign weights to the criteria and assign scores to the alternatives on every criteria, we can make use of the following methods of Goodwin and Wright (1991):

Swing weights: To assign weights to the criteria we have to take two steps. First, we have to rank the criteria. Next, we have to assign the importance weights. If importance weights are used, they should be adjusted so that the smaller the range over which the criteria is assessed, the smaller the importance weight should be. However, there is no clear evidence from research that people do take the range into account when assigning importance weights. To rank the criteria we have to imagine a hypothetical alternative with all scores on the least-preferred levels. Then the decision maker is asked to choose the criteria that is most preferred to get a score on the highest level. This process is repeated until all criteria have been ranked.

To assign the importance weight to each criterion, we simply start with assigning a weight of 100 to the most important criterion. For the second criterion, we have to compare the swing from the lowest score to the highest score of the most important criterion with the same swing for the second criteria. When this process is repeated for all criteria we simply normalize the weights by dividing each weight by the sum of all weights and multiply it with 100.

Direct rating: To score the alternatives on the criteria which cannot be represented by easily quantifiable variables, we use the direct rating method. First, we rank the alternatives from the most preferred to the least preferred. The most preferred gets a score of 100 and the least preferred a score of 0. Then we have to rate the other alternatives in such a way that the space between the values represents the strength of preference for one alternative to another. This results in an interval scale, which allows only intervals to be compared between points. Although this seems a relatively arbitrary method, it should be emphasized that the scores allocated to the alternatives do not need to be precise. The selection of the best alternative is generally robust, and it often requires quite substantial changes before another alternative is preferred.

Value functions: This method is used to assign scores on the criteria that can be represented by easily quantified variables. Again the alternatives are ranked from most preferred to least preferred. The most preferred gets a score of 100 and the least preferred a score of 0. To score the alternatives in between we make use of a linear function. It is also possible to construct another value function when this is desired. An example could be the floor space of an office. We can imagine that a floor space of $500m^2$ instead of $100m^2$ is relatively attractive for the decision maker because it considerably improves working conditions. However, an increase from $500m^2$ to $900m^2$ might be marginal and make this increase less attractive. Our linear function assumes that equal differences in performances have equal attractiveness for the problem owner.

To compare the alternatives we multiply the score on the criteria with the weight of that criteria and sum this up for every alternative. The total score is divided by 100. Now we can rank the alternatives form best to worst. To see how robust the ranking of these alternatives is, we also execute a sensitivity analysis which focuses on the assignment of weights to the different criteria (Section 6.4.2).

4 Scheduling

This chapter describes the development of alternative structures to support the sequencing of batches at the chemical line. Section 4.1 discusses the position of the scheduling process within the planning hierarchy. Section 4.2 describes the design of three alternative structures.

4.1 Planning on a higher level

In the current situation, the production planning at the chemical line is purely based on detailed production planning. The decision to do a charge of a certain flow is the responsibility of the operators. As already mentioned in Section 2.5.1, there is no general schedule or specific guidelines to decide which flow to perform on which moment of the day or week. Appendix B shows the effect of this policy. There is absolutely no standard policy to perform a certain flow (type) at a specific moment. There is also no general sequence of flow types.

The result of this research should be a general schedule that can be used as a guideline for the detailed production planning. Together with a set of decision rules the operators should be able to decide which flow to do next. When we look at the hierarchy of planning (Section 3.1) this general schedule fits best in the short term production planning. So, the objective is to bring the planning at the chemical line to a higher level in the hierarchy described in Section 3.1 and to generate specific guidelines to construct the detailed production planning during a day or week.

4.2 Scheduling

This section describes the development of different schedules for the chemical line. Section 4.2.1 describes the grouping of the different order types according to their required flow(s). Based on the characteristics of these flows, Section 4.2.2 discusses the planning of these flows on a working day. Next, Section 4.2.3 describes the development of an initial schedule. Based on this initial schedule we distinguish two types of schedules. When all flow types are performed one time during a day, it is a one-cycle schedule (Section 4.2.4). When all flow types are performed two times per day, it is called a two-cycle schedule (4.2.5). Next, Section 4.2.6 describes the construction of a fixed detailed schedule for every day of the week. Finally, Section 4.2.7 discusses the effects of these alternatives for the paint shop.

4.2.1 Order types

As stated before, the goal of this chapter is to get a general schedule for the chemical line. Due to the fluctuating amount of work, the diversity in flows, and combination of flows, we group the orders on a higher level. To group the orders on a higher level, we look at the routing characteristics of the products after the chemical treatment in more detail. As already mentioned in Section 2.3, the amount of charges per flow type is stable during the last years. To cover all orders we make the following distinctions between the flow types:

- *Anodizing orders with bleeding time*: These anodizing orders are the orders that need ‘bleeding time’ of at least eight hours. This ‘bleeding time’ is needed before a visual inspection of the parts can be done. The orders involved are all the orders that only need flow 33, so without a preceding penetrant flow, and a fraction of the orders that only need flow 6. These orders have to be painted within 24 hours after the chemical treatment. These 24 hours include the eight hours of bleeding time

- *Anodizing without bleeding time, alodine, and chromate orders*: These anodizing orders do not need ‘bleeding time’, because they already have had a penetrant inspection or only need a visual check. These anodizing orders directly go to paint shop after the chemical treatment. The alodine and chromate orders also directly go to the paint shop after their chemical treatment. As mentioned before, all these orders have to be painted within a certain amount of time, mostly 24 hours.
- *Passivation orders*: This cleaning process is needed to prepare the part for the chemical milling process. After the passivation process these parts are directly brought to the chemical milling department that is located close to the chemical line.
- *Penetrant inspection orders*: These orders need a penetrant inspection to check whether the parts are damaged. Most of the orders need an anodizing, alodine, or chromate treatment after they are approved by the penetrant operator. These orders go back to the beginning of the chemical line, where they are combined with other orders depending on their flow numbers. Some orders directly go to the paint shop after the penetrant inspection. These parts do not need a paint job but are only stamped at the paint shop.
- *Rush orders*: These orders can be of any combination of flow types. The planners marks these order with a red label or they inform the team leader when an order needs extra attention when it arrives at the chemical line.
- *Cleaning charges*: These charges are used to clean the tools of the chemical treatment installation.

With this distinction we grouped the flows with the same product routing characteristics. The chemical line can do every flow at every moment during the day but has to take into account the succeeding processes. In Section 4.2.2 we analyze the different groups. Based on this analysis, it is possible to determine the best moment of the day to perform a specific group of flows.

4.2.2 Scheduling of flow types

To get an initial schedule, this section discusses the favourable moment of the day to perform a group of orders according to the routing of these orders. A working day starts at 7:00 and ends at 24:00 for both the chemical line and the paint shop.

For the anodizing flows with bleeding time it is clear that it is most efficient when these flows are performed at the end of the day, such that the bleeding time is in the night. In this way the paint shop has almost the whole next day to finish the paint job.

As mentioned before, the orders of the anodizing flows without bleeding time, the alodine flows, and the chromate flows, directly go to the paint shop after the chemical treatment. For the efficiency in the paint shop it is better that these orders arrive close to each other, such that they can wait for more orders to make bigger batches of the same program. Products of the same program need the same paint and can be handled together by one operator. To be sure that the paint shop has enough time to finish the paint job within the time window of 24 hours, it is better that these flow are done at the beginning of the day.

For most of the penetrant flows it holds that the orders need another treatment after the items are approved during the inspection. Because these flows are labour intensive and need at least 60 minutes before the next penetrant orders can move into the line, it is not efficient to do these orders directly after each other. So, it is be better to mix these flows with flows of another type such that the line is used efficiently and the operator can handle the workload.

The passivation orders directly go to the chemical milling department. For these orders it does not matter at which moment of the day they arrive at the chemical milling department. The process time of this flow is relatively short (110 minutes). So, this flow can easily be combined with penetrant flows to use the chemical line more efficiently.

For the cleaning charges it also does not matter at which moment of the day they are done. To have enough clean tools it is important that these flows are scheduled regularly.

For the rush orders that have to be done as soon as possible it may be necessary to reserve some time. Because it is not known at which moment of the day a rush order arrives and which flow(s) it needs, the handling of these orders is discussed later.

4.2.3 Initial schedule

Now we know the different characteristics of the different flow types it is possible to develop an initial schedule. Without taking into account the different processing times and the number of flows that can be done, we propose the schedule displayed in Figure 10.

The day starts with performing all the flows that directly go to the paint shop after the chemical treatment. To start directly in the morning at a day and use the chemical line as efficient as possible, it is important to prepare 2-5 carriers at the end of the previous day. The operators can release these carriers directly in the morning. While these carriers are in the chemical line the operators can start to prepare carriers for the penetrant and passivation flows. As stated before, these can easily be mixed with each other. Between these flows it is also possible to do a cleaning flow to clean the tools of the chemical line. At the end of the day the anodizing flows with bleeding time can be done. As stated before it is best to have the bleeding time in the night, because the items have to wait for eight hours.

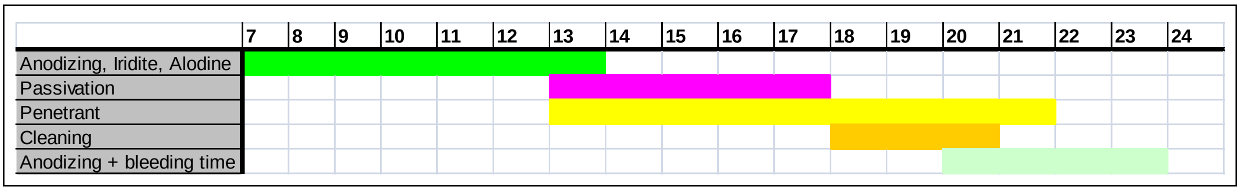


Figure 10: Initial schedule of flow types

Within this initial schedule we did not take into account the processing times of the different flows. It is only a starting point to develop a number of alternative schedules. Sections 4.2.4, 4.2.5, and 4.2.6 discuss these alternatives.

4.2.4 One-cycle schedule

Based on the initial schedule of Section 4.2.3 and the data of the different flows (see Appendix C), we are able to construct a more detailed schedule. Although the chemical line can handle multiple charges at the same time, there should be enough time between two succeeding carriers before they can enter the chemical line. The time between two charges depends on the specific process time of a flow and the tanks the carrier has to visit. To develop some alternative schedules, we set the minimal time between two charges to 60 minutes.

On a working day it is theoretically possible to process 15 or 16 flows when every hour a carrier is released into the line. Based on the average charges per day (see Appendix C), we construct a schedule where every flow type is scheduled at least once per day. Figure 11 displays this so-called one-cycle schedule. The processing time of each charge is based on an arbitrary chosen flow number of the specific flow type and is rounded up to the nearest quarter. So, the end of the process can differ from this figure. Most important is the time between two consecutive carriers. This time is needed to be sure that the carriers do not interfere with each other and the cranes have enough time to move the carriers.

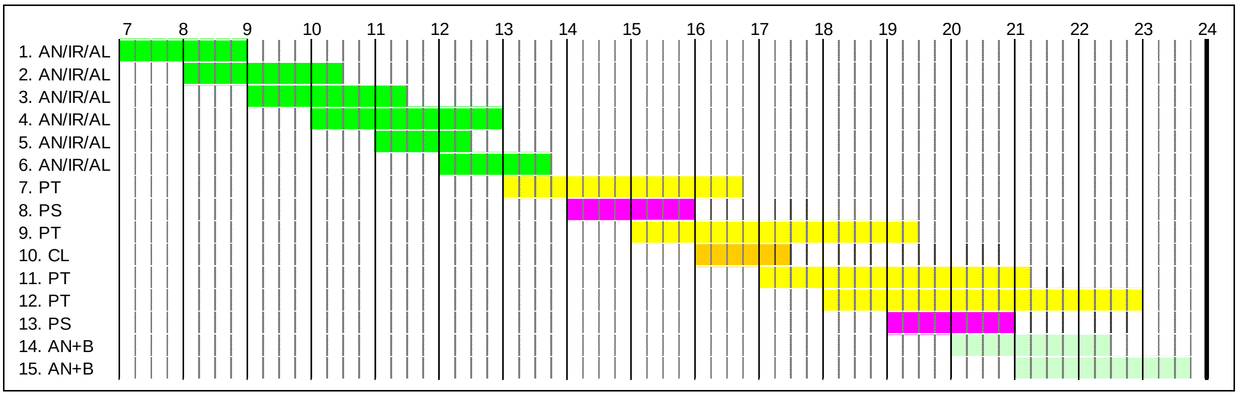


Figure 11: One-cycle schedule

This one-cycle schedule has the following advantages:

- All orders that go to the paint shop are ready before 14:00, so the paint shop can wait until 14:00 to start with the orders of a certain day. In this way it is possible to make larger batches at the paint shop. The paint job process can therefore be done more efficiently.
- The operators of the chemical line can divide the work more easily. At the end of every day they have to put the items on the carrier for the next morning. In the morning they can prepare the carriers for the penetrant, passivation, and 'bleeding time' orders. In the afternoon one operator should focus on the penetrant inspection.
- The orders with 'bleeding time' are scheduled such that the 'bleeding time' takes place during the night.

Besides these advantages, this one-cycle schedule has also some disadvantages:

- It is not possible to process an order that needs a penetrant inspection and an anti-corrosion treatment within one day. All penetrant orders are processed in the afternoon and the anti-corrosion treatments are processed in the morning.
- Although the work at the chemical line can be assigned to an operator more easily, it may be better that the activities are more spread out over the working shifts. In the one-cycle schedule, all the penetrant inspections, which are most labour intensive, are in the second working shift. The second shift should also prepare the carriers for the next morning. The first shift has to bring the orders to the paint shop and prepare the carriers for the second shift.
- When a rush order arrives, it could happen that it cannot be processed on that day, because the time window of that flow type has already past. Within this one-cycle schedule every group of flows just have one time window.
- In the current situation, the operators combine the anodizing orders that need 'bleeding time' and the orders that do not need that time, in one charge early in the morning. In this way they can transport the orders that do not need bleeding time directly to the paint shop and the other orders can wait until the afternoon. In this one-cycle schedule it is only possible to combine these orders when all the orders have to

wait until the next day. The result of this is that the paint shop has to paint all these parts within 16 hours. So, it is still possible to combine the orders but it increases the work pressure for the paint shop.

Now we know the advantages and disadvantages of this one-cycle schedule, we propose another schedule that might overcome some of the disadvantages. Section 4.2.5 describes the development of a so-called two-cycle schedule.

4.2.5 Two-cycle schedule

Another possible schedule can be constructed from this one-cycle schedule. For a more balanced workload for the two working shifts (7:00-15.30 and 15.30-24.00) and more flexible loading opportunities to handle rush orders faster, we can duplicate this cycle schedule. Figure 12 displays this two-cycle schedule. Within this two-cycle schedule, it is theoretically possible to react faster on rush orders, because the different flow types are scheduled at two different time periods within a day. We took the same number of charges per flow type to get a schedule comparable with the one-cycle schedule.

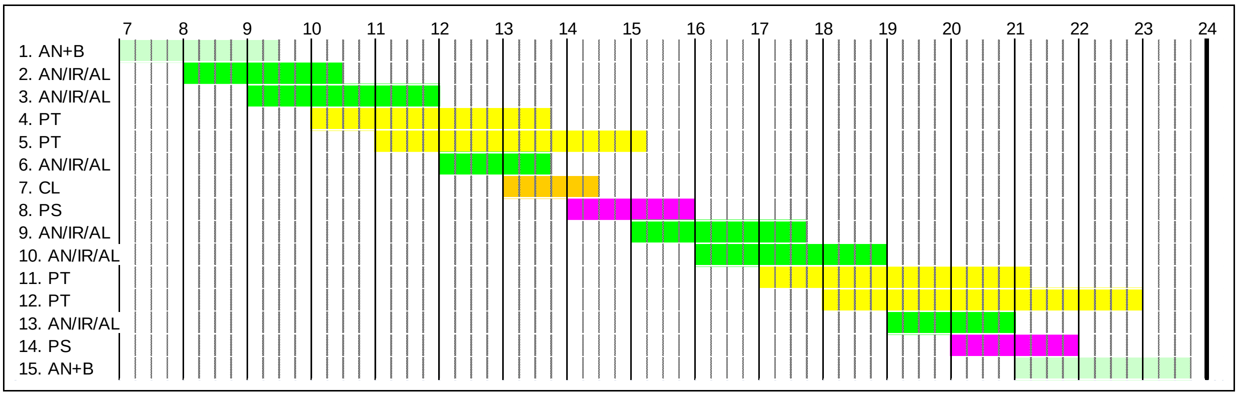


Figure 12: Two-cycle schedule

With this schedule it is possible to finish an order that needs a penetrant inspection and an anti-corrosion treatment in one day. The time between the penetrant and the next flow is short but it is possible. Another improvement is to start the day with an anodizing flow with bleeding time. This flow can combine orders with and without 'bleeding' time, without losing time for the orders without 'bleeding' time. These orders can directly go to the paint shop. So, although this schedule compensates some of the problems of the one-cycle schedule, it has some other disadvantages:

- For the paint shop, this schedule results in less efficiency, because the orders arrive spread out over the day. In the best case, they can batch the order on two moments of the day. This will be around 14:00, and between 21:00 and 22:00.
- The time windows for every group of flows are smaller, so the operators have less time to secure the items on the bar. The operators also have to switch between activities more often.

Now we have two different schedules that contain the same amount of flows in another sequence, we are able to construct a more fixed schedule. Based on historical data we know the number of charges needed to complete all the orders. To eliminate the involvement of the operators in deciding the next charge, we construct a fixed detailed planning. This means that the schedule specifies the flows for every day of the week. Section 4.2.6 describes the development of such a schedule.

4.2.6 Detailed schedule

Where the number of charges per flow type seems stable over the last three years, the number of charges per flow number varies a lot more. To construct a detailed schedule, we make use of the historical data. For a more suitable schedule for the future we may need more data on the expected number of order per flow number. For the simulation runs, we also make use of the historical data to simulate the arrival of orders at the batching zone.

We make use of the data of the average number of charges per week and per flow number. Appendix C shows the average number of charges per day and per week for each flow. In the current situation there is only one working shift at the paint shop on Friday. The chemical line processes a limited amount of work for the paint shop and uses the time to perform other activities, such as cleaning tools and processing charges on the s-line and k-line. In our detailed schedule, the Friday is also be used for other activities. We do not schedule any regular flow on the Fridays. It should be clear that the orders with high priority or orders that could not be done during the week, can be processed on Friday (morning). Flows 15 and 31 are not scheduled on a fixed moment in the week because there are simply too less orders of these flows. When an order of these flows arrives, it can be processed whenever the line is available. The other flows are scheduled over two weeks. For the sequence of the flows we use the initial schedule, as we did with the one-cycle schedule. To construct the schedule, we use the following guidelines:

- Try to keep a constant number of days between the flows. So, when a flow should be done 2 times a week it should be scheduled on Monday and Wednesday or on Tuesday and Thursday. When a flow should be done one time per week it should be done on the same day every week.
- Try to keep the number of flows per day evenly spread. So, when a flow should be done 3 or 5 times a week these flows should be scheduled on the days with the least number of already scheduled flows.

We construct a detailed schedule according to these guidelines. Figure 13 displays the result of this scheduling.

MA	DI	WO	DO	VR	MA	DI	WO	DO	VR
6	7	6	14		6	6	14	6	
14	26	32	33		29	26	32	33	
32	33	12	11		32	33	12	11	
12	35	4	4	28	12	35	4	4	28
4	4	16	16		4	4	16	16	
16	16	17	17		16	16	17	17	
17	17	36	34		17	17	36	34	
36	34	28	28		36	34	28	28	
28	28	33	6		28	28	6	33	
33	6				33	33			

Figure 13: Detailed schedule

As mentioned before, flow 15 and 31 are not scheduled on a fixed moment in the week but can be done whenever there is time available. On Friday every flow can be done. Some flows are only done one or two times per two weeks. This means that the waiting time could be more than three days. In these cases the Friday can be used to do these flows.

4.2.7 Paint shop

Within the one-cycle schedule and the detailed schedule, the paint shop can start with the actual paint job around 14:00. Before 14:00, they can finish the work of the day before, such as applying top paint, packaging, or stamping. It is more efficient for the paint shop to wait until all orders have arrived for that day so they can batch more orders of the same program. Before all orders arrive they can prepare the first parts by masking and taping them. To start the paint job as early as possible, it is better to do the orders that need a lot of masking and taping first at the chemical line.

Within the two-cycle schedule the paint shop can start their orders at 14:00 and 21:00. However, it is also possible to just start the paint job as soon as the orders arrive, since the probability that we can make larger batches is considerably less than with the other schedules.

5 Design of a simulation model

To measure the performance of the schedules from Chapter 4, we make use of a simulation model. This chapter describes the developed simulation model. Section 5.1 gives a global overview of the basic model and discusses the main assumptions. To implement the model into a simulation software package, Section 5.2 describes the process steps in more detail. Section 5.3 explains the choice of the software package to implement the model. Section 5.4 checks the validity of the simulation model based on detailed historical data. Finally, Section 5.5 describes the experimental design.

5.1 Model overview

Based on Figure 6 and Figure 7 we construct a model that includes both the chemical treatment process and the paint shop. Figure 14 shows the main flowchart of this model. The model starts with the arrival of production orders at the batching zone at the chemical installation. As mentioned before, the orders are batched according to their specified flow number(s). Figure 6 shows the detailed flowchart of this decision. After a chemical treatment, the order has three routing possibilities:

- Transport to the paint shop for a paint job.
- Move back to the front of the chemical line for the next chemical treatment.
- Move to another department (not the paint shop) for the next processing step.

The orders that are transported to the paint shop are batched according to their specified program. After the paint job, the order is reported as finished. This is the end of the modelled process. The main assumptions behind this model are:

- The processes before the batching zone are not included. The arrival of orders is based on historical data.
- The chemical line is modelled as a ‘black box’. Because the chemical line is (almost) completely automated, we assume deterministic processing times.
- An order that only needs a passivation treatment (flow 4) or a penetrant inspection is removed from the model after the chemical treatment. In reality, some of these orders come back to the chemical line for another treatment before they go to the paint shop. Since the lead time between these treatments is unpredictable, we model these orders as two separate independent orders.
- We do not take into account the probability that an order does not pass the penetrant inspection. The number of orders that is rejected is not significant and cannot be influenced by the chemical line or paint shop. Basically, these orders are covered by the orders that only need penetrant inspection, because these orders are stopped when it fails the penetrant inspection. The historical data does not show if the orders that only completed the penetrant inspection should have had another treatment

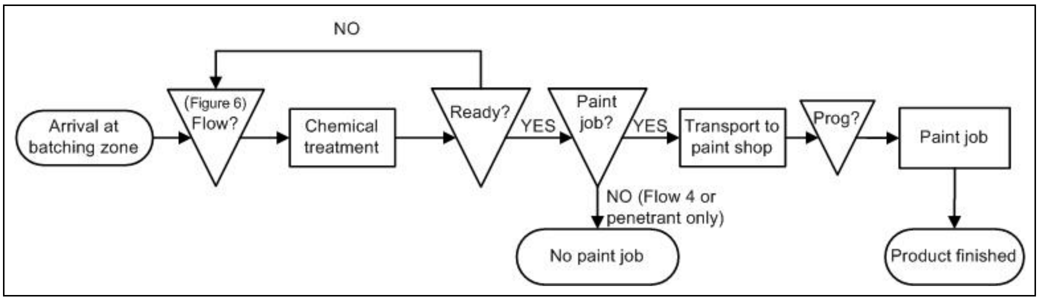


Figure 14: Model flowchart

The objective of the research is to reduce the lead time (T1), by improving the efficiency of the chemical treatment and the paint job. To evaluate the performances of the schedules we use the following key performance indicators (KPIs):

Lead time:

- Average lead time of orders in days
- Number of orders delivered to the paint shop within 3 days

Efficiency:

- Chemical line: Number of orders per charge
- Paint shop: Number of orders per batch

To analyse the effects of the schedules on these KPIs, Section 5.2 describes the processes in more detail.

5.2 Process properties

The complexity of the production system is determined by:

- The stochastic arrival process. Different numbers of orders arrive at different moments of the day. The required chemical treatment(s) are not known on beforehand.
- The batches at the paint shop are not the same as the batches at the chemical line. Both departments are more efficient when they can handle larger batches
- The choices made at the chemical line directly effects the processes at the paint shop due to the paint requirements.

To analyse the effects of the different schedules on the performance of the chemical line and the paint shop, we have to specify the processes in more detail. Table 8 shows a summary of the process characteristics. We explain these process characteristics below.

Arrival Process (stochastic)		
	3 times per day	$\mu = 15$ $\sigma = 5$
	Waiting time	75 minutes per order
Chemical line (deterministic)		
	Time between charges	1 hour
	Capacity of carrier	unlimited
	Processing time (see Appendix C)	deterministic per flow
Transport (deterministic)		
	Transport time	45 minutes
Paint shop (deterministic)		
	Processing time	4 hours

Table 8: Process characteristics

Arrival process:

- Every day, on average 45 orders arrive at the batching zone. To simulate the arrival process, we randomly pick orders from the empirical distribution (histogram), based on the historical data of the chemical line. The empirical distribution specifies the required chemical treatment flow(s) and the program of every order. The orders arrive 3 times per day, at 9:00, 13:00, and 17:00. The amount of orders is described by a

normal distribution. Based on historical data, on average $\mu = 15$ orders arrive with a standard deviation of $\sigma = 5$.
- Before the orders are ready to be put on the carrier, they wait for 75 minutes. It is not realistic that an order is put on a carrier immediately upon arrival.. The operators first have to notice the order is there and they need enough time to put it on the carrier. The same holds for orders that have had a penetrant inspection and need another treatment.

Chemical line:
- The time between two consecutive charges should be at least one hour. This is independent of the flow numbers.
- The capacity of a carrier is assumed to be unlimited. The dimensions of the items and the number of items per order can differ a lot per order. We verify the loading of the carriers with the real situation in Section 5.3.
- The processing times are assumed to be deterministic and differ per flow number.
- Based on the historical data, the average number of charges per day is almost 8. We plan 9 orders on Monday until Thursday and 3 on Friday to make a fair comparison between the schedules. Section 5.4 describes this in more detail.

Transport:
- The transport time is fixed. We assume that the orders are directly transported after the chemical treatment is finished. To include some time to get the items from the carriers, the total transport time is set to 45 minutes.

Paint shop:
- The process time of a paint job is set to four hours. We assume that from the moment the operator decides to start a certain batch, the primer is applied within four hours.
- As already mentioned in Section 2.2.4, the paint (primer) requirement for a certain product is the maximum time between the end of the chemical treatment and the moment the primer paint is applied. The top paint requirement is the maximum amount of time between the moment the primer is applied and the moment the top paint is applied.
- A new batch can start at the paint shop every hour. With schedules based on the one-cycle schedule, the paint shop starts at 14:00 to work on new batches. With the other schedules, it starts at 8:00. The paint shop does not start a new batch after 21:00.
- We assume that the paint shop can handle an unlimited amount of orders within one batch.

5.3 Implementation

According to Pritsker (1986), discrete-event simulation is a powerful technique to evaluate or analyze dynamic behaviour of complex production systems. We incorporated all properties and assumptions of Sections 5.1 and 5.2 in an event-based simulation package, named Tecnomatrix Plant Simulation. This package is especially developed for dynamic behaviour of complex production systems. Besides this, Plant Simulation has powerful visual properties. By visualizing the process flow, it is easier to understand what happens during the processes and it is easier to validate the model. For a technical description of the model, we refer to Appendix D. Section 5.4 checks whether the simulation model is a good representation of the actual process.

5.4 Validation

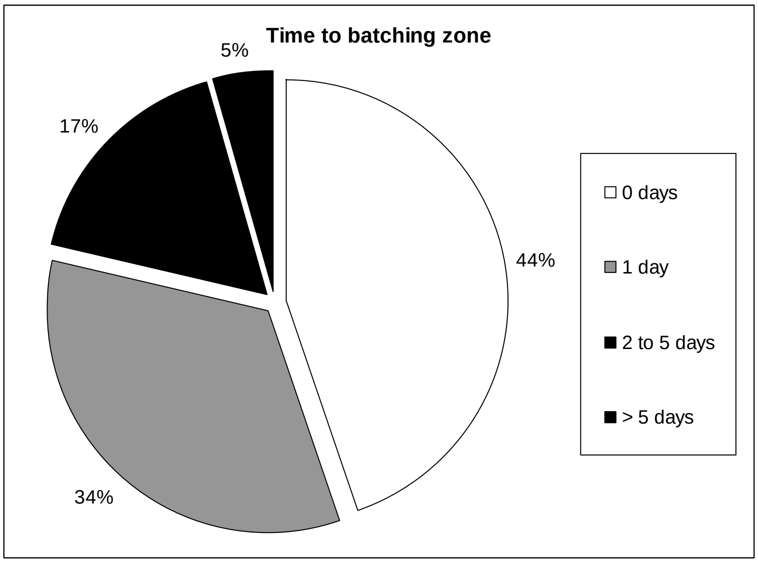
To analyse if the model is in line with the reality we have to validate the model. Law (2007) gives the following definition: *Validation is the process of determining whether the simulation model is an accurate representation of the system, for the particular objectives of the study. The idea behind validation is that if the simulation model is conceptually valid, then it can be used to make decisions about the system similar to those that would be made if it were feasible and cost-effective to experiment with the system itself*.

This chapter describes the validation process. Section 5.3.1 discusses the data of the historical lead times. Although the available data of the historical lead times is minimal and the reliability seems low, we managed to construct a good approximation. Section 5.3.2 describes the way we calibrated the simulation model with reality. Sections 5.3.3 and 5.3.4 check the validity of the model with respect to the distribution of the lead times and the number of orders on a carrier per charge. Note that randomness in the system is unavoidable, because the arrival process is stochastic. The historical data used for the input and performance measurement of the system can contain errors and is just one realisation of the stochastic process.

5.4.1 Historical data

To get more insight in the actual lead times at the chemical line, we make use of the data gathered by scanning the orders on the moment they arrive at the batching zone for about 8 weeks. In combination with the data of the orders reported as finished at the preceding process and at the end of the chemical treatment, we are able to split the lead time in two parts, namely the time between the preceding process and the arrival at the batching zone, and the actual lead time at the chemical line.

In the current situation, the measured lead times at the chemical line start from the moment the orders are reported as finished at the preceding process. This means that the time it takes to get the orders to the batching zone is also on the account of the chemical line. Graph 1 shows that 22% of the orders that arrive at the batching zone are reported as finished at the preceding process two or more days before. 5% of the orders arrive at the batching zone after more than five days.



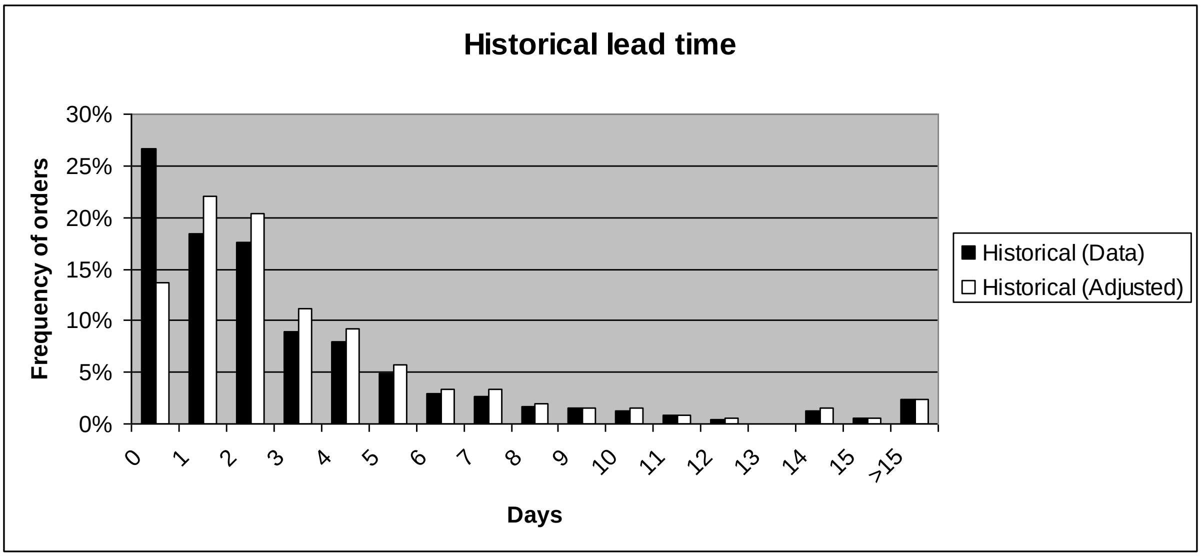
Graph 1: Lead time to batching zone

An order is on time when it is reported as finished within three days. When orders arrive at the batching zone after more than two days, these orders will never be on time. With the 22% of orders that have two or more days of delay before they arrive at the batching zone, the performance indicator of orders finished on time is not reliable. To make decisions based on this indicator becomes difficult and probably not effective.

Graph 2 shows the historical lead times. During our research, we measured the lead time in more detail by scanning all orders at the batching zone for a period of 8 weeks. The black bars show the lead times of these order during a period of 8 weeks. We see that more than 25% of the orders are finished within one day, which seems unrealistic because there are a lot of orders that need more than one treatment, that arrive later on the day, or need bleeding time. When we look at the data in more detail, we conclude that we have to make the following adjustments:

- Some orders are scrapped before they arrive at the chemical line. These are registered as finished in the system to close the order. These orders are deleted from the data.
- The orders for test panels are not scanned and get a lead time of 0 days. These are also deleted from the data.
- There is a substantial amount of orders that take a lot of time between the preceding process and the moment they arrive at the batching zone. At the chemical line these orders are reported as finished within one day. A lot of these orders have a preceding process close to the chemical line. With internal transport, these orders are gathered from the different locations and transported to the chemical line multiple times per day. It seems unrealistic that these orders need 2 or more days to get to the chemical line. We adjust the lead time of the orders in the following way. We set the time before the arrival at the batching zone to one day. The rest of the time comes on account of the chemical line.

The white bars in Graph 2 show the historical lead times after these adjustments. According to the team leaders, these adjusted lead times are more realistic.



Graph 2: Historical lead time

Although the lead times seem more realistic, the period of 8 weeks that we gathered the data is still just a snapshot of the real situation. Section 5.3.2 discusses the validation of the model with respect to the historical lead times in more detail.

5.4.2 Calibration of simulation model

As mentioned in Chapter 2, the operators at the chemical line do not have a structured way of working and the selection of the next flow is based on personal preferences, randomness, and requests from planners or program managers. While calibrating, our objective is to match the distribution of the lead times and the number of orders per carrier with the historical data. To simulate the current way of working and to mimic the historical performance, we iteratively adjust the following characteristics:

- Priority rules/batching concepts
- Number of charges per day
- The number of orders on a carrier (adding capacity restrictions)

Because we do not exactly know the current way of working, we approximate it in two ways to initiate the calibration process. The first schedule (ValHist) uses a schedule of four weeks that was performed in practice. After four weeks, it starts again with the first week. The second schedule (ValRand) randomly selects a flow number based on the historical frequencies and performs this flow with all available orders. Appendix E shows the details of these schedules.

Graph 4 shows the distribution of lead times in days for these two batching concepts. We see that the historical data show significantly more orders with a lead time of zero days. So, these orders are ready on the same day as they arrived at the chemical line. A good explanation would be that the operators select the next flow based on the orders that just arrived. Another explanation would be that there are a lot of orders that have a high priority according to planners or program managers. This seems to cause (a lot of) delay for the orders that are already waiting at the batching zone. We see substantially more orders that have a lead time of more than ten days compared with the schedules used for the validation of the model.

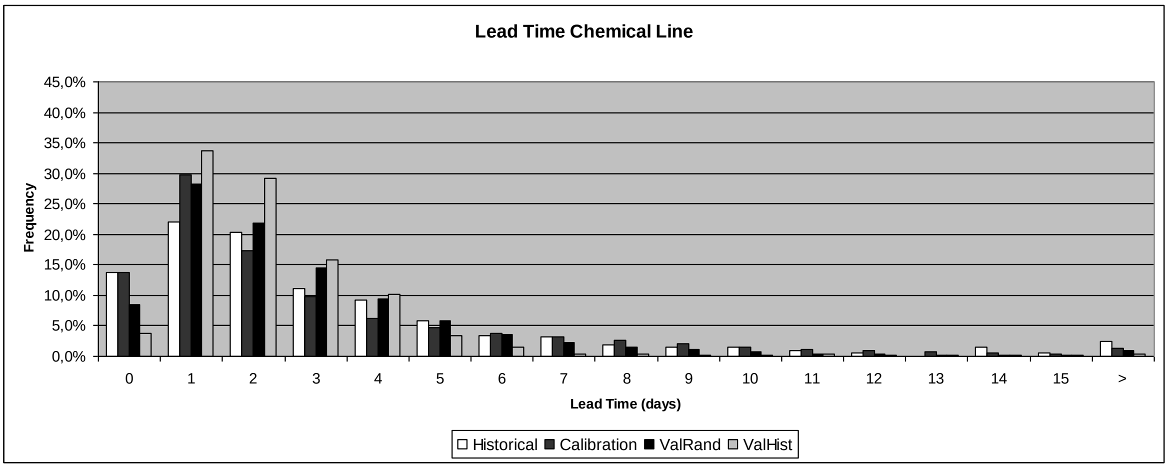
To simulate the real situation, we changed the random schedule (ValRand) in the following way:

- Iteratively add one or more extra randomly selected charges per week.
- Add one charge every two weeks that selects the order according to the FIFO concept.
- Specify a charge that, instead of doing all orders when selecting a random flow, just does 1 order.
- Instead of selecting a random flow, select the next flow based on the LIFO concept.
- When selecting a random flow number and there are more than 25 orders available of that selected flow, the model selects just a portion of these orders.

Appendix E shows the calibrated version of the ValRand schedule (Calibration), that has the results closest to the historical data. Sections 5.4.3 and 5.4.4 discuss the validity of the model with respect to the lead time at the chemical line and the number of orders per charge.

5.4.3 Lead time chemical line

With the historical schedule (ValHist), the model realized almost 83% of the orders on time, so within 3 days. With the schedule based on the empirical distribution (ValRand), the model realized 73% of the orders on time. The schedule that results from the calibration phase results in about 70% of orders on time. From the historical data, (by scanning all orders) the average percentage of orders that is finished within three days is around 67%. Graph 3 shows more details about the distribution of lead times in days.



Graph 3: Lead time distribution chemical line

Although the shapes of the distributions of the lead times are comparable with each other, the model consequently finishes more orders after one day. With the calibration schedule this is compensated with less order after two days. To check the lead time on a higher level, Table 9 shows some descriptive statistics of the lead times of all orders. We see that the historical data shows an average lead time that is higher than the three schedules and a higher standard deviation. The average lead time of the calibrated schedule (Calibration) is closer to the historical data.

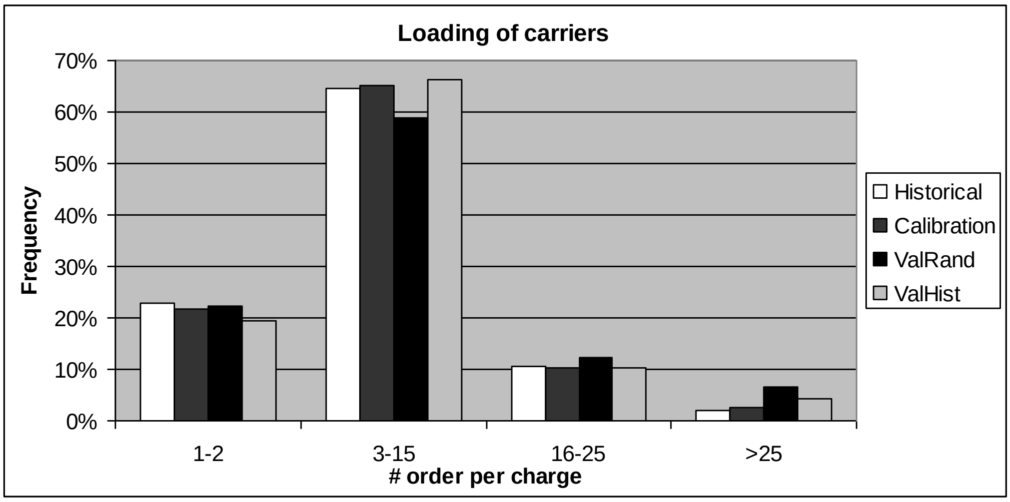
	Historical	Calibration	ValRand	ValHist
AVERAGE	3,50	3,20	2,96	2,46
STDEV	4,22	3,63	4,07	3,09
MIN	0	0	0,16	0,16
MAX	33	36	167	120
# Orders	1.255	73.939	73.615	72.736

Table 9: Lead time chemical line

We already conclude that the (unstructured) flexible way of working in the real situation has a clear negative impact on the lead time of the chemical treatment process. We see that using just a realized schedule (ValHist) results in a significant shorter lead time. Since the operators do not use standardized priority rules, it is difficult to incorporate this way of working into the simulation model.

5.4.4 Orders per charge

The distribution of the number of orders per charge is an important indicator to check the validity of the model. To validate the model, we constructed two different schedules. For one of these schedules, we take four weeks of the historical data (ValHist). For the other schedule, we let the model pick one of the flows according to the empirical distribution (ValRand). The model performs these schedules with the arrival process as described in Sections 5.1 and 5.2. Graph 4 shows the histogram constructed from a sample of more than 700 charges from the historical data and ten simulation runs. From this graph, we conclude that the simulation model is a good reflection of the reality. Although the arrival process is randomly selected from historical figures and the capacity of the carriers is unrestricted, the loading of the carriers within the simulation model are in line with the historical data. Only with the schedule based on the empirical distribution, we see that it has relatively more carriers with a high number of orders. In reality these orders have to be divided over more than one carrier.



Graph 4: Loading of carriers

Based on the results of lead times and orders per charge of the schedules used for validation, we conclude that the simulation model is a good reflection of reality and can be used to analyze the alternative schedules. Now we have checked the validity of the model, we are able to design an experiment to compare the different schedules and construct better schedules.

5.5 Experimental design

This section describes the design of the simulation experiment. Section 5.5.1 describes the experimental factors. These are the batching concepts that control the planning of the chemical line. Section 5.5.2 describes the performance indicators that are used to analyse the performance of each batching concept. Finally, Section 5.5.3 describes the length of the warm-up period, the simulation length, and the number of replications that have to be performed to get statistically valid data.

5.5.1 Batching concepts

The experimental factors of this simulation experiment are the batching concepts as incorporated in the schedules constructed in Chapter 4. The schedules constructed in Chapter 4 make use of the following batching concepts:

- First In First Out (FIFO)
- One block of charges for every flow type (OneCycle)
- Two blocks of charges for every flow type (TwoCycle)
- Fixed schedule of flow numbers (Detailed)

We now explain these concepts in more detail. To get a good benchmark, we start with a First-In-First-Out (FIFO) schedule. Without any restrictions, the model selects the flow that contains the oldest orders and the most orders. On Monday until Thursday, it selects nine flows and on Friday three flows. On average the operators perform eight charges per day. Friday is also used to perform other activities (see Section 2.2.2). With the FIFO schedule, the lead time of the orders will be close to the minimum. The percentage of orders that is delivered within three days will be close to the maximum with the capacity of nine charges on Monday until Thursday and three charges on Friday.

The one-cycle and two-cycle schedules, constructed in Sections 4.2.4 and 4.2.5, have respectively 15 and 16 moments to start a new charge. To be comparable with the FIFO schedule and to be realizable in the practical situation, the number of charges per day should be reduced. We adjust these schedules in such a way that they contain nine charges on Monday until Thursday and three charges on Friday. The number of charges per flow type is based on the historical data. The relative amount of charges per flow type is stable for the last three years (see Table 5) and should result in a robust schedule.

The detailed schedule, constructed in Section 4.2.6, contains fewer charges. When there is no flow defined, the system checks whether there is an order available for flow 15 or 31, because these are not scheduled in the detailed schedule. Based on the historical amount of work, this should be enough to complete all orders. In reality, it is possible that a charge should be split up because the number of orders does not fit on the carrier. With the detailed schedule, this is not a problem, because the schedule contains two charges less than the other schedules. This time can be used to perform an extra charge when the orders of a certain flow do not fit on one carrier. We also run the schedules used for validation during the experiment to get more data to compare with. These schedules also contain the same number of flows but more spread out over the days. For more details of the schedules, see Appendix E.

5.5.2 Performance indicators

To compare the different schedules, we report on the following main performance indicators:

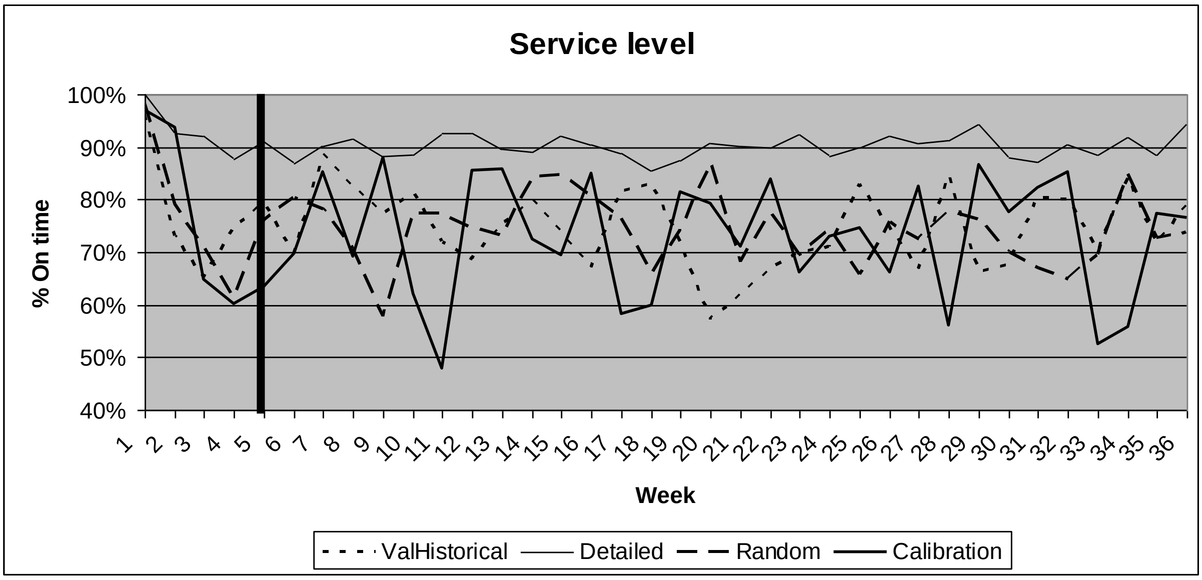
- *Lead time*: Average lead time of orders in days
- *Service level*: Average percentage of orders delivered to the paint shop on time (within 3 days)
- *Efficiency chemical line*: Average number of orders per charge
- *Efficiency paint shop*: Average number of orders per batch

For more in-depth research, we are able to extract the following data from the simulation model:

- Distribution of the lead time on the level of single orders
- Percentage of orders on time per week
- Distribution of the number of orders per charge on the level of single charges

5.5.3 Simulation setup

Warm-up period: 4 weeks. Since the simulation starts with an empty system, we need a warm-up period. When the system starts empty, the performance of the system is different when we compare this with a steady state system. For example, in the first weeks orders have relatively short waiting time since they have just arrived. To analyse when the effects of the initial empty system are not present anymore, we look at the percentage of orders that are reported as finished on time (within three days) in more detail. We use the detailed schedule, the random schedule, and the schedule based on a historical schedule to determine the warm-up period. Graph 5 shows that in the first weeks the percentage of orders finished on time declines. After three to four weeks, the percentage of orders finished on time remain within certain bounds. Since we analyze cyclic schedules of 1, 2 or 4 weeks, we use a warm-up period of 4 weeks and start the actual performance measurements in the fifth week.



Graph 5: Warm-up period

<u>*Simulation length:* 32 weeks.</u> The simulation length should be much larger than the warm-up period (Law, 2007). Here we choose for a simulation length of 32 weeks (eight times larger than the warm-up period), which is large enough.

<u>*Number of replications:* 10 runs.</u> A simulation run is one realisation. By performing multiple runs, we create different realisation of the stochastic arrival process and we are able to give reliable performance measurements. Every run uses different random numbers but the random numbers are the same for every schedule. In this way we get multiple independent experiments.

To determine the number of replications, we make use of the sequential procedure (Law, 2007). We used this procedure for the different batching concepts and the four most important criteria, namely: average percentage of orders delivered on time, average orders per charge, average orders per paint job, and average lead time in days. We take a confidence interval (1-α) of 95% and a maximum relative error (γ) of 0,05[1]. In most cases, two to five replications is enough but for some combinations of criteria and batching concepts, we need seven or eight replications. Appendix F contains an example of the sequential procedure. Since the simulation runs do not take a lot of time, we set the number of replications to ten to get enough data for a statistically valid analysis.

After performing all simulation runs, we have data available for analysis of 320 weeks for every schedule. This means 1.600 days with a total of around 72.000 unique orders for each alternative schedule. Chapter 6 discusses the results of this experiment.

5.5.4 Iterative improvements

Next to the schedules developed in Chapter 4, it is possible to construct more alternative schedules that might improve the performance. The first one is a combination of the one-cycle schedule and the detailed schedule. The flows that are performed every day or every two days are fixed in the schedule (Combi). On the other moments of the day, the system selects the flow according to the same mechanism as with the one-cycle and two-cycle schedule.

[1] Half of the 95% confidence interval may not deviate more than 5% of the average.

The next alternative schedule is also based on the one-cycle schedule. Based on a simulation run with the one-cycle schedule, we select two weeks of the realized schedule and take this as a new detailed schedule (DetImp). In this way, we automatically incorporate the relations between different flows, such as penetrant and anodizing. For more details of all schedules, see Appendix E.

6 Simulation results

In Chapter 5 we discussed the design of the simulation model. We validated the model and described the most important properties of the simulation experiment. This chapter shows the results of this simulation experiment. Section 6.1 gives the numerical results. Section 6.2 analyses the sensitivity of the performance indicators. Section 6.3 discusses the qualitative aspects of the alternative working schedules. To decide which schedule gives the best results we make use of a multi-criteria analysis (SMART). Section 6.4 describes this multi-criteria analysis. Finally, Section 6.5 gives the most important conclusions.

6.1 Quantitative results

Table 10 shows the performance scores of the different schedules on the four most important factors, namely: average percentage of orders delivered on time, average orders per charge, average orders per paint job, and average lead time in days. The reported numbers are averages of the ten simulation runs.

Schedule	Orders On Time	Orders Per Charge	Order Per Paint Job	Average Leadtime (days)
FIFO	99,9%	7,7	4,3	1,57
OneCycle	98,9%	7,7	5,9	1,67
TwoCycle	99,4%	7,7	5,4	1,67
Detailed	90,4%	8,5	6,6	1,86
DetImp	96,1%	7,9	6,1	1,73
Combi	96,4%	7,5	5,9	1,64
Historical	67,3%	8,0	Unknown	3,50
Calibration	70,8%	8,2	4,6	3,20
ValRand	73,0%	9,6	5,8	2,98
ValHist	82,9%	8,7	5,9	2,23

Table 10: Performance figures

Based on Table 10 we conclude that the developed schedules perform considerably better than the current way of working. The percentage of orders that is finished on time is considerably higher and the average lead time considerably lower.

When we look at the efficiency of both departments in more detail, we see that the number of orders per charge is slightly lower than in the current situation. With the detailed schedule we see this number is higher. With this detailed schedule the flow numbers are fixed. So, it is possible that there are no orders available of a certain flow. This means that we perform fewer charges for the same number of orders. With the improved detailed schedule this effect is lower because the schedule incorporated combinations of flows that are common. So, there is less chance that there are no orders available for a certain flow.

More interesting is the number of orders per paint job. We see significant differences between the schedules. With the FIFO schedule, the paint job can receive orders at any moment of the day and has almost no opportunities to combine orders from different charges. The difference between the one-cycle and two-cycle schedule is a good representation of the gain in efficiency for the paint shop when we deliver all the orders before 14:00 and not spread out over the day. The combination schedule (Combi) scores the same as the one-cycle schedule.

This is logical because the schedules are the same except for the most common flows, which are fixed within the combination schedule.

Table 11 shows more details about the lead time for every schedule. Because the numbers are based on the lead time of all orders of the ten runs, instead of averages of the results of ten runs, they are probably slightly different from the numbers in Table 10. Besides the huge improvement in average lead time, the standard deviation is also considerably lower, which results in a more reliable lead time.

	FIFO	OneCycle	TwoCycle	Detailed	DetImp	Combi	Historical	Calibration	ValRand	ValHist
AVERAGE	1,57	1,67	1,67	1,85	1,73	1,64	3,50	3,20	2,96	2,23
STDEV	0,73	0,83	0,80	1,17	0,95	0,89	4,22	3,66	4,07	1,62
MIN	0,16	0,16	0,18	0,16	0,16	0,16	0	0,16	0,16	0,18
MAX	3,89	4,72	4,07	12,69	10,06	4,81	33	36,26	167,39	20,88
# Orders	73.701	73.762	73.580	73.594	73.561	73.014	1.255	73.992	73.615	73.591

Table 11: Detailed figures on lead time (days)

We discuss the results in more detail in Sections 6.3 and 6.4 but first we study the sensitivity of the KPIs.

6.2 Sensitivity analysis of KPIs

The arrival of orders is based on the historical data of the product/flow mix (Section 2.3). We are interested in the sensitivity of the results when we change the arrival process. We analyse the following changes:

- Replacement of so-called 'exotic' flows. Which are flows that are only needed a couple of times per year. (Section 6.2.1)
- Change of product mix by adjusting the production level of a specific program. (Section 6.2.2)
- Stop or start of a program. During a year, a program can end or a new program can start within Fokker Aerostructures B.V. This also changes the product mix (Section 6.2.3).

The next sections discuss the most interesting effects of these changes.

6.2.1 Replace 'exotic' flows

We replace the 'exotic' flows 7, 15, 29, 31, and 35 (see Table 6) with respectively the more common flows 6, 16, 32, 32, and 12. This represents 2,17% of the total number of orders. The change shows what the impact of having flows that are only needed a couple of times per year.

Average Lead time (days)	Historical	No 'exotics'	Difference
FIFO	1,57	1,41	-10,06%
OneCycle	1,66	1,49	-10,40%
TwoCycle	1,67	1,51	-10,09%
Detailed	1,86	1,79	-3,72%
DetailedImproved	1,73	1,73	-0,37%
Combi	1,64	1,53	-6,74%

Table 12: Effect of 'exotic' flows

Table 12 shows us that when we do not have to perform charges for the unusual flows, the schedules based on the FIFO concept perform more than 10% better on average lead time.

The fixed detail schedules do not change dramatically. These schedules only skip the charges of these flows. The combination schedule shows a change in-between the other changes. This is logical because it combines the properties of the other schedules.

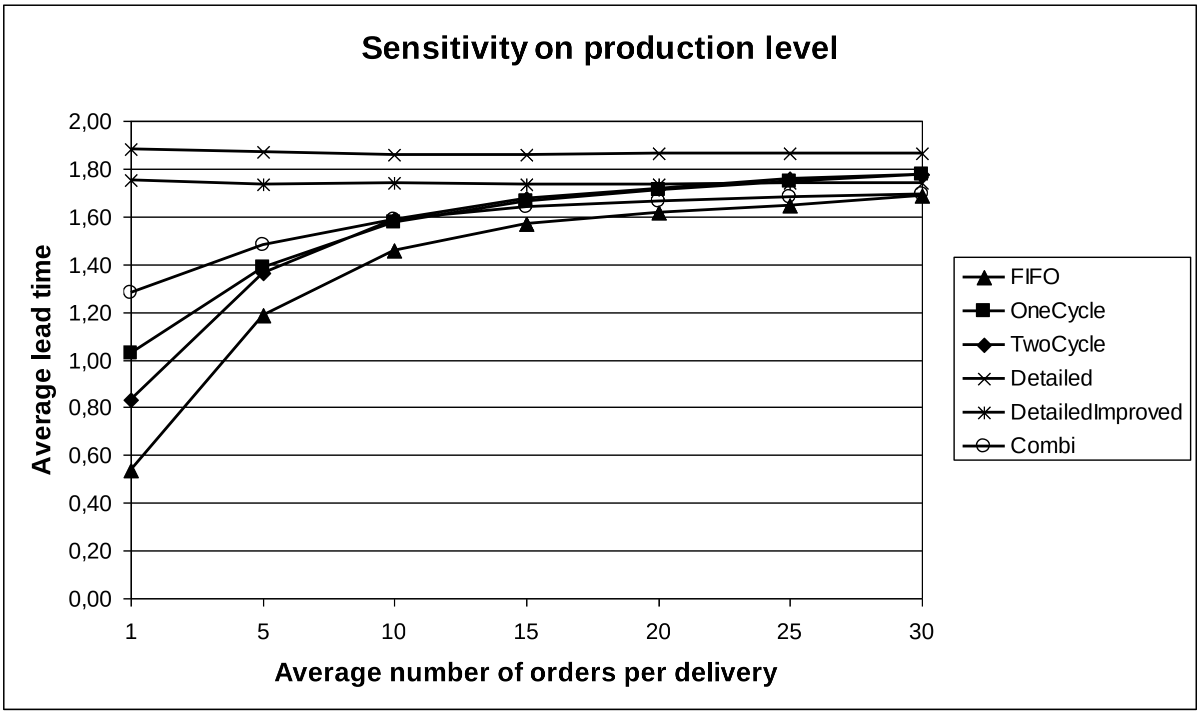
6.2.2 Change in production level

To see the effect on the service level of the amount of orders that arrive at the batching zone, we adjust the average number of orders per delivery from 1 to 30. The standard deviation remains one-third of the average. With this analysis, we still assume unlimited capacity. In reality, this assumption does not hold when there arrive too many orders. The chance that not all the orders of a certain flow can be put on one carrier becomes considerably higher. In these cases, we assume that the schedules are adjusted to get the work done. This means that we need to perform extra charges at the chemical line. Within the simulation model we assume that there is enough capacity. So, all the orders are loaded on one carrier.

Graph 7 shows us that the detailed schedules are performing relatively constant and that the schedules based on the FIFO principle are gradually performing worse. This can be clarified by the fact that, within the detailed schedule, every flow has its own fixed number of moments that it is performed. As already explained in Section 5.5.1 we use two rules for the FIFO concept, which is used in the FIFO, one-cycle, two-cycle and combination schedules. First, we check the orders that are at the batching zone for the most time. Second, when there are multiple orders from different flows, we select the flow with the most orders available. When substantially more orders arrive, the chance that there are multiple flows available becomes considerably higher. So, the second selection rule becomes more dominant. As a result, the flows with more orders are selected more often. Furthermore, the probability that the orders of the less common flows are not be finished on time becomes higher.

Graph 6: Sensitivity on production level, percentage on time

Graph 7 shows the average lead time at different production levels. Again, we see that the detailed schedules show relatively stable results but the average lead time is consequently higher. We also see that the results stabilize and move to the same level (around 1,80 days). This is probably caused by the assumption of unlimited capacity. Finally, we see that the schedules based on the FIFO-concept are performing relatively better when the production level is low.



Graph 7: Sensitivity on production level, average lead time

6.2.3 Program changes

Another realistic change in the product mix is the number of programs that are active. A program can stop when a contract is over or a new program can start when Fokker is selected as the supplier of a component of a (new) aircraft, helicopter, or space rocket. It is also possible that the production level of a certain program increases or decreases. The model is not detailed enough to show reliable results for these changes, because of the unlimited capacity of the carriers. By changing the product mix, only the number of orders per carrier per flow number will change considerably. When, on average, the same number of orders arrive, the performance indicators do not change significantly. Our simulation model will not show changes in the KPIs. To analyse the effects of a changing product mix, we have to incorporate the size of the items, the amount of items and the capacity of a carrier.

In general, we expect that the detailed schedules are less robust when these product mix changes occur then the schedules based on the FIFO-concept. Since the charges are fixed in the detailed schedules, it is only possible to react on these product mix changes by changing the schedule. The schedules based on the FIFO-concept are more robust, because they automatically select other flows when the mix of arriving orders is different.

6.3 Qualitative analysis

This section discusses the most important advantages and disadvantages of the alternative schedules besides the results with respect to the KPIs discusses earlier. We focus on the following qualitative criteria:

- *Difficulty level*: Level of difficulty to select next flow and o execute the schedule?
- *Robustness of the schedule*: How well does the schedule react on changes in the product mix and/or arrival process?

With the FIFO schedule we do not take into account any restrictions on the type of flow that is scheduled. This means that the arrival of orders at the paint shop is unpredictable and we cannot guarantee that the products are painted on time. For the operators of the chemical line, it is more difficult to decide which flow to perform next, because all options are open. This schedule is optimized to ensure the highest percentage of orders finished on time at the chemical line. Due to the unpredictable stream of orders at the paint shop and because it is questionable whether this schedule can be performed in practice, this schedule may not be the best alternative to implement but performs relatively good on average lead time and service level.

The one-cycle and two-cycle schedules divide the problem of selecting the next flow into smaller sub problems, based on the type of chemical treatment. The one-cycle schedule provides the operators for both the chemical line and the paint shop with a structured way of working. Using this schedule, there is no possibility to finish an order that needs a penetrant inspection and an anodizing treatment in one day anymore. The two-cycle schedule provides each work shift with a comparable working schedule. Using this schedule, it is still possible to finish an order that needs a penetrant flow and an anodizing flow in one day.

The two detailed schedules are completely fixed schedules, so the involved employees (operators and planners) know which flow is performed on which day and at which time. Although this kind of schedules may be easy to use, they are more sensitive for changes in the number of flows, relations between flows, and the amount of orders that are available. The detailed schedules are not able to react on changes within the arrival process. Besides this, we need a lot of historical data and a good forecast for the product mix in the future to construct a valid schedule. With the improved detailed schedule, we took a realized schedule of the simulation with the one-cycle schedule and repeat this schedule every two weeks. In this way the relations between flows and the number of charges per flow are automatically incorporated in the detailed schedule.

With the combination schedule we combined the properties of the FIFO concept and the detailed schedules. We only fixed the most common flow numbers to be sure that these flows are performed on a regular base. The other ‘free’ charges are filled according to the same rules as the one-cycle schedule. So, it selects the flow with the oldest and most orders. This combination schedule results in a shorter average lead time and a higher percentage of orders finished on time than the detailed schedules. The combination schedule is easier to use than the schedules based on the FIFO concept, because there are less decision moments. However, the combination schedules is less capable to react on changes in the arrival process.

In the next section the advantages and disadvantages are used to score the alternative schedules. We make use of the multi-criteria analysis described in Section 3.3.2.

6.4 Multi-criteria analysis (SMART)

To determine which schedule is the best to use in the practical environment, we analyse the performances of the schedules. Besides the four key performance indicators that can be measured within the simulation model, we need to incorporate the qualitative criteria, introduced in Section 6.3. The first one is the robustness of the schedule. A schedule is better when it is able to react on (small) changes in the product mix and still shows good performances. The second qualitative criteria is the level of difficulty to execute the schedule. The process of selecting the next flow should be as easy as possible. This depends on the possible number of flows that can be selected on a certain moment of the day and the administration that is needed to make these choices. So, to select the best batching concept we score the schedules on the following criteria:

- Robustness of the schedule
- Difficulty level
- Average percentage of orders finished on time
- Average number of orders per charge
- Average number of order per paint job
- Average lead time in days

6.4.1 Scores and weights

We use the Simple Multi-Attribute Rating Technique (SMART) method (Section 3.3.2) to select the best alternative schedule. To determine the scores of the schedules on the KPIs, we take a scale of 0 to 100 and use a linear value function (Section 3.3.2). For the KPIs, we give the worst alternative 0 points and the best alternative 100. The other alternatives get a score between 0 and 100, based on the measured performances from the simulation runs.

We use the direct rating method (Section 3.3.2) to assign score to the qualitative criteria robustness and flexibility. We rank the alternatives from best preferred to least preferred. The best alternative gets 100 points and the worst gets 0 points. The other alternatives get 20, 40, 60, or 80 points. It is not possible to use a linear scale for these criteria, so we simply use the rank of the schedules. When two or more alternatives have the same rank, we add the scores and divide this by the number of equal alternatives; they therefore get the same amount of points.

To determine the weights of the criteria, we use the 'swing weights' method (Section 3.3.2). As mentioned in Section 3.3.2 this method contains two stages. Bases on the swing weights method we ranked the criteria in the following way:

1. Average percentage of orders finished on time
2. Average lead time in days
3. Average number of order per paint job
4. Robustness of the schedule
5. Average number of orders per charge
6. Level of difficulty

The second step of the 'swing weights' method is to assign the weights to the criteria. Table 13 shows the weight as they are constructed with the problem owners at Fokker. To normalize the score, we divide the weight of every criteria with the sum of all weights and multiply this with 100. Table 13 shows the final weights of the criteria

Schedule (Rank)	*Robusteness*	*Difficulty*	*% On time*	*Orders per charge*	*Order per paint job*	*Average leadtime*	*Aggregate value*
Swing weights	*65*	*20*	*100*	*45*	*65*	*80*	*375*
Normalized weights	*17*	*5*	*27*	*12*	*17*	*21*	*100*
FIFO (2)	100	0	100	3	0	100	65,7
OneCycle (1)	70	40	89	16	72	65	66,1
TwoCycle (3)	70	20	95	15	49	65	62,8
Detailed (6)	0	90	0	100	100	0	34,1
DetailedImproved (5)	20	90	60	34	79	43	51,2
Combi (4)	40	60	63	0	70	75	55,2

Table 13: Scores and weights on the criteria

Table 13 shows an overview of the scores, weights, and ranks. The last column shows the normalized total score. Based on this result, we conclude that the one-cycle schedule is the best alternative and the detailed schedule is the worst alternative.

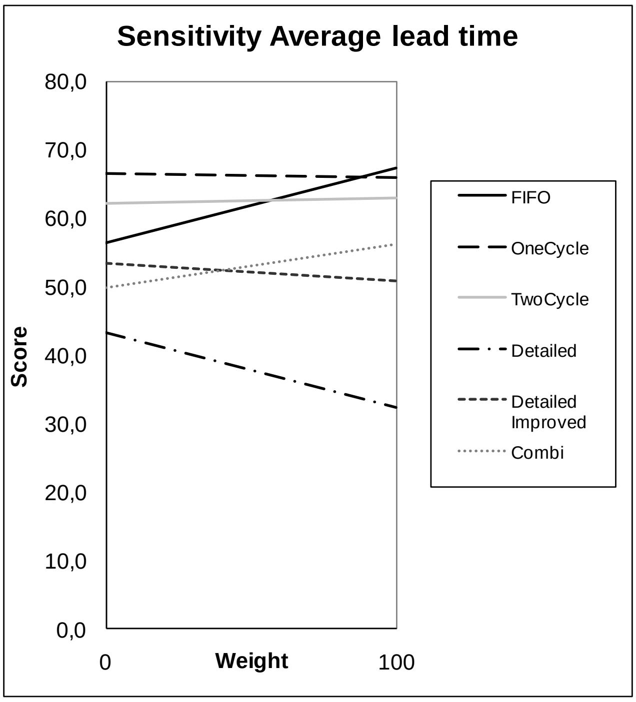
6.4.2 Sensitivity analysis of weights

To get more insight in the robustness of the total scores, we do a sensitivity analysis. The idea behind the sensitivity analysis is to get more insight in the influence of the assigned weights. Because the weight assigned to a KPI can differ depending on the view of the researcher or the management, we have to analyse whether we would make another decision if the weights are different. To do this, we successively change the weight of every criteria from 0 to 100 (within the 'swing weights' phase), while keeping the other weights the same. We display the changes of the total scores in a graph. To get more insight in this sensitivity analysis, Graph 8 provides the scores of the different schedules when we change the weight of the KPI average lead time. When we look to the graph we see three different patterns of the scores of the schedules:

Stable: The score can stay at (almost) the same level. This means that the weight of the KPI hardly influences the total score of this alternative. Graph 8 shows that this is the case for the one-cycle and two-cycle schedule.

Increasing: The score can increase when the KPI gets more weight. This means that increasing the weight of the KPI results in a higher score of this alternative relatively to the other alternatives. Graph 8 shows that the FIFO schedule and the combination schedule both get higher scores when the weight of average lead time increases.

Decreasing: The score can decrease when a KPI gets more weight. This means that increasing the weight of the KPI results is a lower score of this alternative relatively to the other alternatives. Graph 8 shows that the improved detailed schedule and the detailed schedule both get lower scores when the weight of average lead time increases.



Graph 8: MCA sensitivity analysis, average lead time

Because all of these three patterns can occur, it is possible that the ranking of the alternatives change. As an example, Graph 8 shows that when the weight of the KPI average lead time is higher than 90 the FIFO schedule scores better than the one-cycle schedule.

Appendix G shows the same graphs for the other KPIs. Based on these graphs, we conclude that the assignment of different weights does not influence our selection of the best alternative. For all KPIs it hold that the one-cycle schedule remains the best alternative or becomes the second best option. When it becomes the second best option the FIFO schedule becomes the best option. We advice to use the one-cycle schedule.

6.5 Conclusions

Now we have more insight in the performances of the schedules and the robustness of the multi-criteria analysis, we make the following conclusions:

- Using a fixed way of working, according to one of the schedules, results in a substantially better performance with respect to on lead times and service levels.
- Based on the SMART-analysis we conclude that the one-cycle schedule is the best schedule to be used in practice.
- The FIFO concept, which is used to decide which flow to perform next, is essential from better performances.
- The ‘exotic’ flows have a disturbing effect.
- While using a schedule based on the FIFO concept, the second selection rule becomes (too) dominant when the production substantially increases and we need extra charges to finish all the orders of a particular flow.
- When the production level substantially increases, the average lead time of the schedules come close to each other.

Before implementing one of the schedules, Chapter 7 discusses the most important implementation issues.

7 Implementation

Chapter 6 concluded that the one-cycle schedule is the best alternative to test in practice. Whether this test is positive or negative, there are a number of implementation issues that have to be addressed before implementing one of the alternative schedules. This chapter discusses the most important implementation issues. Section 7.1 describes the basic requirement of the organization of the new situation. Section 7.2 describes the way we do a pilot of one week to test the one-cycle schedule and discusses the results of this pilot. Finally, Section 7.3 describes how the batching concept of the one-cycle schedule can be maintained for the future.

7.1 Organization

This section describes the basic requirements of the organization for the new situation. The most important aspect is the implementation of the FIFO concept (Section 7.1.1) that is used to decide which flow to perform next. Whether the one-cycle schedule becomes the new way of working or not, the ability to know how many orders are in the batching zone and for how long they are there, is essential knowledge to improve the performances at the chemical line. To be able to perform the one-cycle schedule, we need a certain amount of operators that can perform specific tasks (Section 7.1.2). Finally, we give simple decision rules and objectives that the operators can apply in their work (Section 7.1.3).

7.1.1 FIFO concept

To implement a FIFO system, the most important change is to get more insight in the work in progress (WIP) at the batching zone. We have to know how many orders are available per flow and for how long each order is already there. There are different possibilities to do this:

- Scanning all orders and registering flow numbers. The current system cannot do this; therefore, we need an additional application.
- Use coloured labels on the production orders to indicate the day that an order arrives at the batching zone and use some kind of display (e.g. an abacus) to indicate how many orders of a certain flow are available.
- Register every order by hand on a whiteboard.

7.1.2 Workforce planning

To operate the chemical line and use the one-cycle schedule, we assume that the minimal workforce should be:

- 7:00-15:30: 1 operator to unload and transport the early carriers and to perform penetrant inspection and 1 operator to load the penetrant carriers for the late shift and to unload and transport the last carriers of the early shift (before 14:00).
- 15:30-24:00: 1 operator to perform penetrant inspection and to load carriers for the next day and 1 operator to load penetrant carriers and to prepare the carriers for the next day.

Next to these 4 operators, we need 1 operator for a whole week to perform magnaflux inspection. This amount of 5 operators is the absolute minimal number of operators needed to execute the one-cycle schedule. With 5 operators, we cannot perform the schedule when somebody takes a day off or one of the operators gets ill. Therefore we advice to have one extra operator. To be more flexible, it is recommended that this operator is allowed to do penetrant inspections. Table 14 shows the basic workforce planning for the chemical line.

7 8 9 10 11 12 13 14 15	16 17 18 19 20 21 22 23 24
unloading + penetrant	penetrant + loading
loading + unloading	loading + other activities
Magnaflux	penetrant + loading + other activities

Table 14: Basic workforce planning chemical line

For the paint shop we estimate the following minimal workforce:

- 7:00-15:30: 1 operator to package and stamp the finished orders and to mask the items that have just arrived and 1 operator to finish the paint job of the day before and to fill in the production orders that are finished (registration of layer thickness, material codes of the used primer paint and top paint, and time stamps).
- 15:30-24:00: 2 operators to perform the paint job of the orders that arrived that day, and 1 operator than can (un)mask the items and package and stamp the orders that are finished.

These 4 operators are the absolute minimum number of operators needed to execute the one-cycle schedule. Although the painters can perform the other activities such as masking, stamping, and packaging and it is sometime possible to divide the work to the next shift, we recommend that there is one additional operator available to assist the painters in the shift from 15:30-24:00. It might be better to have a 'in-between' shift from 11:00 to 19:30, such that all orders of the day before can be stamped and packaged and all orders can be masked for the 2 painters in the late shift. Besides these regular activities, an operator needs time to solve problems, such as: incomplete production orders, missing drawings and missing tools. Table 15 shows the basic workforce planning of the paint shop.

7 8 9 10 11 12 13 14 15	16 17 18 19 20 21 22 23 24
packaging/stamping + (un)masking	applying primer (+ top paint)
applying top paint + fill in production orders	applying primer (+ top paint)
	packaging/stamping + (un)masking

Table 15: Basic workforce planning paint shop

7.1.3 Decision rules

Besides the workforce planning, it is important to instruct the operators and give them clear decision rules to decide which flow to perform next. The decision process is summarized as follows:

1. Look for the orders that are longest in the batching zone and select the flows where these order belong to.
2. Count the number of orders of the selected flows and select the flow with the most orders.

To clarify these rules we provide a small example. Suppose we have the simple system of 5 flows that directly go to the paint shop (anodize/iridite/alodine) and 2 penetrant flows. Table 16 shows the system status on Tuesday around 15:00. Suppose we have to perform a penetrant flow. First, we select the flows that contain the oldest orders. Flows 16 and 17 both contain orders from Friday. So, we select flows 16 and 17. Because flow 17 contains 9 orders and flow 16 only 7 orders, we select flow 17.

Anodize/Iridite/Alodine						
Flow	Friday	Monday	Tuesday	Wednesday	Thursday	Friday
6	~~IIII~~					
12	II	III	III			
26		II				
32	II	I	II			
33		III	III			
Penetrant						
Flow	Friday	Monday	Tuesday	Wednesday	Thursday	Friday
16	IIII	I	II			
17	I	~~IIII~~	III			

Table 16: System status Tuesday 15:00

After the penetrant inspection is started, the system status is updated. At 22:00 we have to select a flow that directly goes to the paint shop. Table 17 shows the system status at that time. We see that the orders of flow 17 are moved to flow 32 and 33. It is important that these orders are registered on the day that they arrived at the batching zone. Again, we select the flows with the oldest orders. Based on Table 17, we select flows 6, 12, 32, and 33. Since flow 32 contains the most orders, we select flow 32. This process is repeated on every moment a new charge can be started.

Anodize/Iridite/Alodine						
Flow	Friday	Monday	Tuesday	Wednesday	Thursday	Friday
6	~~IIII~~					
12	II	III	III			
26		II				
32	II	~~IIII~~ I	III			
33	I	III	~~IIII~~			
Penetrant						
Flow	Friday	Monday	Tuesday	Wednesday	Thursday	Friday
16	IIII	I	II			
17						

Table 17: System status Tuesday 22:00

Next to these decision rules, we constructed simple objectives for the operators of the chemical line according to the one-cycle schedule:

Early shift:
- Unload the carrier with anodizing orders with bleeding time and deliver them to the paint shop.
- Perform, unload and deliver 4 charges to the paint shop before 14:00.
- Perform 1 penetrant inspection.
- Make sure that there is 1 charge available for penetrant inspection for the late shift.

Late shift:
- (Load) and perform 2 charges of penetrant inspections.
- Load and perform 1 charge with passivation orders.
- Load and perform 1 anodizing order (with bleeding time).
- Load 4 carriers for the early shift.
- Make sure that there is 1 charge available for penetrant inspection for the early shift.

When these objectives are completed within each shift, the performances significantly increase.

7.2 Pilot one-cycle schedule

Before implementing the one-cycle schedule, we do a pilot of one week. During this pilot, we want to have answers to the following questions:

- Can the schedule be performed by the operators of both the chemical line and the paint shop?
- Do we encounter any problems that have to be solved before implementing the one-cycle schedule?
- What are the most important disturbing factors?

During the pilot we manually registered all the incoming work and also the orders that are processed. Table 18 shows the realized schedule. We do not discuss all the details of this realized schedule but we make the following remarks:

- The early shift did not meet the objective to perform and deliver 4 charges before 14:00.
- Most of the charges are performed according to the schedule and 4 charges are performed that were not on the schedule.

1-Cycle															
Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Monday	7	6	14	23	34				16		17		4	28	6
Tuesday	32	X	X	33	36				X		X	4	4	28	6
Wednesday	27	X	X	X	16	16			36		36		4	32	33
Thursday	33	33	26	X	X				16		17		X		33
Friday	33	**4**	34	28			33								

Table 18: Realized schedule during pilot

That we were not able to perform all the charges specified by the one-cycle schedule, is the result of different disturbing factors. The most important disturbing factors that became clear during the pilot are:

- Low and changing workforce during the day and week
- Iridite flows and one anodizing flow were not allowed because the involved tanks failed the tests to check the chemical
- Wrong production orders
- Broken tools

After we evaluated the pilot with the team leaders and production leaders we make the following conclusions:

- During the pilot we did not delivered the maximal amount of work to the paint shop. According to the one-cycle schedule this should be one anodizing charge with bleeding time (directly in the morning) and 4 charges before 14:00.
- The workforce is small and the capabilities are not always matched with the schedule. For example, there is not always an operator available that is allowed to do the penetrant inspection.
- The one-cycle provides the operators with a clear working plan.

- During the pilot the operators worked on the right orders. This means the orders that are in the batching zone for the most time.
- The administration of incoming orders and to keep track of the WIP is time consuming.
- The operators of the paint shop are positive, because they know when they can expect new orders.
- The operators of the paint shop had the idea that they got too less work during the pilot but the chemical line had a relatively high output.

After this pilot we decided to stick to the schedule as much as possible. Before the chemical department and the paint shop can get full advantage of the schedule, we extracted three main objectives for the next months:

1. Match the workforce with the requirements of the schedule.
    a. The number of operators
    b. The capabilities of the operators
2. Reorganize the batching zone.
    a. Label the orders with coloured labels for each day of the week
    b. Clearly visualize the WIP
3. Perform a time study at the chemical line and the paint shop
    a. Look for the most important disturbing effects and eliminate them
    b. Analyse the workforce requirement of the schedule in more detail

When these objectives are achieved, we have to be able to react on (significant) changes in the product mix or production level. Section 7.3 gives practical guidelines to maintain a schedule.

7.3 Practical guidelines for (re)scheduling

To be able to react on changes in the product mix, we recommend that the performances of the chemical line are reported more explicitly. During our research, we encountered some problems with the available data. This section discusses the monitoring of the lead time in the current situation and how it can be done in the new situation.

The way the lead time is measured in the current situation is not convenient. Because the lead time of the chemical line starts from the moment the orders are reported as finished at the preceding department, the waiting time at the batching zone is unknown. To make the indicator more reliable, there are two options. First, it is possible to start measuring the lead time from the moment the orders arrive at the batching zone. The time it takes to get the order to the batching zone should be on account of the preceding process, or else, this time is not registered at all. In this case, it is required that all orders are scanned when they arrive at the batching zone. The second and better option is to reduce the time between the two processes. The objective should be to reduce this time to at most one day. To measure the performances on lead time at the chemical line, we can simply take one day as transport time.

Although this seems a good alternative, the data we retrieved from the systems seems still unreliable due to all kinds of exceptions. It is easy to see whether the chemical line is performing well or not, by using the template shown in Tables 16 and 17. Based on the simulation model, we can guarantee (without unexpected disturbing events) a lead time of 4 days. So, when an order is in the batching zone for five day or more, something is not going well. When this occurs, this can basically have two reasons:

- The long waiting time is a result of not achieving the objectives.
- The objectives are achieved but there is still too much waiting time.

When the long waiting time is a result of not achieving the objectives from the schedule (see section 7.1.3), this is not a scheduling problem. Not achieving the objective can be the result of many events, like not enough operators or a failure of the chemical line, but the schedule does not have to be changed. When the product mix changes too much, it may happen that the recommended one-cycle schedule is not capable to finish all the work within 4 days. Since we only used 9 of the 16 possible charges (see Section 4.2.4), we can change the schedule easily. When this is not workable anymore or results in other problems, there are some other alternatives:

- Start working at the chemical line earlier to create extra time to perform charges for the paint shop. This directly increases the capacity of the chemical line to finish more charges before 14:00.
- Start working at the paint shop later. This makes it possible that the deadline of 14:00 can be set later on the day which creates extra time for the chemical line.
- Perform a charge for the paint shop at the end of the day. The paint shop can start this job directly in the morning. To avoid unnecessary batches at the paint shop the operators need extra knowledge about the orders that are performed the next morning.

Figure 15 shows the decision tree that is applicable to the monitoring of waiting time at the batching zone. It is a schematic overview of the decision process as described in this section.

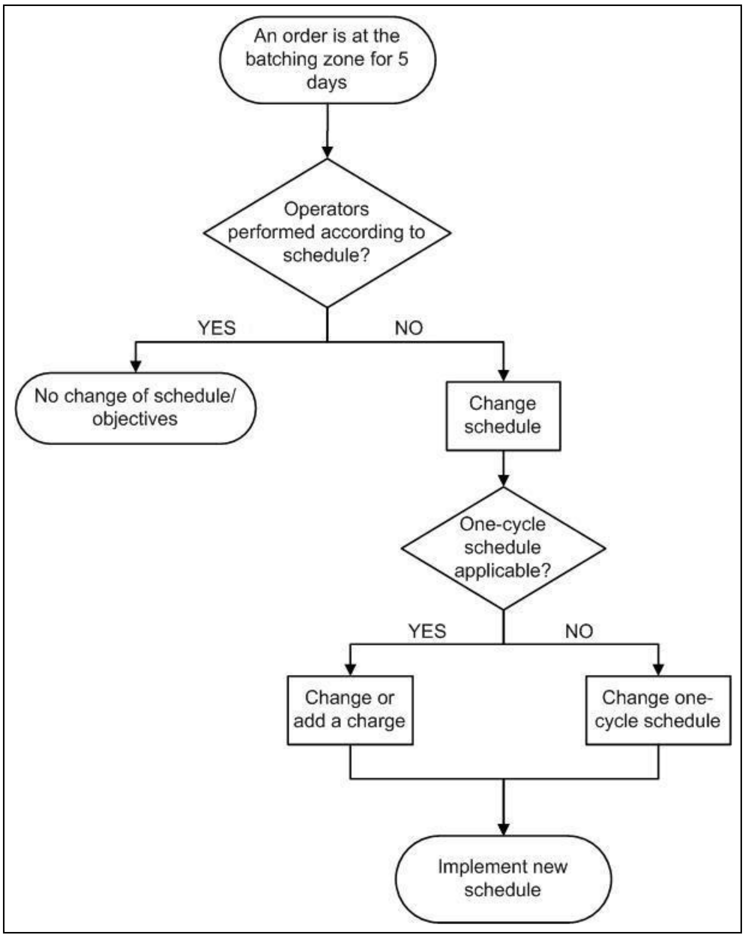


Figure 15: Decision tree

After we did the pilot with the one-cycle schedule, we have a good indication of the actions that has to be taken to take full advantage of the schedule. Chapter 8 summarizes the main conclusions and gives recommendations for further research.

8 Conclusions & recommendations

In this thesis we analysed the current situation to find opportunities to improve the control the chemical treatment installation and paint shop at Fokker Structures B.V. and to reduce the lead time of orders that need a chemical treatment and (mostly) a paint job. The research started with a description of the current situation and a literature study. Subsequently, we developed different schedules that can be used to manage the chemical treatment installation. To compare the alternative schedules, we designed a simulation model. The results of the simulation runs are analysed according to the SMART method. Finally, we proposed a solution and did a pilot to discover the main implementation issues. This chapter discusses the main conclusions from our research, by giving answers to the research questions (Section 8.1) and gives the main actions to be taken to successfully implement the proposed solution and a number of recommendations for further research (Section 8.2).

8.1 Conclusions

This section discusses the main conclusions of our research. Sections 8.1.1. presents the main conclusions based on our analysis of the current situation and the available literature. Next, Section 8.1.2 discusses the main conclusions based on the analysis of the results of the simulation experiment. Finally, Section 8.1.3 presents the main conclusions of the pilot of one week with the one-cycle schedule.

8.1.1 Literature study

After our analysis of the current situation and the literature study, we concluded the following with respect to the current situation:

- To reduce the lead time of the production orders that need a chemical treatment and (mostly) a paint job, we have to reduce the waiting time at the batching zone at the chemical line.
- It is (hardly) impossible to construct a fixed detailed schedule that is robust enough to handle the diversified and changing product mix and the fluctuating arrival process.
- The limited amount of literature that is available suggests a mathematical model (’baking problem’) to optimize the scheduling of orders at the chemical line and the paint shop.
- It is not possible to find a optimal solution for the problem, due to the extra complexity of the practical situation and the long computation time.
- To get a robust schedule that results in significant better performances, we have to plan on a higher hierarchical level.
- Instead of a fixed detailed schedule, we can cut the problem into smaller problems by scheduling on the level of flow types, because the relative amount of orders that needs a certain type of chemical treatment is almost constant during the past three years (Section 2.3).

8.1.2 Simulation experiment

To develop alternative schedules, we introduced the FIFO concept. Selecting orders based on the time that they are in the batching zone, is crucial to reduce the waiting time at the batching zone, which directly reduces the total lead time of the production orders. Next to the FIFO concept, we cut the problem in smaller problems by scheduling the flow types on specific time windows during the day and week. By putting these alternative schedules in our model and doing a simulation experiment, we get quantifiable performance measurements and we were able to compare the different schedules with each other and with the current situation. Based on the analysis of the performances of the developed alternative solutions during our simulation experiment, we conclude the following:

- The implementation of one of the developed schedules results in a significant increase in performances:
    - *Service level*: increases from 65% - 70% to 90% - 99%.
    - *Average lead time:* decreases from 3.5 days to 1.5 - 2 days.
    - *Reliability of lead time*: standard deviation of the lead time decreases from 4 days to 1 day.
- The increase in performances can be achieved without decreasing the efficiency at the chemical line, which is still around 8 orders per charge.
- With the one-cycle schedule the operators at the paint shop are able to paint more orders in the same batch, so the efficiency increases.
- The one-cycle schedule is the most promising schedule that should be tested in practice.

8.1.3 Pilot

To test whether the results within our model are representative for the practical situation, we did a pilot for one week with the one-cycle schedule. Based on this pilot we conclude that:

- The one-cycle schedule is workable for the chemical department and the paint shop.
- There are too many disturbing factors that prevents the operators to structurally achieve the working objectives of the one-cycle schedule.
- There is enough involvement of production leaders, team leaders and operators to successfully implement a new way of working.
- Applying the FIFO concept by visualizing the WIP at the batching zone should provide the operators with enough information to work on the orders that are in the batching zone for the most time.
- The operators at the paint shop can work in a much more structured way and they have more knowledge about the moments of the day they can expect new orders.

Besides these main conclusion, we recommend a number of actions to be taken in the near future to successfully implement the one-cycle schedule. Section 8.2 discusses these recommendations and suggest a number of improvements of the simulation model that probably results in further improvements at the chemical line and the paint shop.

8.2 Recommendations

After the analysis of the different schedules, we selected the one-cycle schedule as the best alternative to be implemented. We have tested this schedule during a pilot of one week. After evaluation of this pilot, we recommend the following actions to be taken in the coming weeks or months:

- Match the workforce with the requirements of the schedule.
    - The number of operators
    - The capabilities of the operators
- Reorganize the batching zone.
    - Label the orders with coloured labels for each day of the week
    - Clearly visualize the WIP
- Perform a time study at the chemical line and the paint shop
    - Look for the most important disturbing effects and eliminate them
    - Analyse the workforce requirements of the schedule in more detail

Next to these practical actions, there is also the opportunity to improve the simulation model. By putting more details into the model, we would be able to do a more sophisticated analysis of changes within the arrival process and the product mix. The main improvement that could be made is to introduce detailed information about the loading of the carriers in at the chemical installation. We need additional information about the size of the products, the number of products per order, and the loading capacities of the carriers and the different tools. For the objectives of this research, this detailed information was not necessary (Section 5.4). With more insight in the loading of carriers, the schedules can probably be improved or the loading of the carriers could be optimized. This results in a further increase of the efficiency at the chemical line.

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Appendices

Appendix A: "Baking" Problem

Integer programming formulation of the 'baking problem'

Notation:

N: Total number of jobs to be scheduled.

T: Total number of time periods for which the schedule is to be developed (planning horizon).

D_i: The due delivery time for job *i*.

J_i: The arrival time of job *i*.

C: Capacity of the machine.

B: Number of time periods each batch must be processed.

X_{it}: The state of job *i* in the time period *t*,

= 1 if baking for job *i* starts at time *t*.

= 0 otherwise.

A_{it}: Delay in delivery for job *i*, if it begins processing at time t (days).

Objective function: minimize the total tardiness penalty:

$$MIN \sum_{t=1}^{T} \sum_{i=1}^{N} A_{it} * X_{it}$$

With $A_{it} = t + B - D_i$

Constraints:

Processing requirements:

$$\sum_{t=J_i}^{T} X_{it} = 1 \qquad \text{for } i = 1,2,\ldots,N$$

Capacity constraints:

$$\sum_{i=1}^{N} X_{it} + C * y_t <= C \qquad \text{for } t = 1,2,\ldots,T$$

With $y_t = 0$ or 1

Continuous processing time:

$$\sum_{t=g}^{t+B} y_t - B * Z_{1,g} - (B-1) * Z_{2,g} = 0 \qquad \text{for } g = 1,2,\ldots,T$$

With $Z_{1,g} + Z_{2,g} = 1$

Appendix B: Realized schedule

M	D	W	D	V	M	D	W	D	V	M	D	W	D	V	M	D	W	D	V	M	D	W	D	V
Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow	Flow
PT	AN	PS	AN	PT	AN	PT	AN	AN		AN	AN	IR	AN	PS	AN	AN	AN	AN	AN	AN	PT	PT	PT	PT
AN	AL	PT	PT	AN	PS	AN	PT	AN		IR	PT	PT	AN	PS	PT	PT	AN	AN	PT	PS	PT	AN	28	PT
AN	PS	AN	AN	AN	IR	PT	AN	IR		IR	PT	PT	PT	PT	AN	PT	PS	AN		IR	AN	PT	PT	AN
	PT	PS	AN	PT	PT	AN	AN	PT		AN	PS	AN	AN	AN	AN	PT	PT	PT		PT	PT	IR	IR	PT
	IR	PT	AN	AN	PS		PT	AL		AN	PS	PS	IR	IR	PT	AN	PT	AN		AN	AL	PT	AN	
	AN	AN			PT		PT	PS		PT	28	AN	PS		28	AN	AN	PS		AN	28	AN	AN	
	PS	PT			PS		AN	28		PT	PS	AN	28		28		PT	IR		AN	AN	PS		
	AN	AL			AN			PT		IR		AN	28		AN		AL	PT			AN			
	AN	AN						AN		AN		AN	AN		PT		PT	IR						
								PT		AN			AN		AN									
								AN					AL		AN									

Table A: Snapshot of a realized schedule

Appendix C: Charges

Flow	Flow Type	Deterministic Process time (min)	# charges	Average charges / day	Average charges / week
4	PS	110,0	77	0,83	4,14
			77	0,83	
6	AN	140,5	50	0,54	2,69
7	AN	108,5	12	0,13	0,65
14	AN	161,0	32	0,34	1,72
26	AN	171,5	21	0,23	1,13
29	AN	163,0	8	0,09	0,43
31	AN	146,0	2	0,02	0,11
32	AN	156,0	41	0,44	2,20
33	AN	150,5	79	0,85	4,25
			245	2,63	
11	AL	113,5	15	0,16	0,81
			15	0,16	
12	IR	91,0	38	0,41	2,04
35	IR	86,0	19	0,20	1,02
			57	0,61	
15	PT	260,0	4	0,04	0,22
16	PT	289,0	79	0,85	4,25
17	PT	246,0	67	0,72	3,60
34	PT	219,0	36	0,39	1,94
36	PT	244,5	35	0,38	1,88
			221	2,38	
6	AN+B	140,5	25	0,27	1,34
33	AN+B	150,5	50	0,54	2,69
			75	0,81	
28	CLEAN	86,5	93	1,00	5,00
			93	1,00	
Totals			783	8,42	

Table B: Historical number of charges and process times

Appendix D: Simulation model

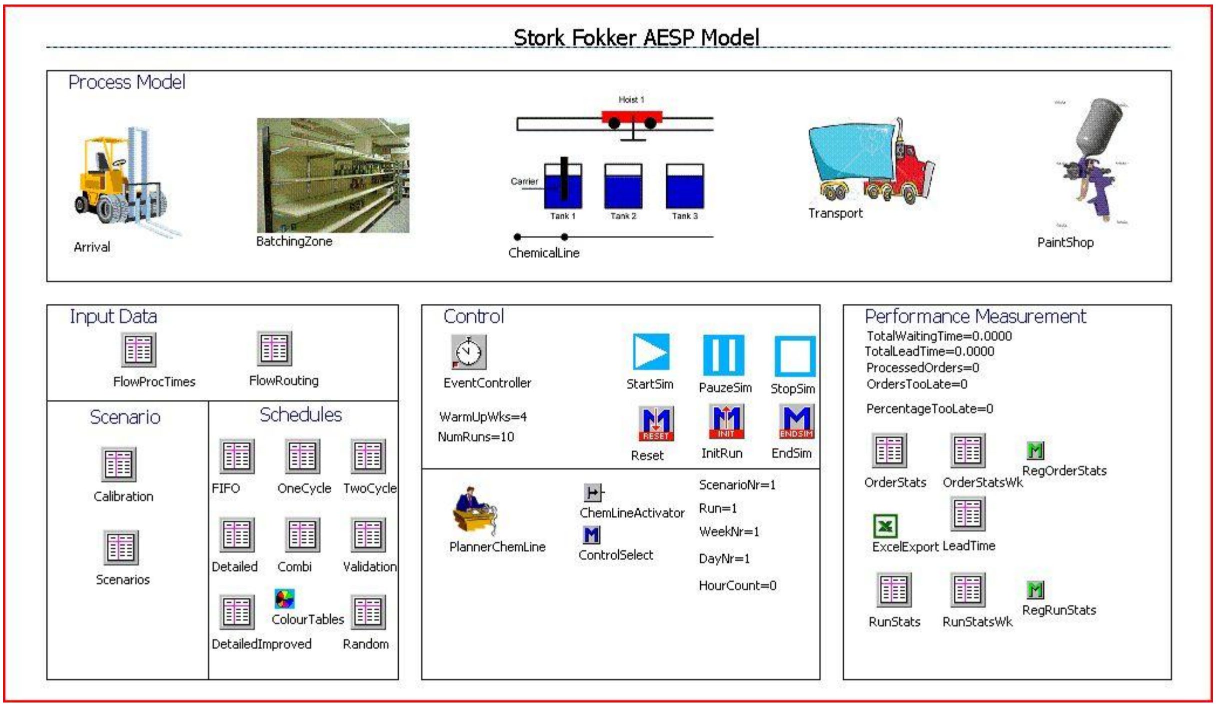


Figure A: Capture of simulation model

Figure A shows a capture of the simulation model within Tecnomatrix Plant Simulation. This section explains the most important elements of the model.

Input Data: The first element is located in the left lower corner of the model, the input data. Besides the processing times of the flows and the historical product mix the different schedules are defined in this section.

Control Panel: In the middle of the model we see the control panel. Besides the standard event controller we see the planning module. PlannerChemLine selects the right schedule and contains the control methods that select the right orders. It also registers the performed flows and all the other statistics of the chemical line like orders per charge and the number of charges per flow.

Performance Measurement: In this section we measure the most important statistics. We register the following data:

- The lead time of every order in whole days and in exact numbers
- The number of processed orders per week and the number of processed order that are too late
- Summary of the key performance indicators as selected in Section 5.4.2
- The percentage of orders finished on time for every week

Process Model: The model of the actual process is located at the top of Figure A. We describe the different elements of the process in more detail from left to right.

Arrival process

The model starts with the arrival of orders. Based on the historical data, an average of 45 orders arrive per day with a standard deviation of 15 orders. An order has the following attributes:

- OrderNumber: An order number is assigned to every order that arrives starting with 1
- Program: This specifies the program. At the paint shop this attribute is important to batch the orders before painting
- ProgramCode: A short notation of the program name
- Flow1: The first chemical treatment the order needs.
- Flow2: The second chemical treatment the order needs. 0 = not applicable.
- Flow3: The third chemical treatment the order needs. 0 = not applicable
- NextFlow: The chemical treatment that is needed next.
- BleedingTime: Does he order need eight hours of bleeding time? True or false
- CreationDay: The day the order arrived at the chemical line
- ArrivalTime: The time the order arrives at the batching zone. This is the moment the waiting time starts. This time is needed to calculate the total waiting time at the batching zone.
- LeadTime: The lead time from the moment that the orders arrives at the batching zone for the first time, until it arrives at the paint shop.
- WaitingTimeBZ: The amount of time the orders waited in the batching zone

After the orders are created they arrive at the batching zone after one hour. The batching zone contains a buffer for every flow. The orders are put in the buffer according to their required flow. The number of orders that are present in each buffer are displayed next to each buffer. For every program the icon of the order has a different colour. Within the batching zone it is easy to see how many orders are present in the buffer and the programs involved.

Chemical line and transport

The chemical line is the object where the chemical processes are simulated. From the moment the carrier is released to the first tank the process is controlled by the chemical installation and the process time is deterministic depending on the flow number. For this simulation model the chemical line is simulated by a black box. It can handle more than one flow at the same time. It takes at least an hour before the next carrier can enter the chemical line after the last one entered the chemical line.

When a chemical process is done, the order should be checked whether it needs another treatment before forwarding. When an order only needs a penetrant inspection or a passivation treatment, it is reported as finished and is deleted from the model. The same hold for the orders that fail the penetrant inspection. When the order need another treatment it is sent back to the batching zone and is put in the buffer of its next flow. When an order completed all treatments it is transported to the paint shop. The transportation time is set to 45 minutes.

Paint shop

At the paint shop there is a buffer for every program. When the orders arrive at the batching zone they are put into the buffer of its program. The paint job processor can handle an unlimited amount of orders of the same program at the same time. While the batch before is in the oven he operator can start with the next batch. This is possible after an hour. Within this hour the operator can apply the first layer of primer on the preceding batch, put the parts of the new batch on the table, and get the right paint from the inventory. For case of simplicity we assume that the masking and taping activities are done before the paint job starts. In reality the operators can start with the order that do not need a lot of masking or taping. The other operators can do the masking and taping while the paint job of another batch is done.

The processing time of the paint job is set to four hours. In this time it is possible to apply the primer coating on every order from the moment the paint job starts. We assume that the orders that need a top coat can be handled within the time windows. The other activities, such as stamping and packaging, are assumed to be done whenever there is time to do it and an operator is available.

Appendix E: Schedules

Validation Historical

Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	33	32	6	4		4		17	7		33	16			331
2	12	36	33	12		17		14	16						331
3	31	32	6	33		16			16						61
4	33	14	4	26		14		36	17		16	36			61
5	4	33	34	16											
6	34	14	33	11		36		17						61	331
7	6	12	33	17		17		6	16						331
8	16	4	32	32		17		14	12						
9	4	33	34	4		33		14	7		29				
10	34	26	36	16		17		35	16						
11	12	17	33	6				32	14		4	16			331
12	6	32	4	34		36		17	33			16			61
13	12	32	33	32		4		11			33	36			61
14	36	4	17	4		35		33	16						331
15	14	32	17	16											
16	17	16	33	6		4		32	29		33				331
17	34	17	26	14		7		4	33		12				331
18	12	16		36		6		32							
19	6	34	35	17		14		4	16		33	32			61
20	33	34	17												

Validation Random

Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	1	1		1		1		1		1		1		1
2	1	1	1		1		1		1		1		1		1
3	1	1	1		1		1		1		1		1		1
4	1	1	1		1		1		1		1		1		1
5	1	1	1												

Calibration

Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	3	4	3		3	0	2		2		3		3	3	3
2	3	4	3		3	0	2		2		2		3	3	3
3	3	4	3		2	0	2		2		3		3	3	3
4	3	4	3	3	2	0	2		2		3		3		3
5	3	4	3												
6	3	4	3		3		2		2		3		3	3	3
7	3	4	3		3		2		2		2		3	3	3
8	3	4	3		2		2		2		3		3	1	3
9	3	4	3	3	2		2		2		3		3		3
10	3	4	3												

1 = FIFO 3 = Randomly selected, all orders
2 = LIFO 4 = Randomly selected, 1 or 2 orders

1-Cycle

Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Maandag	1	1	1	1	2				2		2		3		4
Dinsdag	1	1	1	1	2				2		2		3		4
Woensdag	1	1	1	1	2				2		2		3		4
Donderdag	1	1	1	1	2				2		2		3		4
Vrijdag	1	1	2												

2-Cycle

Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1	1	2	3			2		1		1		2		4
2	1	1	2	3			2		1		1		2		4
3	1	1	2	3			2		1		1		2		4
4	1	1	2	3			2		1		1		2		4
5	1	1	2												

Detailed

Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	6	14	32	12			16		17		36		4		331
2	7	26	33	35			16		17		34		4		61
3	6	32	12				16		17		36		4		331
4	14	33	11				16		17		34		4		61
5															
6	6	29	32	12			16		17		36		4		331
7	6	26	33	35			16		17		34		4		331
8	14	32	12				16		17		36		4		61
9	6	33	11				16		17		34		4		331
10															

Detailed improved

Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	33	11	12	26			16		17		36		4		331
2	14	6	32	33			16		34		17		4		61
3	29	7	26	12			36		16		17		4		331
4	32	33	35	6			16		34		17		4		61
5	14	31	36												
6	33	11	26	7			16		17		36		4		331
7	33	32	12	6			34		16		17		4		61
8	14	35	33	7			36		34		17		4		331
9	35	6	33	12			16		36		17		4		61
10	26	32	16												

Combi

Day/Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	6	32	1	1			16		17		36		4		331
2	33	1	1	1			16		17		34		4		61
3	6	32	1	1			16		17		36		4		331
4	33	1	1	1			16		17		34		4		61
5	1	1	2												
6	6	32	1	1			16		17		36		4		331
7	6	33	1	1			16		17		34		4		331
8	32	1	1	1			16		17		36		4		61
9	6	33	1	1			16		17		34		4		331
10	1	1	2												

Appendix F: Sequential procedure

For the sequential procedure we are looking for the number of runs that is enough to have enough data to do an analysis that is statistically valid. The number of runs is enough when:

$$\frac{\delta(n,\gamma)}{Average} \leq \gamma'$$

With:

Delta = $\delta(n,\gamma) = t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}$

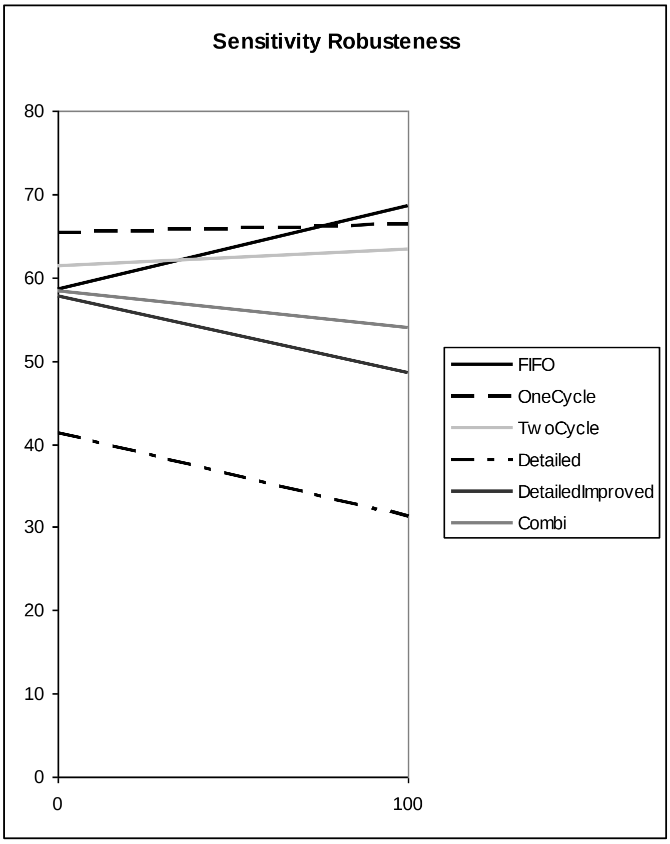
relative error = $\gamma' = \frac{\gamma}{1+\gamma}$

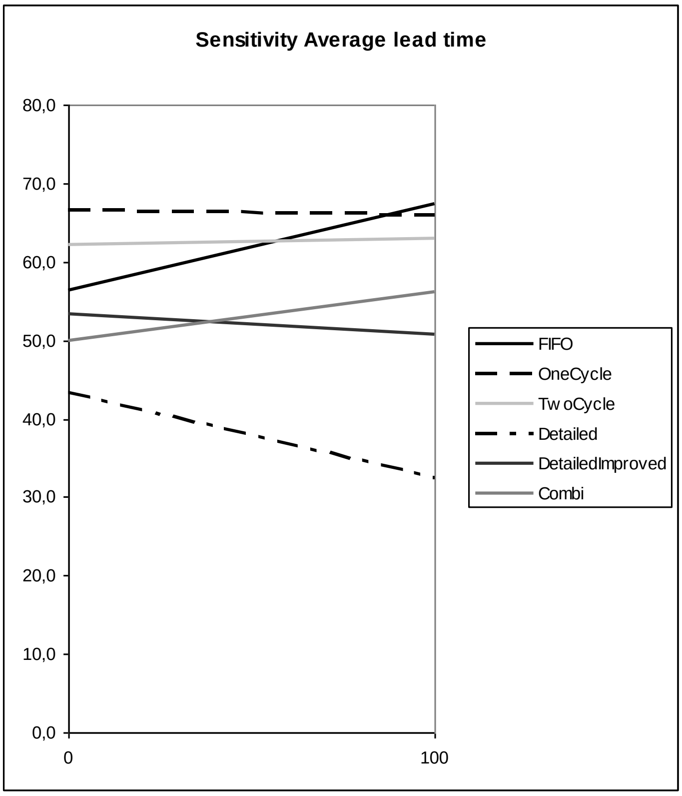
Table C shows an example of the sequential procedure for the KPI average lead time with the calibration schedule. We see that for this KPI and schedule we need at least 7 runs to have statistically valid data.

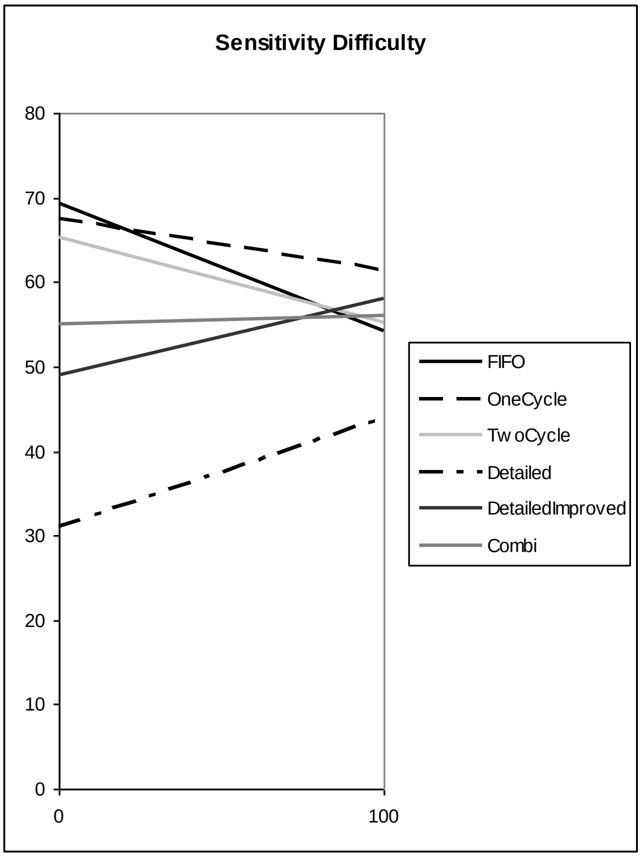
		Average Lead time				
N	**KPI**	Average	StDev	Delta	Error	Runs
1	**3,334204**	3,334204	0	0	0	NOT OK
2	**2,942946**	3,138575	0,276661	2,485698	0,791983	NOT OK
3	**3,214604**	3,163918	0,200493	0,498052	0,157416	NOT OK
4	**3,205061**	3,174204	0,164989	0,262535	0,082709	NOT OK
5	**3,029258**	3,145215	0,156901	0,194818	0,061941	NOT OK
6	**2,990035**	3,119351	0,153973	0,161585	0,051801	NOT OK
7	**3,14443**	3,122934	0,140877	0,13029	0,04172	OK
8	**3,253514**	3,139257	0,138357	0,115669	0,036846	OK
9	**3,321769**	3,159536	0,143007	0,109925	0,034791	OK
10	**3,559876**	3,19957	0,184948	0,132304	0,041351	OK

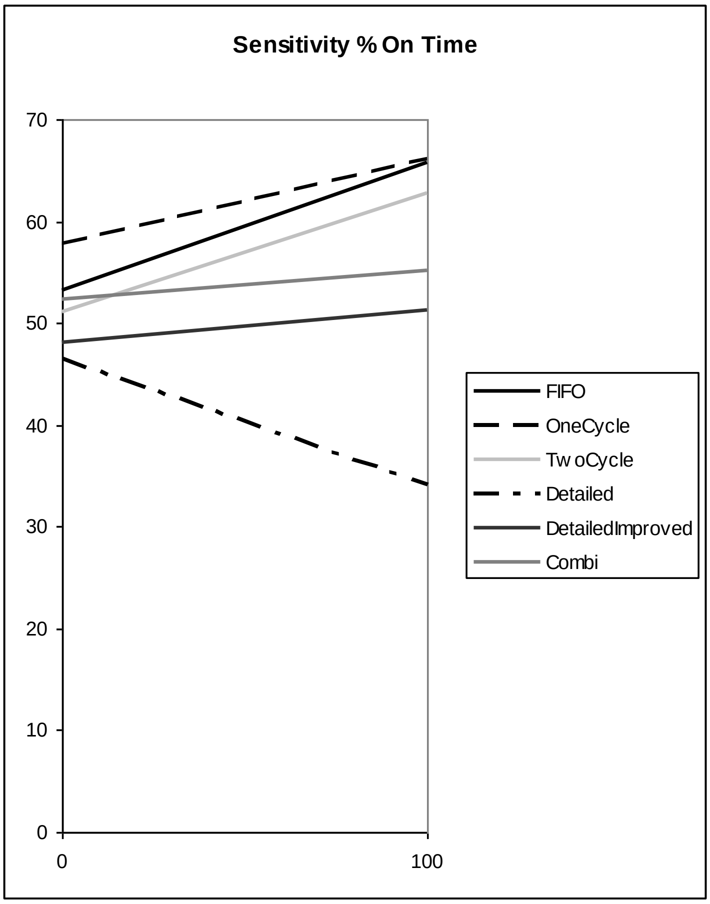
Table C: sequential procedure

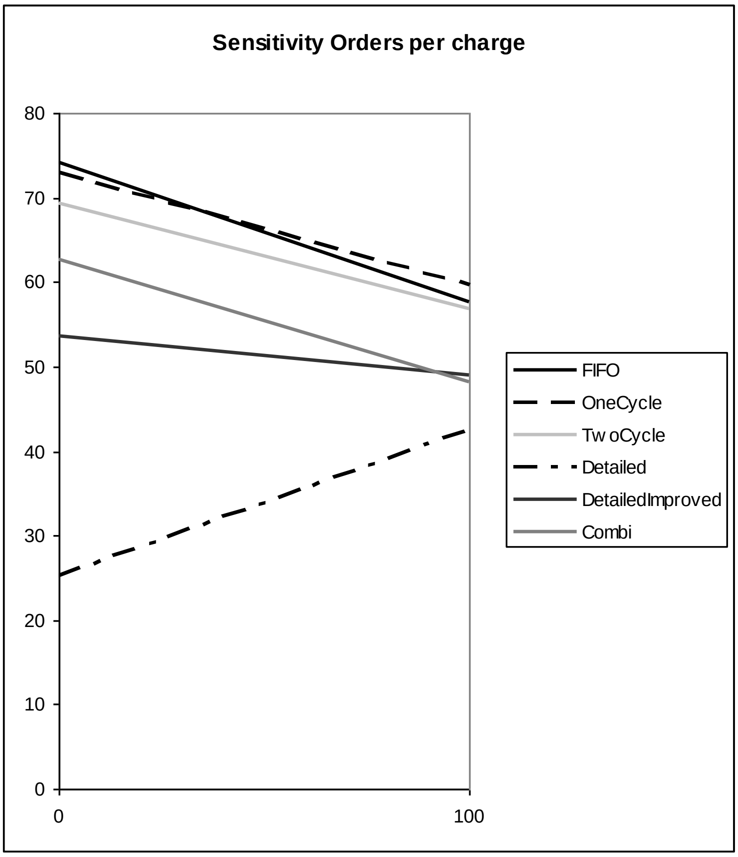
Appendix G: SMART sensitivity analysis

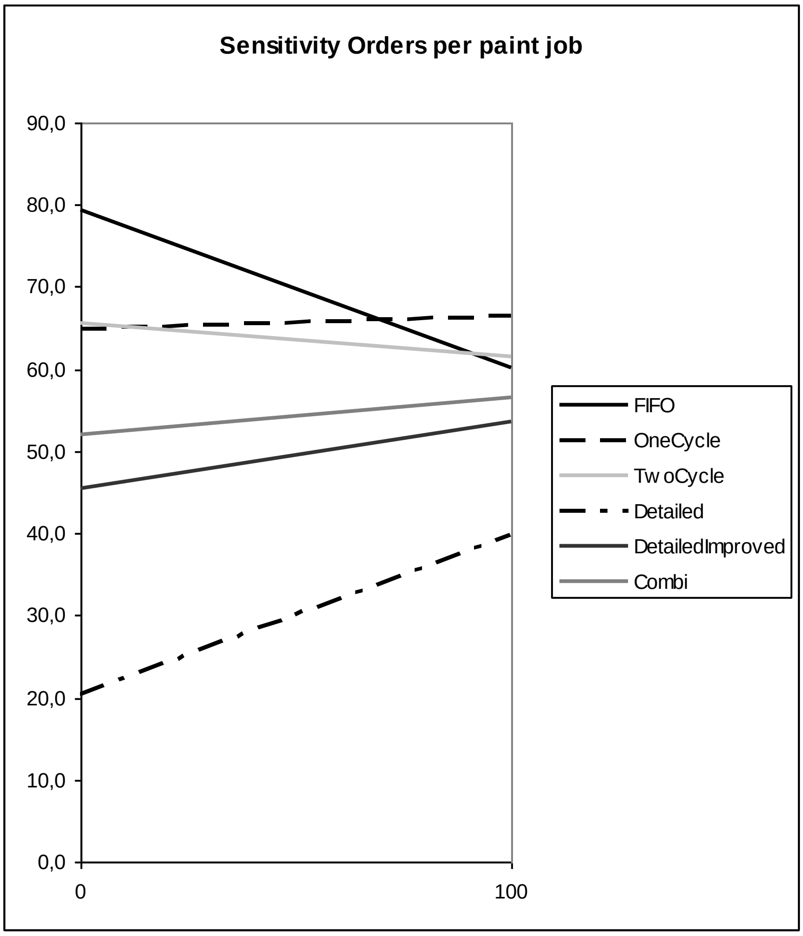





Sensitivity Difficulty
80
70
60
50
40
30
20
10
0
0
100
FIFO
OneCycle
Tw oCycle
Detailed
DetailedImproved
Combi


Sensitivity % On Time
70
60
50
40
30
20
10
0
0
100
FIFO
OneCycle
Tw oCycle
Detailed
DetailedImproved
Combi


Sensitivity Orders per charge
80
70
60
50
40
30
20
10
0
0
100
FIFO
OneCycle
Tw oCycle
Detailed
DetailedImproved
Combi


Sensitivity Orders per paint job
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
0
100
FIFO
OneCycle
Tw oCycle
Detailed
DetailedImproved
Combi