# Preventing a third work shift during peak demand at the multi-model circular conveyor belt of Power-Packer Oldenzaal

*Master Thesis [Public Report]*

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# Management summary

Power-Packer Oldenzaal is a manufacturing company mainly responsible for producing hydraulic actuation systems for the medical and truck industry. They produce a high variety of products which reflects into their production (sub)departments. The departments of interest are the paint and after-paint department. The paint and after-paint department are connected by a circular conveyor belt. The conveyor drives transport beams on which products are attached through different stages.

Recently, a demand peak occurred which forced both the paint and after-paint department to extend their capacity from a two- to a three-shift system. However, management observed that there was not enough work to fill the third work shift completely. Given the additional cost of the third-shift, it is unfavourable to repeat this way of working. Another observation by management is idleness in the paint department for which they believe the after-paint department may be the bottleneck. Therefore, the central research question of this research is as follows:

*'How can the company prevent a third-shift for the paint and after-paint department during a **demand peak** – similar to the one experienced in 2018-2019 – **through productivity improvements**? In particular, to what extent may a **new paint scheduling strategy** reduce the idleness in these departments?'*

In order to answer the research question, we first dive into the demand peak to see how likely it is that the peak will return. Secondly, a root cause analysis is performed to find out what is causing the idle time at the paint department. From this analysis, it is found that the idle time is strongly related to the various hierarchical planning levels. These hierarchical levels are: tactical planning, operational schedule, and specifically the schedule of the paint department. The wish of the company is to develop an adequate scheduling strategy for the paint department, for which a case study is performed. Lastly, a generic roadmap is developed to support the planners of Power-Packer in improving the planning strategies for the remaining hierarchical planning levels.

**The demand peak**

We performed an intensive data analysis and developed a data structure to retrieve data. The biggest challenge was to filter painted items from the customer demand. For this reason, a categorizing method was developed that defines which product categories are included as a paint item, which had a validity of 99,9% coverage. The demand peak was analysed on various characteristics namely: (1) yearly, monthly and weekly seasonality, (2) the development of the product mix and its outstanding items, and (3) the forecast. Given these characteristics, it is predicted that a demand peak of a similar size is not returning soon. Furthermore, it is found

that Power-Packer is looking into the possibility to source out one of the medical segments. This will reduce the pressure on the paint and after-paint department and contributes to preventing a third-shift. Despite this finding, there is still relevance to research the idle time at the paint and after-paint department and to see if it can be reduced.

**The case study: development of the paint schedule**

The case study contains three objectives:

The first objective is to find scheduling heuristics for the multi-model line (circular conveyer) at paint and after-paint, with the objective to minimize the idle time of the various workstations and to minimize the make span of the day schedules. A literature study was performed to search a suitable and promising heuristic for the multi-model line of Power-Packer. We proposed a hybrid approach of simulated annealing with tabu-list and compared it with the current scheduling strategy. By using discrete event simulation, a digital twin of the production environment was developed to test the scheduling strategies. For five weeks of simulation, the run-time of the model is approximately 8 hours. From the results, it is found that simulated annealing & tabu-list with reduced order size is the best performing scheduling strategy. This scheduling strategy performed 24% better than the current scheduling strategy as can be seen in Table 0-1. However, the average idle time of the simulated period is still high (>40%). Thus, there is still room for improvement.

The second objective is to find out what the impact would be, when a medical product group would be outsourced. The results can be found in Table 0-1. The make span is improved by an additional 10%, but the idle time at the after-paint department increased.

Table 0-1 Best solutions objective 1 and 2 of the case study

| **Scheduling Strategy** ***Three-shift system*** | *Make span improvement relative to current strategy* | *Average idle time of the workstations at after-paint* | *Average idle time first station paint department* | *Backlog paint department on 5-Oct-2018 (num. orders)* |
|---|---|---|---|---|
| Current strategy | - | 47.1% | 58.3% | 88 |
| Annealing & Tabu-list + order size reduction | 24.0% | 40.4% | 39.9% | 31 |
| Annealing & Tabu-list without medical segment + reduced order size | 33.1% | 43.6% | 22.1% | 0 |

The aim of the third objective is to find a configuration (e.g. additional weekend shifts, increased workstation capacity) that prevents the third-shift in case of a similar demand peak experienced in 2018-2019. It is found that a two-shift system alone, is not enough to prevent the third-shift. Table 0-2 shows the best configuration for the simulated weeks. It shows that depending on the week, additional shifts are required to make sure that the backlog at the end of the week is acceptable. In the case that weeks 38 till 40 all work in a two-shifts system with increased workstation capacity, and week 40 receives three additional weekend shifts, then the backlog is still acceptable. Besides, it is calculated that this configuration comes with a cost reduction of roughly 20%. Although, the average make span reduced significantly, the average idle time of the simulated period is still close to 30%. Thus, there is still room for improvement.

**Table 0-2 Best solutions objective 3: week 38 - 40 work all in a two-shift system with increased capacity. Week 40 requires three additional weekend shifts to prevent a large backlog.**

| | Annealing & Tabu list + reduced order size. Increased capacity from two to three workstations per assembly line | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Average Make span improvement | | Average Idle time at paint and after-paint (A-P) | | | | Backlog at the end of the week | |
| | Two-shift system | Two-shift system + 3 weekend shifts | Two-shift system | | Two-shift system + 3 weekend shifts | | Two-shift system | Two-shift system + 3 weekend shifts |
| | | | A-P | Paint | A-P | Paint | | |
| **week 38** | 42.7% | 43.0% | 26.1% | 17.5% | 28.9% | 28.7% | 15 | 0 |
| **week 39** | 28.4% | 31.2% | 25.2% | 21.7% | 30.0% | 39.8% | 7 | 0 |
| **week 40** | -2.2% | 32.0% | 33.8% | 31.3% | 31.5% | 25.3% | 70 | 1 |
| **Average period** | 23.0% | 35.4% | 28.4% | 23.5% | 30.1% | 31.3% | | |

### Generic roadmap

In the problem cluster, it is found that multiple hierarchical planning levels affect the performance of the paint and after-paint department. To support the planners of Power-Packer in improving their planning strategies a generic roadmap is made. The roadmap contains tips and warnings to address their planning problems. It is developed as a visionary document built upon literature research, the reflection of the paint schedule development and extensive work floor experience. The roadmap consists out of four phases: *problem statement*, *data & control*, *establishing product families* and *selecting the planning strategy*. An impression of this document is visualized in Figure 0-1.

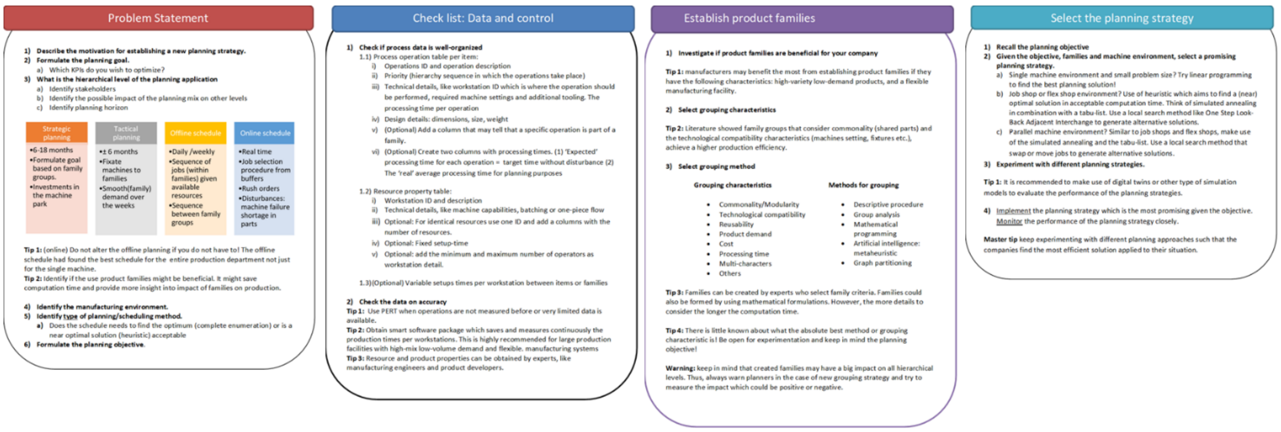


Figure 0-1 Impression of the Generic Roadmap (Appendix G)

## Contribution to practice and literature

Annealing is a procedure that evaluates neighbourhood solutions. Each iteration, a new *candidate solution* is compared to the *current solution* by means of an objective and is accepted or not to become the new current solution. Typically, in many real-life cases where annealing is applied, the objective of the candidate solution can be computed incrementally. For instance, the small computation time of a swap is all that is required to obtain the objective value of a neighbour. This is not the case in this research. Due to partly dependency of today's *day schedule* on yesterday and tomorrow, the calculation of the objective takes considerable amount of time. This makes annealing non incremental. Although annealing requires a huge considerable amount of time, annealing still finds impressive solutions and even with a low number of iterations to reduce the computation time!

## Recommendations

The first recommendation is to redesign and *review database structure* on a yearly base, such that data extraction becomes more user friendly. Use tips and tricks of the generic roadmap as guideline to streamline data accordingly.

If the data is in order, it is recommended to *optimize the tactical planning*. The tactical level smooths the production demand over the weeks and months at Power-Packer. An even better smoothening of orders over the weeks, minimizes additional weekend shifts and overtime.

## Recommendations for future research

The simulation model developed for the case-study can be extended in different ways. Recommendations to increase the performance of the paint schedule:

- *Rerun the simulation model with updated processing times:* The current model contains input data that represents the worse-case scenario. A rerun, provides a better estimate of the increased performance when using annealing as paint schedule strategy.
- *Add operators to the simulation model:* In this way, the number of required operators per shift can be optimized and it improves the cost estimate.
- *Relax the constraints that only certain items can be assembled at certain assembly lines:* The relaxation potentially improves the performance of the schedule.

The idle time at the after-paint department is still high and also the domino-effect still occurs after implementation of the new scheduling strategy. These issues are mainly caused by blockages at the after-paint department. The following experiments are recommended to find solutions for the blockages:

- *Reduce the order size even further:* This may improve a smooth flow through the three assembly lines at after-paint.
- *Experiment with a different after-paint lay-out*. Think of two large assembly buffer lines instead of the current three small ones. Furthermore, relocate the fill-, DPU- and DTU stations to create more space for the assembly buffer lines.
- *Disconnect the after-paint department from the conveyor drive chains that also run through the paint department.* This change makes it possible to reduce the conveyor speed in the paint department which reduces the domino-effect.

# Preface

This thesis is written to obtain my master's degree in Industrial Engineering and Management at the University of Twente. This report is the result of extensive research into the paint and after-paint department at Power-Packer Oldenzaal. Many people accompanied me in this process. Here, I would like to take the opportunity to thank them.

Firstly, I would like to thank my supervisor Peter Schuur for his guidance, feedback and many inspiring stories during this project. Furthermore, I would like to thank Ipek Seyran Topan for the straightforward and clear feedback, which lifted the thesis to another level.

I had a love-hate relationship with the circular conveyer belt at the paint and after-paint department. This is probably the main reason why it kept me fascinated and driven during the whole period. I owe great thanks to Jaco Schmal: If it would not be for him, it would be my life's purpose to keep optimizing the paint and pack system. To all my colleagues at the manufacturing engineering department, you guys always had my back and truly became my second family.

To my family, I owe the most thanks. For all the unrelentless support in so many different ways. To keep me energized with moral support, love, but especially food. In addition I would like to thank them for making the thesis accessible/understandable for everyone.

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## List of definitions and abbreviations

**Cool zone exit strategy:** Strategy in which production orders are allowed be split among different assembly lines. This is the current strategy of the after-paint department.

**Day schedule:** The day schedule determines the paint order sequence of the simulation. It is determined at 6AM of each workday and contains all the order in the paint buffer until then. The day schedule is independent from the next day. In the case backlog occurs, the backlog is not rescheduled, but first finished before the next day schedule is simulated.

**Domino-effect:** The domino effect is appliable to the circular conveyor at the paint and after-paint department. In example, if a production workstation is blocked than all previous stations become idle since they are not able to 'push' their finished work to the next stage.

**Invoice/ bill of lading:** A documents that lists the quantities and prices of goods the company sells to the buyer

**Line of Business (LOB):** The industries where the company is currently active in.

**Offline operational planning**: Reflects in advance planning operations, determine the production sequence.

**Online operational planning:** A control mechanism which monitors if all processes are going conform planning and responds to unplanned events.

**Product demand mix:** The range of product types bought by the clients.

**Product mix planning**: The mix of product types or items used in production to increase the production efficiency.

**Promised date**: The date that the company promised the client to ship the order(s).

**Request date for shipping**: The client's preferred shipping date.

**Roadmap**: A roadmap is a strategic plan that defines a goal and includes the major steps required to reach it.

**Sales invoice date**: The day the invoice is printed this is usually the day of shipping.

**Scheduled completion date:** The date that production must finish the job.

**Scheduled shipping date**: The date set by the company that the order will be shipped to the client.

**Seasonality:** There is a fluctuation in demand over time that is predictive due its cyclic behaviour.

**Strategic planning:** Long-term decision are often reflection of company goals which are often structural decisions made by the highest management level.

**Tactical planning:** Mid-term decision making, translate strategic goals into processes for the operational department.

**Transaction date/booking date:** The date that production finished any (single) products.

**Yield:** Production orders that are processed per shift by the paint and after-paint department.

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# 1 Introduction

In the framework of completing the Master Study Industrial Engineering and Management at the University of Twente, I performed research at Power-Packer Europa B.V. in Oldenzaal. The company is coping with a *disturbed flow* on the production department where products are finalized by painting and package them. This production department can be characterized as a one-piece flow circular overhead conveyor belt. The company believes that a new *product mixing strategy* could improve the flow in the department which is therefore the topic for research. This chapter is structured in the following way: Section 1.1 provides background information about the company and shows examples of products that Power-Packer manufactures. Subsequently, Section 1.2 explains the motivation for research which involves a preliminary investigation. Section 1.3 describes the research design which is followed by the research deliverables Section 1.4 and the outline of the report Section 1.5.

## 1.1 About the company

Power-Packer develops and manufactures high quality (electro-) hydraulic actuation systems since 1970. These actuation systems are imbedded in a wide range of products that require controlled movement. The result is that Power-Packer operates in various markets like the Automotive-, Emissions-, Truck-, Medical-, Off-Highway-, Military- and Special Vehicles and Equipment industries.


Figure 1-1 Examples of hydraulic systems per line of business

Figure 1-1 shows four market segments or ‘lines of business’ with an example of a Power-Packer application. The first example shows one of the medical solutions. It is an electro-hydraulic system that lifts and lowers the stretcher into the ambulance. Similar systems are also applied in hospital beds and operations tables. The second example reveals a cap-tilt mechanism which is implemented in trucks. The third example shows a convertible roof top actuation which is developed for the automotive industry. Other applications for this industry are: doors, hoods, spoilers and other body panel actuations. The last example shows applications for the special vehicles like off-highway (agriculture and construction equipment) and marine machineries. Similar to the trucks, special cab-tilt actuation, hood-lift actuation and locking systems are developed for this sector.

Notice that the special vehicle solution (later mentioned as “Specials”) is built up out of a cylinder and a pump similar to the Truck and Medical solutions. The big difference with the medical solutions is that the pump is directly attached to the cylinder. The “Specials” and truck-pumps and cylinders are usually boxed separately and shipped to the client. However, there is an exception namely the hycab product family. A hycab is assembled from an electro-pump and a cylinder, meaning that also this product (like medical) is sold as one-piece.

Based on the examples, it can be concluded that their hydraulic actuations have many applications which lead to a wide range of clients all around the globe. This is one of the reasons that sales offices and manufacturing plants are found on every continent. To provide an idea, their manufacturing facilities can be found in The Netherlands, France, Turkey, India, China, Brazil, Mexico and the USA.

Worldwide, around 1000 employees serve the client wishes. Power-packer has over 40 years of experience in motion control systems. The head-quarter of Power-Packer are located in Oldenzaal. This site is the location of our research.

## 1.2 Motivation for research

Our journey starts with a simple question from the Manufacturing Engineering Department of Power-Packer Oldenzaal. This team is responsible for the performance of all manufacturing machineries and production methods. Their question is as follows:

*How can Power-Packer Europe improve their production process of the Paint and After-paint Department* without *investing 200k for the bottleneck determined by them?*

Although this is not how the question was exactly formulated, this question does grasp the knowns and the unknowns at the beginning of this research. In the upcoming sections, the above question is split into pieces. The first Section (1.2.1) explains the beginning, because why should Power-Packer improve their production process? The subsequent Section (1.2.2) describes the bottleneck determined by management as well as a simplified representation of the production process of the paint and after-paint department. In the last Section (1.2.3), the 200k solution is explained along with the reason why the company has decided that further research is required.

### 1.2.1 How it all begins

It all starts as a success story: a significant market demand peak in the period of September 2018 - August 2019, has led to prosperity and wealth in the company. The company was happy to announce more staff was required to increase their production capacity for as long as the demand peak holds. Figure 1-2 shows the effect from the demand peak on the production output. The peak starts in week 38 and the effect lasted until week 14 which represents a period from September 2018 till March 2019. A side note: Figure 1-2 represents all booked assemblies by the *paint and after-paint department*, including sub-assemblies and final products.

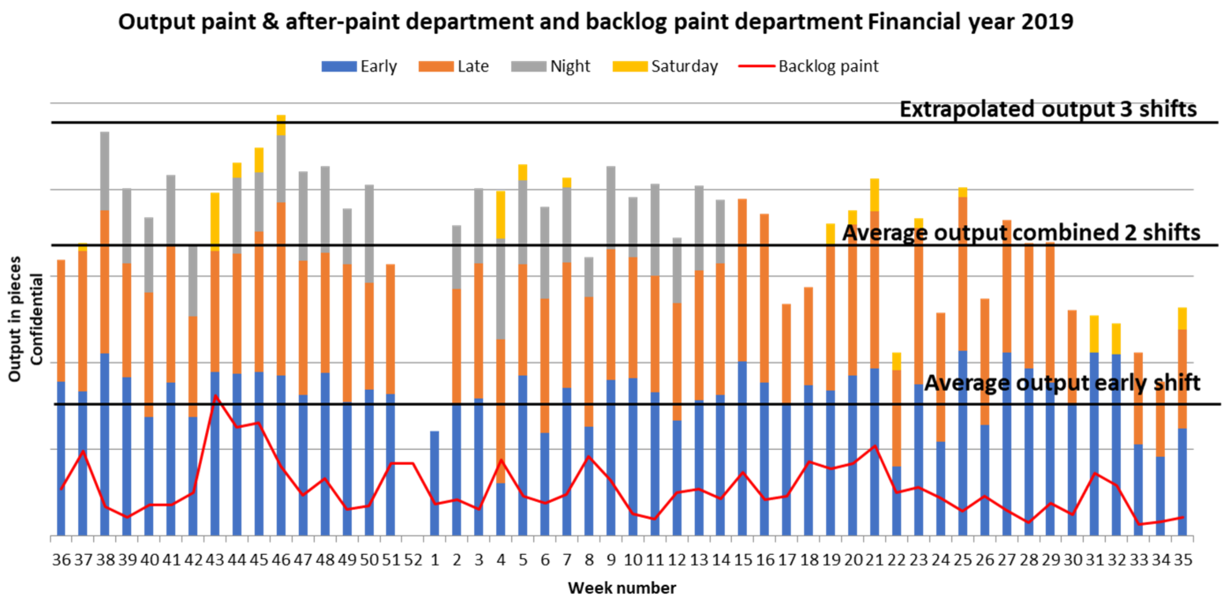


**Figure 1-2 Production output per work shift (early, late, night, Saturday) per week including the backlog of production sub-department Paint and After-Paint of financial year 2019. (Sources: Yield list after-paint & loading.forecast.medisch)**

In this period the entire production department was producing 24 hours a day in three work shifts, with fluctuating working weeks of five or six days. A large part of the production department always worked in three-shifts, but with less operators. For two subdepartments, paint and after-paint, working in a three-shift system a rare phenomenon.

Management argued that these two subdepartments handled the demand peak very well since the maximum paint backlog was kept below two production days. This means that working in the weekends dissolves the backlog easily. However, the output fluctuation shown in Figure 1-2 indicates that working in a three-shift system was not very efficient. The figure shows the average output of the two-shift system. Extrapolating this number to three-shifts results in the ambition output target per working week. Observe that while working in three-shifts, this ambition is never met! The workweek had to include a Saturday to meet the target and even then, they only met the target once.

Management explains that there is not enough work for three-shifts, five days a week. Along with the additional energy cost -to keep the paint line up and running- and the night shift allowance makes it unfavourable to repeat this way of working. For this reason, management seeks a solution that avoids the third-shift in the future.

### 1.2.2 Bottleneck identification by company

The easiest way to prevent a third-shift for the paint and after-paint department would be to reject new orders, but like every other company it wants to grow. The second method they could think of to prevent the third-shift is to increase the productivity of these two departments. This means that they have to find the bottleneck.

All assemblies that require a layer of paint are sent to the paint and the after-paint department. The paint department adds a, so called, wet coating to protect the product against corrosion. The after-paint department finalizes the products and makes sure that the products are carefully packed for a safe journey to the client or warehouse.

The paint and after-paint department have a different lay-out compared to the other production departments. Paint and after-paint are connected by a one-piece flow overhead conveyor belt, where the other production departments are arranged as a job shop system. A schematic overview of how the overhead conveyor belt is connected with paint and after-paint department is shown in Figure 1-3.

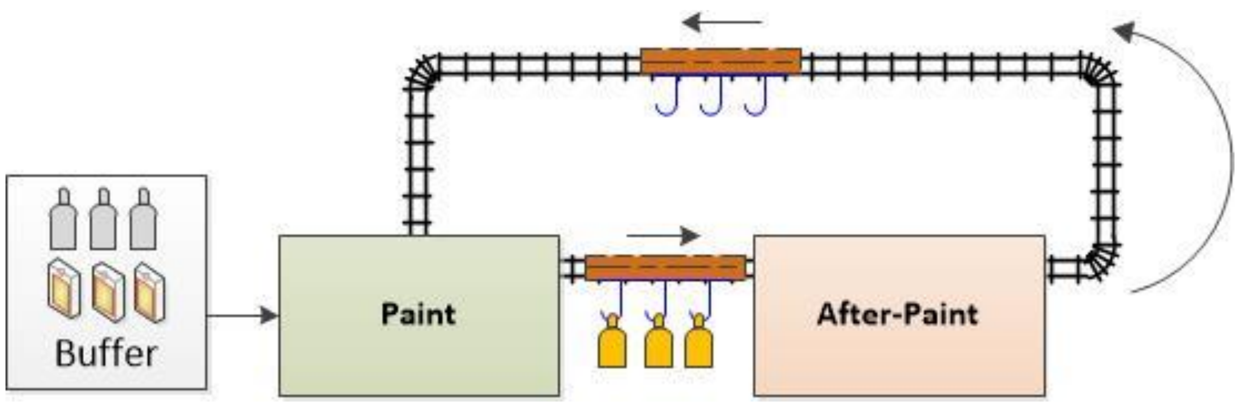


Figure 1-3 Overhead conveyor belt circling between Paint and After-paint department

The paint department selects an order from the buffer and attaches it to the beams on the overhead conveyor belt. Then the products are painted while hanging on the beam. After approximately 4 hours, when the paint is dry, the beam is released to after-paint. Here, the products are unhooked one-by-one from the beam, assembled and packed onto a pallet. After the beam is emptied, the beam is sent back to the paint department. More details about the paint and after-paint departments, like guidelines on how to select an order from the buffer and the paint procedure, are described in Chapter 3.

Management observes idle time at the paint department. Two root causes are discovered that result in the idle time:

- Lack of beams to hang products on since the after-paint has not released any empty beams.
- A blockage at the exit of the paint department, because the after-paint department is "saturated." Or in other words the department is not accepting new beams at a certain point in time for an unknown duration.

From this observation, it is most likely that the after-paint department is the bottleneck. However, further research is required to quantify the idle time and to know if after-paint is the rightly accused bottleneck.

### 1.2.3 Proposed 200k solution & decision for further research

In the previous Section 1.2.2 a possible bottleneck is identified. It seems that the after-paint department jams the production process. Management selected a multi-disciplinary team and organized a brainstorm session from which the 200k solution emerged.

The aim is to prevent that the paint department has to work within a three-shift system. The expected savings from working in a two instead of a three-shift system involve less labour cost and a significant reduction in energy consumption.

The multi-disciplined team believes that *the capacity of the paint department* is high enough to process within two-shifts enough products *for an additional third after-paint shift*. The consequence is that the products for the third-shift need to be buffered between the paint and after-paint department, see Figure 1-4. The buffer location does not exist yet, so the overhead conveyor belt needs to be expanded. The execution of this idea comes at a price estimate between €200-250k.

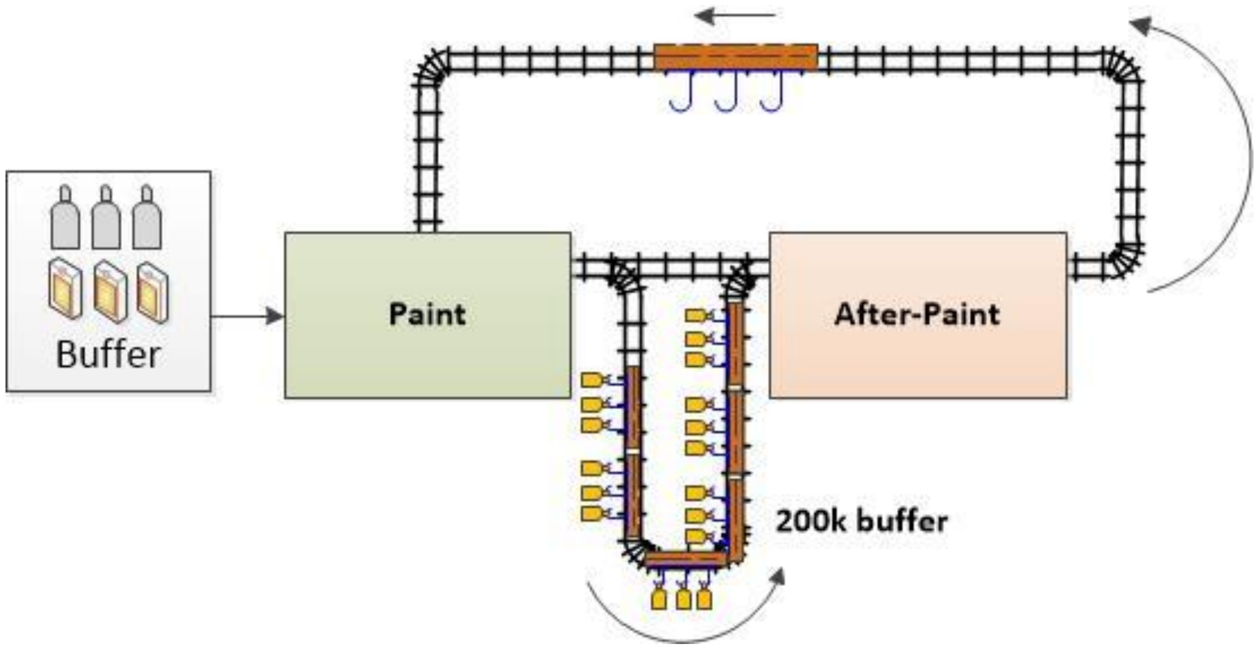


Figure 1-4 The 200k euro Solution

Mainly the high investment cost is holding management back to implement this solution. Besides, it is uncertain if the proposed solution works! They did not test the solution in a simulation study or real-life experiment. Moreover, is the buffer required in the future? How likely will this size of demand peak return?

For these reasons, the multidisciplinary team thought of an alternative solution, namely the order selection procedure from the buffer, or product mix. Each product has its own (final) assembly time in the after-paint department. The more products with a relatively long assembly time enter the after-paint department, the quicker the department gets 'saturated.' The paint department uses mixing guidelines to alternate products with a long assembly time and relatively short assembly times. However, the mixing guidelines exist for over 15 years and it is therefore uncertain if they still comply. For this reason, the product mix becomes part of interest in this research.

In the end, the company wants alternative solutions that contribute to avoiding a third-shift and wants to make sure that the solution has a proven positive effect on the production process.

## 1.3 Research design

The research design includes the research goal with the central question in Section 1.3.1. The next Section 1.3.2 presents the research questions. The subsequent Section 1.3.3 provides the scope. Section 1.3.4 describes how other companies could benefit from this study.

### 1.3.1 Research goal

The motivation of the company is clear. They want to prevent a third-shift in the paint and after-paint department in the case of a similar demand peak. They determined idleness in the paint department and believe that the after-paint department is the root-cause. The company proposed a '200k solution.' Nonetheless, they are highly interested in alternative solutions, especially in a new (product mix) planning strategy for the paint department. In other words, this research deals with: demand fluctuations, a possible capacity problem at after-paint, and planning strategy development for the paint and after-paint department.

Note that the reason that company worked in a three-shift system was due to a long-lasting demand peak from September 2018 - August 2019. However, Section 1.2.3 described that it is unclear if the demand peak from this size and this duration returns. This leads to the question: if the demand peak is not likely to return, is there any purpose for research left?

In consultation with the Manufacturing Engineers of the company, it is decided that although there is no sign of a demand peak, the company is interested in what to do if this scenario occurs. Besides, perhaps cost can be saved by improving the productivity of the production department by preventing the idleness in the paint department. The Manufacturing Engineers see high potential in a new planning strategy for the paint and after-paint department or in other words a buffer selection procedure. Therefore, the research goal and central question is formulated as follows:

*'How can the company prevent a third-shift for the paint and after-paint department during a demand peak – similar to the one in experienced 2018-2019 - through productivity improvements? In particular, to what extent may a new paint scheduling strategy reduce the idleness in these departments?'*

This research aims to provide inside in the following aspects:

- Define characteristics of the historical demand peak and predict the likeliness of occurrence in the future.
- Analyse the current production methods and planning strategies.
- Point out aspects to improve the productivity of the paint and after-paint departments.
- Develop a simulation model.
    - Determine impact of the current planning strategy used by the paint department on the productivity of the after-paint.
    - Develop an alternative planning strategy for the paint and after-paint department and determine the impact.

The results of the aspects mentioned above resulted in a generic insight in which the pervasive need for a roadmap is discovered to establish a production planning. The demand and product mix fluctuations, the variety and needs of the various production departments, the lack of valid data and the lack of a supporting data structure make it hard or even impossible to create solid and functional production planning for the various hierarchical levels in the organisation. Therefore, the following aim is added to this research:

- Provide a generic roadmap for the Power Packer Oldenzaal plant, which specifies a planning design applicable to each particular production department.

### 1.3.2 Research questions

The central question is supported by research questions. In total four research questions are formulated and motivated. The motivation includes how information is obtained.

**Research question 1:** *How likely is it that the demand peak experienced in 2018-2019 returns?*

1.1. *What are the characteristics of the historical demand peak?*
1.2. *What does the sales forecast predict given new and phased-out products?*

The characteristics of the demand peak provide more insight in the predictability of the peak. If the sales forecast predicts that the demand exceeds the productivity of a two-shift system in the paint and after-paint department then this increases the support for this research. Additionally, in the case that product groups are responsible for the demand peak, then it is useful input for developing a new product mix planning strategy later on. To answer the research questions, an analysis is performed on historical sales data and the sales forecast.

**Research question 2:** *What are the causes for the idle time at the paint department?*

2.1. What are the main production activities for painted items and which production departments assemble them?
2.2. Which steps and planning methods are used to realize the production schedule and how do they deal with fluctuating demand?
2.3. What is the current impact of the planning strategy used by the paint department on after-paint? Thus, how large is the idle time at the after-paint?
2.4. What problems are causing the idle time at the paint department? In particular, which problems or factors influence the paint schedule?

The aim to getting to know the production and planning procedures is to identify improvement opportunities that may increase the productivity. To gain the know-how, a broad range of employees are interviewed to make sure that possible improvements are reviewed from various perspectives. If possible, the interviews are supported by data and measurements.

**Research question 3:** *What is an adequate planning strategy of the paint and after-paint department?*

3.1. What is planning and control?
3.2. What are the most frequently mentioned planning methods described by literature and which of them may be applicable to Power-Packer's situation?
3.3. What does literature describe about the implementation of product mix strategies into production schedules and how to form them?
3.4. How does a new planning strategy perform on the paint and after-paint department and will it prevent the third-shift?

With the results obtained by Research question 2, it is noticed that creating a production planning remains challenging. To provide more insight into different planning and control steps, a small literature study is performed. Next, the focus is back on creating a production schedule for the paint department. Through literature, suitable planning strategies identified for the production environment of Power-Packer as well as for the use of a product mix strategy. The planning strategies found are put to the test by implementing them in a case study for which a digital twin is developed. The digital twin makes use of the same tactical production planning used as in the peak period.

**Research question 4:** *How may this research be extended to other production departments?*

A roadmap is developed that summarises the steps made in this research. Besides, a small literature study is added to provide tips and tricks about overlooked issues found during the problem analysis underneath Research Question 2. The roadmap should be an application for any production environment that want to develop new planning strategies.

### 1.3.3 Scope

This research is limited to products that require a paint job. For this reason, not all production stations are incorporated in this study, but only departments or workstations that directly or in directly supply the paint department with products.

### 1.3.4 How can other companies benefit from this research?

One of the aims of this research is to provide a roadmap to establish the ideal production planning strategy for (individual) production departments. Given the fact that the case company is built-up out of several departments with different manufacturing systems makes this research interesting. The company makes uses of identical parallel machines, job shops and the unique one-piece flow circular conveyor belt with multiple exits. Thus, the companies may identify themselves with the manufacturing systems and see if it applies to their situation.

## 1.4 Deliverables

This research yields the following deliverables:

- An overview of product groups which might be part of interest in the creation of a production planning.
- A case study which shows and proofs the performance of different planning strategies by the creation of a digital twin.
- Steps required for implementation of a new planning/ production strategy.
- A roadmap to be able to extend this research to other production departments.
- A list of recommendations for further research.

## 1.5 Outline of the report

Chapter 2: → Research Question 1: analysis of the demand peak

- An analysis of the historical demand peak based on the sales data
- An analysis of the demand forecast to see if the demand peak returns
- Provides product group of interest

Chapter 3: → Research Question 2: analysis current situation

- Analyse the current production methods and planning strategies.
- Introduces method which help us quantifying the idle time at the paint department and its result.
- A problem cluster which shows the factors that resulted in idle time in the paint department.
- An identification of aspects which support a better product mix result.

Chapter 4 → Research Question 3: the literature study

- What are the different activities in planning and control?
- How to form product families?
- Which planning and scheduling methods are suitable in developing a product mix strategy?

Chapter 5: → Research Question 3: developing the case-study

- Develop a conceptual simulation model.
- Construct the simulation model and explain its features.
- Develop the experimental design.

Chapter 6: → Research Question 3: results experiments

- Outcome of the experiments.
- Requirements to implement a new planning strategy for the paint and after-paint department.

Chapter 7: → Research Question 4: generic roadmap

- A small literature study into overlooked issues found in Chapter 3 and how to tackle them.
- The roadmap as application for developing planning strategies for any production environment.

Chapter 8: Conclusion and recommendations.

# 2 Demand peak uncovered

The demand peak experienced from September 2018 - August 2019 is part of the motivation for this research. The size of the peak forced the production departments to work in a three-shift system, since the capacity of the two-shifts was insufficient. For this reason, there is an interest in the causes of the demand peak and an interest in the likeliness to return. The higher the likeliness for return the more support is gained for this research. We performed an intensive data analysis and developed a data structure to retrieve data. The data acquisition and data validation concerning the demand peak can be found in Appendix A. Section 2.1 analyses the characteristics of the demand peak with the aim to find product categories that might be responsible for the demand increase. With this knowledge, the predictability of the peak is determined in Section 2.2. Furthermore, new insights about specific product growth given the forecast might be worthy to keep in mind while developing a new paint scheduling strategy in Chapters 4 & 5 & 6. Finally, in Section 2.3, the conclusion is formulated.

## 2.1 Analysis of the historical demand peak

*What are the characteristics of the historical demand peak?*

For the analysis of the historical demand peak, three characteristics are used: seasonality, sales mix and sales growth of specific product items. Section 2.1.1 determines seasonal week and weekday patterns. Section 2.1.2 month and year patterns. The subsequent section, Section 2.1.3, zooms in on the product mix and its outstanding products.

### 2.1.1 Seasonality, week & day patterns

The week and day patterns are obtained by using the *sales order data*. The demand date is represented by the preferred shipping date of the client. First, the weekday patterns are determined. It seems that Monday is with 28% the clients most preferred request day for shipping, see Figure 2-1. The runner up is Wednesday with 23%. The preferred shipping date does not have to be equal to the promise date, since the company can bargain to set the shipping date earlier or later taken into consideration the capacity, planning and material availability.

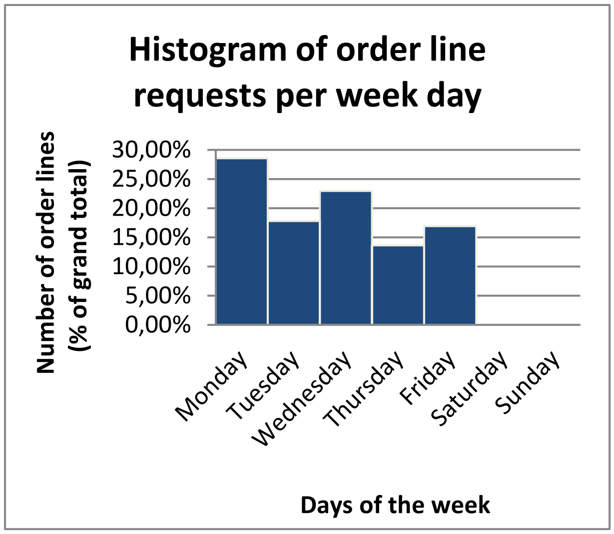


Figure 2-1 Histogram of order line requests per weekday based on *Sales order data* preferred shipping days (cf. Appendix A)

Next, the week patterns are determined. Figure 2-2 shows the number of requested pieces per week by the clients. Observe that week demand in week 52 and 1 are low, because of the Christmas holidays. The same is true for the period week 28-32, which are the summer holidays. Most of the company clients are closed in the holiday period, thus they do not generate demand in this period.

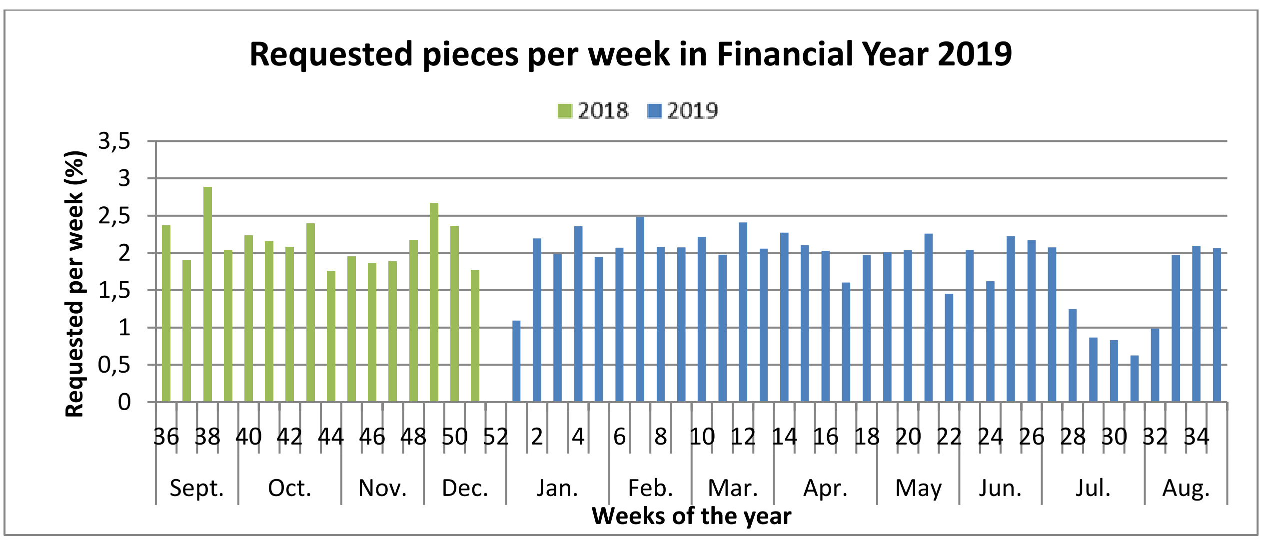


Figure 2-2 Requested pieces per week of paint items based on *Sales order data* preferred shipping days (cf. Appendix A)

Another observation is the fluctuating demand per week, but it is lacking a periodic pattern, see Figure 2-2. By eliminating the low demand weeks (52,1, 28-32) from our result, the average number of requested pieces per week (confidential) is less than the average production quantity per week of a two-shift system! The week fluctuation within a month is interesting though. To provide a better overview of the variation within the months, an interval diagram is obtained shown in Figure 2-3. This makes us wonder how a (production) planner deals with this variation. Later on, Chapter 3 addresses the planning methods used by the company.

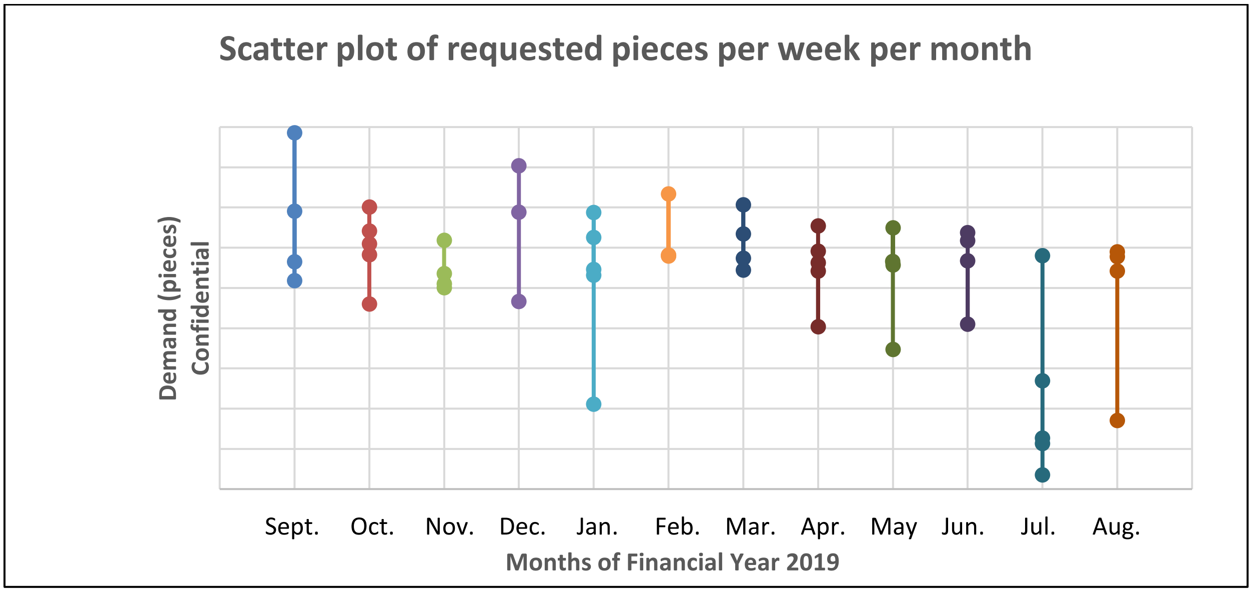


Figure 2-3 Scatter plot of requested pieces per week per month (cf. Appendix A: Confidential)

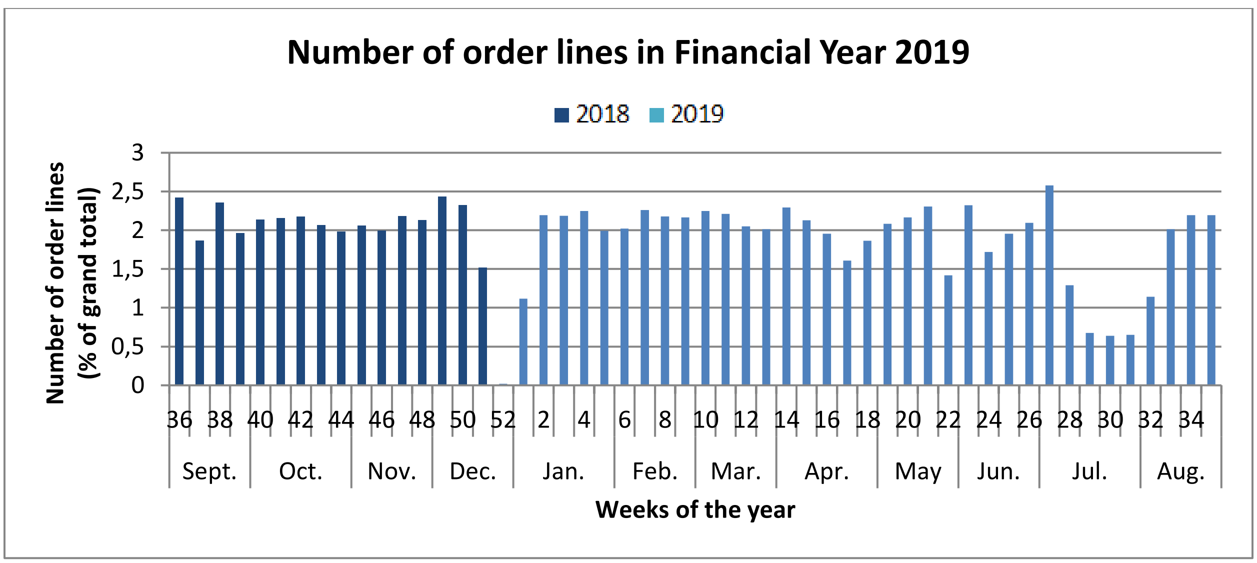


Figure 2-4 Number of order lines per week based on *Sales order data* preferred shipping days (cf. Appendix A)

Figure 2-4 shows the number of order lines per week. Ignoring the holiday periods, the company receives on average 2.1% of the total order lines per week. Comparing this figure with Figure 2-2, it is clear that some order lines have a big impact on the ordered quantities. More order lines per week do not necessarily result in more demand pieces requested per week. Furthermore, Figure 2-4 shows no week patterns in the order lines, with the exception of two "staircase"-phenomena's in May and June this could easily be a coincidence though.

### 2.1.2 Seasonality, month and year patterns

The month and year patterns are obtained by using the *Sales invoice data* (cf. Appendix A). Figure 2-5 shows the estimated demand per month over the last six years. It clearly shows seasonality! The months July and December are the months with the lowest demand. The low demand is explained by the holidays of the clients. If the plants of the client are closed, they do not generate demand.

September (dark blue), October (orange) and November (red), are always the months with the highest demand. This is a clear sign of seasonality. Looking at the peak in October 2018, you notice that this peak is the highest of them all. However, averaging the October 2018 peak by combining it with the months September and November (2018), the average is slightly higher than the previous year 2017, but not remarkable. To conclude, the 2018 peak is not more remarkable than the 2017 peak, but the demand seems less spread.

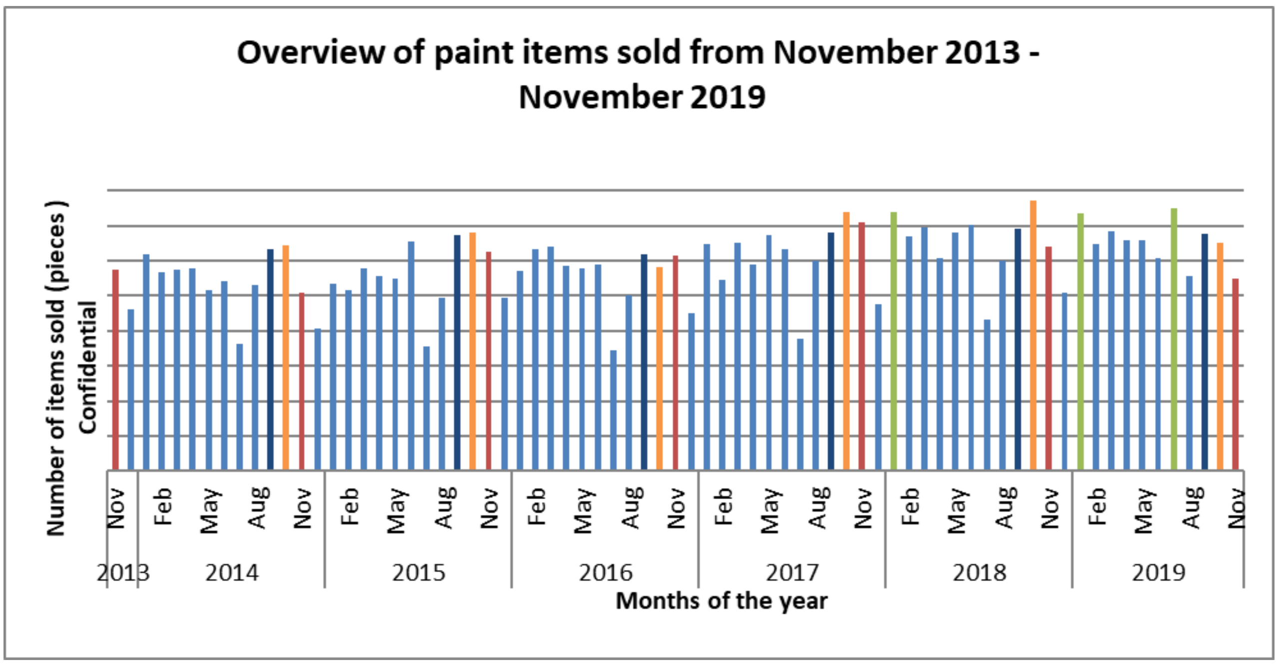


Figure 2-5 Estimate of six year of historical demand based on *invoice data* (cf. Appendix A)

The green peaks in January and July (2018-2019) might both be the effect of holidays. A possible explanation of the July peak is that clients are growing their stocks just before the plant closure due to the holiday. The January peaks are explained by the plant closure in December. Only the difference with July is that the clients choose to get supplies after the holidays. These two months could become new seasonality peaks since they also occur in 2019.

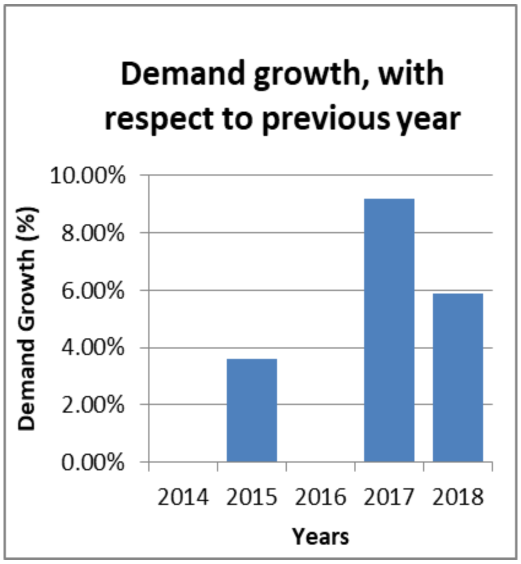


Figure 2-6 Demand growth with respect to previous year. (2013 & 2019 are excluded, these are not full years)

The demand in 2017 shows extreme fluctuations over the months, comparing it to the other years (Figure 2-5). This year is also the first year that there is a significant demand growth of 9.2%, see Figure 2-6. This amount of growth is remarkable since 2016 has almost no growth. Could this extreme growth in 2017 be the cause of a hype? The demand growth continues in 2018 with almost 6%. The demand growth seems to continue in 2019. However, the usual September-November peak seems to return to the demand experienced in the year 2015. Could this be the end of the hype? We are looking for answers in the next section.

### 2.1.3 Product mix & demand growth of outstanding items

Besides determining seasonal patterns from the historical demand, the product mix and its outstanding items are also examined. This section looks into the product mix of the past six years. A change in the product mix identifies which product category grew stronger than others, which would be a reason to focus on the product items in that category. Furthermore, it is determined which specific products have the most impact on production. The *product mix* and the impact of outstanding items are described after one another.

**The product mix**

The case company is active in various markets. Therefore, it is interesting to identify which market(s) or which specific product(s) caused the demand peak. Figure 2-7 shows the product mix over the years which looks the same as the month demand mix. For this reason, the month demand mix is not given. The product mix is divided into truck-cylinders, truck-pumps, medical items and others. The group 'others' contains three product types namely: hycab, valve and latch hydraulic. The product mix shown in Figure 2-7 is stable over the past seven years meaning that the demand growth reflects in all categories. The product mix of truck-cylinders, truck-pumps, medical items and others is on average respectively 46%, 45%, 7% and 1%.

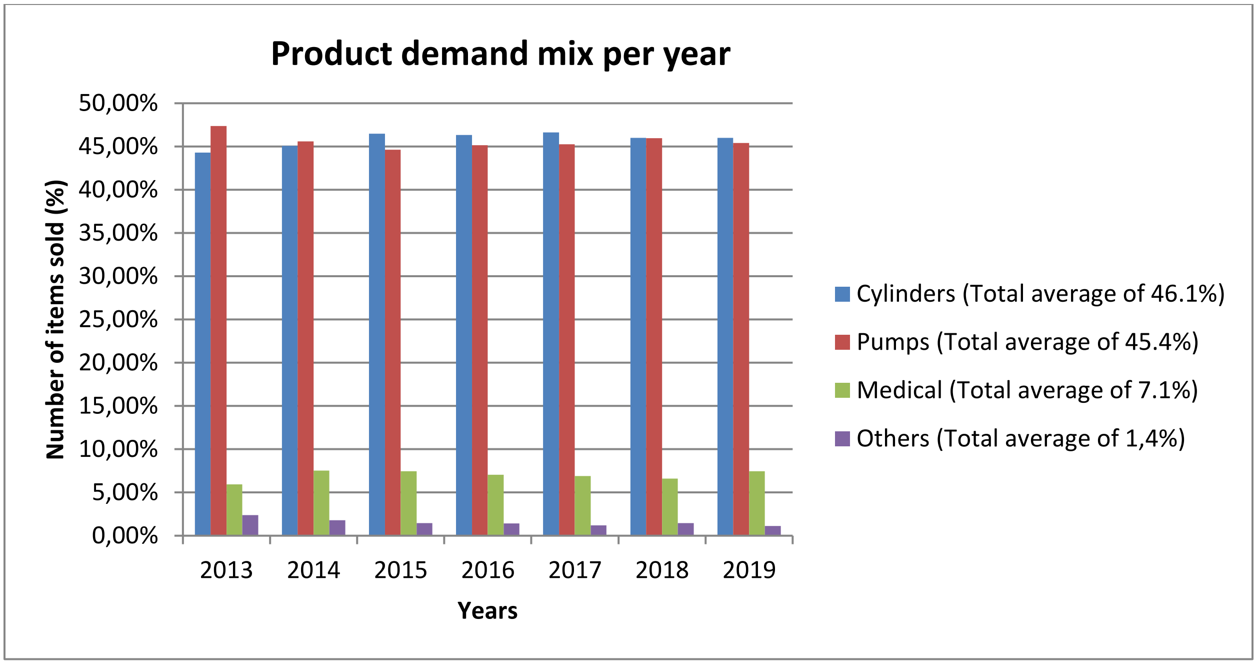


**Figure 2-7 Product demand mix in percentages per year**

Knowing that the product mix was stable over the years makes us wonder if the possible 'hype,' as mentioned in Section 2.1.2, could still be the case. Search the web on 'hype definition' and the results show that the media plays an important role. In the case of a hype everyone with an interest talks about it on social media platforms. Although the companies interest group is not as big as the Pokémon go innovation in 2016 (Andersen, 2016), there may be an impulse that stimulated our clients to purchase more.

The hype may come from an impulse like:

- **Subsidy**. Think of subsidies for research into medical equipment or more environmentally friendly trucks.
- **A change in the law**. Effecting products that use hydraulic mechanisms and therefore lots of products need to be replaced. This happened in 2013 when the law made EURO 6 diesel the new norm. (Regulation (EC), 2007)
- **An event.** Multiple clients won awards over the last few years like, the Product of the year award, Sustainable truck of the year, Fleet Transport Awards, International truck of the year. These awards make a brand interesting for potential buyers which could cause a shift in the market.
- **Market growth or economic boom**. There is one thing that medical and trucks products have in common. The demand of both product types is the effect of a growing population. This results in hospitals with more equipment and more trucks to transport customer product. Figure 2-8 shows the result of the Business Cycle Tracer indicator applied on the Netherlands. The indicator represents the Dutch economy. Is the

indicator above trend, then this means that the economy is growing. Below trend means that the economy is decreasing. We have an interest in the period 2016-2019 which shows economic growth.

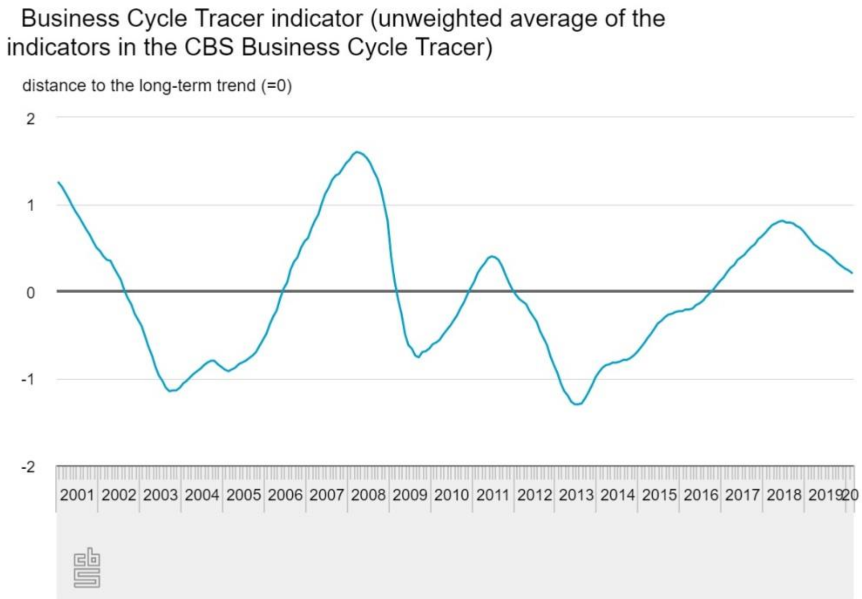


Figure 2-8 Business Cycle Tracer indicator of the Netherlands (CBS, 2020)

Regardless of the impulses mentioned before, the demand growth could come from specific items. These are determined in the next section.

**The impact of specific items per mix category**

The last examined characteristic of the demand peak is the influence and the growth of individual items. In the previous section, it was found that the largest product categories are truck-cylinders, truck-pumps and medical items. For each of these categories a top 5 most sold and top 5 largest impact on growth is made, as described in Appendix B. The two main interesting results are discussed here.

The first result concerns aftermarket products. The aftermarket is the market for spare parts in the automotive industry. Power-Packer produces a wide range of aftermarket products with a relatively low demand, it is therefore decided to group them. Grouped, they compete in the top 5 most sold in the truck-pump and the truck-cylinder categories. The aftermarket is responsible for 4 % of the truck-cylinder sales and 8% of the truck-pumps sales. This emphasises the importance of the aftermarket group. It also increases our curiosity on how Power-Packer deals with these small orders on production- and planning level.

The second result concerns the top 5 of product items that had the most impact on the demand growth of truck-pumps. Two items of the DPU subcategory show up. DPUs' are a combination of a hand and an electro-pump. The growth of this product subcategory should be kept in mind while developing a new production schedule for the paint and after-paint department, because is there enough capacity to produce all these items in a two-shift system in the future?

The previous sections revealed the characteristics of the demand peak. We looked into the seasonality patterns, the product mix and outstanding items responsible for the peak. The next section determines if the demand peak is likely to return by evaluating the forecast on the previously found characteristics.

## 2.2 Forecast

*What does the sales forecast predict given new and phased-out products?*

Usually, demand is not a controllable factor. In some industries the demand is influenced by marketing strategies, but as supplier to automotive industry, the customers forecast is quite accurate to the actual demand. Section 2.2.1 discusses the forecast for truck and off-highway. Section 0 gives insight into the medical forecast with a surprising twist.

### 2.2.1 Truck & off-highway items

The forecast of truck & off-highway items, cylinder and pumps, is created by the sales team. The forecast is missing the months September – November 2019 since these months are already in the past. What is left is the period December 2019-August 2020 which is compared to previous year.

The historical sales counted 22 subcategories, but the forecast contains only 10 subcategories. From the year 2020, the company stops with the production of plough cylinders. However, this explains only two missing subcategories. From this, it is believed that not all items are forecasted. Table 2-1 shows the expected sales growth. Only three subcategories are promising:

- the DPE6 and the DPU2 are both part of the pump category.
- and the very promising DTU2 which is a combination of a cylinder and a pump.

Table 2-1 Forecast Cylinder & pumps

| | Cylinders | | | | Pumps | | | | | Other |
|---|---|---|---|---|---|---|---|---|---|---|
| **Subcategory** | DCD1 | DCD2 | DCF2 | DCM2 | DHP2 | DHP6 | DPE2 | DPE6 | DPU2 | DTU2 |
| **Growth (%)** | -25.7 | -19.1 | -17.6 | -18.6 | -14.9 | -7.6 | -3.5 | 2.0 | 4.9 | 37.9 |

### 2.2.2 Medical items

The medical forecast did not show any abnormalities. To be more precise, it looks the same as sold quantities of last year. The sales managers tell us that most of the medical items are sold through tendering. For this reason, it is hard to predict the demand. In the case the company wins a tender it could have a big impact on the demand of the corresponding month.

The company is looking into the possibility to move the production of a medical segment to a sister plant. Moving the production means that there is more space to increase the production of truck items. Besides, it creates room for new product development. The implementation of this idea would have a big impact on this research, since the output of the production department's paint and after-paint will be reduced. These two departments were the ones that experience flow and capacity issues as is described in Section 1.2.2. Perhaps that the capacity issues are solved by eliminating the medical items? It is yet too early in this research to remove the medical products out of the scope. Besides, moving the production requires a lot of organization, thus for the upcoming year the production of medical items stays where it is. However, we should keep this medical group in mind while experimenting with the paint schedule in Chapter 5 & 6.

## 2.3 Conclusion

In this chapter we described the characteristics of the historical demand peak from the period - 2018-2019 and tried to predict if the demand peak returns. If the demand peak returns, the paint and after-paint department is forced into a third-shift which we like to prevent in the future.

To be able to predict the demand peak, various datasets were analysed for different purposes. It was a challenge to distinguish which items are actually painted. In the end, we used a categorizing method that defines which product categories are included as a paint item. The categorization method results in a validity of 99,9% coverage for the selected data set (see Appendix A).

We looked into various characteristics of the demand peak namely (1) yearly, monthly and weekly seasonality, (2) the development of the product mix and its outstanding items, and (3) the forecast.

It is found that seasonality plays a big role. Both yearly patterns and weekly patterns are found in the sales history. The most interesting finding is the extreme demand variation between weeks within a month. The week variation is random and should be kept in mind, since they may affect the production planning and therefore the paint scheduling strategy. A second interesting finding is that the demand peak from Sep 2018- Sep 2019 seems to have started already in 2017. With respect to previous year, the demand grew with 9.2% in 2017 and grew again with almost 6% in 2018.

What caused the demand peak is hard to say. The product mix of truck-cylinders, truck-pumps, medical items and the category others is stable over the last 6 years with respectively an average mix of 46%, 45%, 7% and 1%. This indicates that the demand of all categories grew evenly. This finding makes it more likely that the demand peak is the result of economic growth and not a hype.

The question remains, will the peak return and will it 'hunt' the production department into a three-shift system again? At least not on the short term, the forecast suggests. There is a strong indication that a third-shift is preventable since the average customer demand is lower than the estimated average shift output found in Chapter 1. Furthermore, there is an indication that the production of one of the medical subcategories is going to be sourced out to one of the sister plants. This will then reduce the pressure on the paint and after-paint department and contributes to preventing a third-shift.

*To summarise the most important findings: a new demand peak of the same size as in 2018 is not expected coming year. There are extreme customer demand variations between weeks of the month. This should be considered when looking into the production planning procedures which is covered in the next chapter. Furthermore, the production of one medical subcategory is likely to reposition to a sister plant. This should be kept in mind when performing experiments on the paint scheduling strategy later on.*

*In the next chapter, we examine the company's production procedures and planning procedures with the aim to identify regions for improvement, to prevent a third-shift in the future. One of the regions turned out to be planning strategy at the paint and after-paint department.*

# 3 Current situation

The previous chapter showed that the high demand peak is not likely to return soon. However, this does not change the objective of this research. The paint department still experiences idle time and productivity improvements may still be found.

To find the root-causes of the idle time, the production process is analysed in Section 3.1. Observations and interviews about the different production departments provide insight into the direct and indirect causes of the idle time the paint department experiences. Furthermore, the buffer selection procedure of the paint department is explained which will be later on mentioned as the 200-200 rule.

Having a clear understanding about the complexity of the production processes, the idle time in the paint department should be quantified. Therefore, a measuring method is developed. The method description and the results are stated in Section 3.2.

After completing the production process analysis, it is time to gain more insight into the planning procedure used by the company. Management believes that a new paint schedule may reduce the idle time. However, the paint schedule is influenced by the tactical planning and operational planning. These two planning procedures are therefore analysed in Section 3.3.

The next step is to look into the performance of the planning and production procedures. This analysis had some surprising results and can be found in Section 3.4.

The three analyses (production process-, planning procedure- and performance analysis) all end with a potential list of problems which may (in)directly cause the idle time of the paint department. Section 3.5 analyses the list of problems. The result is a problems cluster which shows 24 problems that are all connected to each other. Given the size of the problem cluster, the idle time issue is more complex than initially anticipated. This chapter ends with a summary in Section 3.6.

## 3.1 The production processes

The case company has a high variety in hydraulic systems which they produce for different market segments. The different market segments are reflected in the lay-out of the plant, because each segment has their own unique set of activities and machineries. There is one activity that most hydraulic systems have in common which are the paint and after-paint activities. For this reason, these activities have their own department.

Since the case company experienced flow issues and idle time in the paint and pack production system, the focus of this research is restricted to painted items. As is stated in the introduction, a hydraulic system is built up out of a cylinder and an (electric-) pump. Depending on the market segment or product design, the cylinder and pump are either integrated into <u>one</u> (non)detachable product like the medical application or as <u>two</u> individuals (truck application).

The production of the cylinders has caught our interest, because of its many activities and manufacturing systems. In consultation with the case company the production of pump and medical hydraulic systems are going to be treated as a Blackbox. We acknowledge that these departments are there and that they generate products that need to be processed by the paint and after-paint department. The main reason behind this decision is that the research becomes too extensive if we would include all production activities and manufacturing systems as well. To summarize, Figure 3-1 shows the main activities considered in this research.

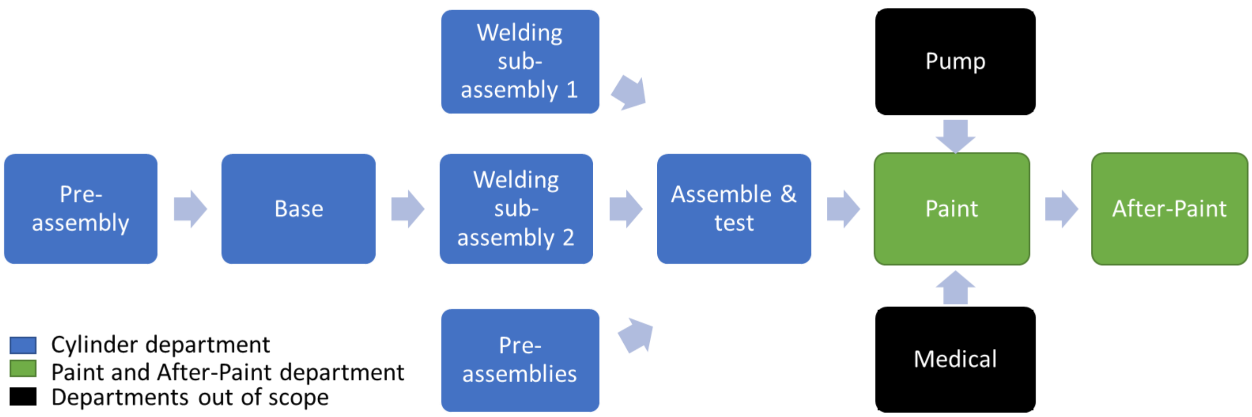


Figure 3-1 Main activities considered during research

The subsequent sections describe the manufacturing processes of the activities of the cylinder department, the paint and after-paint department. Furthermore, the production manager, shift leaders and various operators are interviewed. They are asked individually, if they could think of a happening or activity that disrupts the paint and after-paint department. Moreover, we asked what they would like to see improved about their own departments. Some observations from our side complete the qualitative analysis. To back-up the observations and interviews, data is collected to support observations and to quantify the size of the problems in the case data is available.

### 3.1.1 Cylinder department

Figure 3-1 shows the six main activities of the cylinder department. Each of the six activities are fulfilled at their own section with the help of machines, robots and manpower. The resources used are entirely dependent on the cylinder type. Figure 3-2 shows a fictive representation of the workstation arrangements and shows how two jobs (production orders) move between workstations.

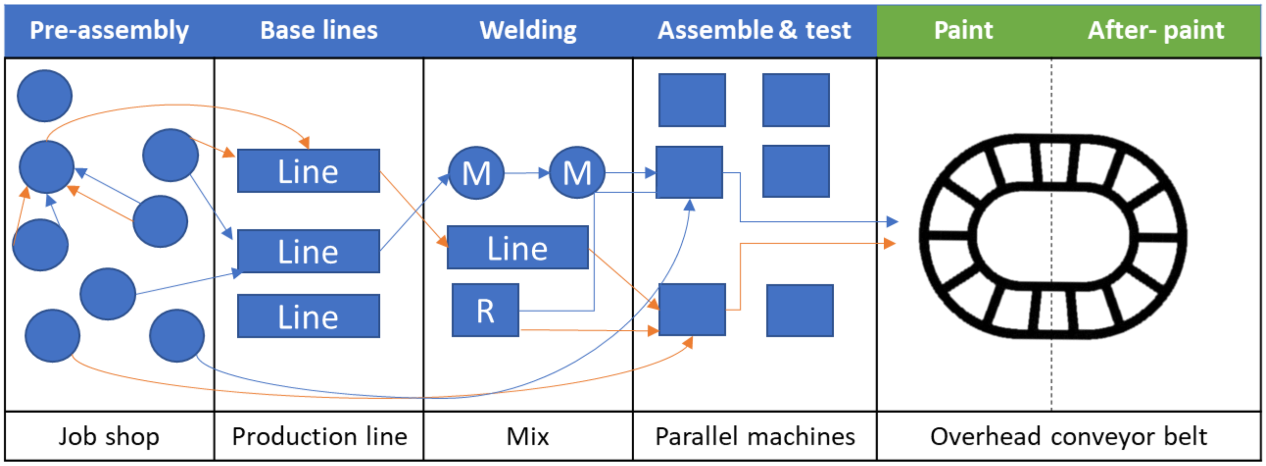


Figure 3-2 A fictive representation of manufacturing systems used by the case company.

Depending on the cylinder, the production starts with creating (multiple) **pre-assemblies**. These pre-assemblies will be embedded in the base-assembly later on. The workstations are one of a kind, but flexible such that a variety of pre-assemblies could be produced at the station. The workstations are equipped with robots or machineries which are supported by operators. There is one thing all stations have in common: each workstation makes use of a one-piece-flow manufacturing process, meaning that each time one part enters, and one part exits the production system. It does occur that a pre-assembly requires multiple workstations, but these are limited.

If the pre-assemblies are finished, the assemblies are delivered at the **base department**. Depending if pre-assembly is a Kanban item or not, the items are placed onto the station or on a trolly to buffer them for later use. The base-stations are actually production lines were usually one, at most two operators assemble the base. All base lines are restricted, meaning that the baselines can only serve certain product families. The base lines make use of a one-piece-flow manufacturing process. If the job is finished, it is boxed and put in a buffer between the baseline and the welding department. The welding department collects the order from the buffer themselves.

**The welding department** contains three types of workstations: manual welding stations, a welding production line and stations containing welding robots. The welding production line is dedicated to welding **sub-assembly 2,** recall Figure 3-1. All the other workstations are dedicated to weld either **sub-assembly 1** or **sub- assembly 2**. Similar to the base lines the stations are restricted to weld certain product families. Only the manual welding stations can be described as flexible parallel workstations. All other workstations are one-of-kind. Similar to the previous departments the welding stations work as a one-piece-flow.

Meanwhile, when welding takes place, other **pre-assemblies** are produced that need to be installed during the next activity: Assemble & Testing. The pre-assembly stations are one-piece-flow parallel flexible workstations. However, there are some exceptions that a station is dedicated to a specific product family.

The **assembly and testing stations** are all flexible parallel machines. Like the name suggests, welding- and pre-assemblies are assembled into a cylinder. Afterwards, the functionality of the cylinder is tested. The test-machines need to be prepared with the right fixture and oil which are both cylinder type specific. The number of fixtures is limited meaning that the deployability of the parallel machines to one production order is also bounded. Thus, the production orders have to wait if fixtures are not available. The cylinders that pass the test are collected on a pallet and placed in the buffer in front of the paint department.

Another interesting characteristic of the cylinder department is that they scrap sub-assemblies that do not pass the test or visual inspections. The pre-assembly stations are able to make replacements for the scrapped sub-assemblies, but the other departments scrap them and continue with a new production order.

During the interviews problems and improvement suggestions were asked to a wide range of people. The problems of the cylinder department (C) are described below.

C1. The interviewees mention **material problems** as most occurring reason for not being able to supply the paint department. Two types of material issues can be distinguished: late delivery by supplier and quality rejection.

C2. **Rush orders** may potentially affect the flow through all departments in a negative way. It occurs that they have to stop producing the current job and changeover to produce a rush order. Depending on the station, changeover takes 5 to 30 minutes. It is unknown what the effect of the rush order is on the flow or the production schedule. Will other jobs become rush orders? Besides, is it worthwhile to interrupt the current production order if the current order was finished in one hour? In the end, did the rush order finish in time? Observations show that a rush order is equal to pushing all the buttons to throw it over the fence as soon as possible, no matter what. Until a sub-department is not aware of the rush order, or is refusing to produce it because other jobs have a higher priority.
According to team leaders, it occurs that there is a list of 20 rush orders. The rush orders are often related to material issues.

C3. Some **aged machines cope with failures**, depending on the failure it could be down for days due to a lack of spare parts or obsolete parts. In this case, only certain cylinders can be produced which is inadequate for the production mix for paint and after paint department.

C4. **Lack of planning by production**. Another observation shows that pre-assemblies required for the assembly and testing department are already finished, while the base line operators have not even started yet, see Figure 3-1. This does not have to be a problem, if you have enough floor space to buffer the components. However, it occurred that there is a sub-department waiting for parts for order 1. In this case the operational planner prioritized the wrong activities. Furthermore, it also occurred that the production department starts producing an order while knowing that it is impossible to finish due to material issues. In this case no finished products are delivered to the paint department which may explain the idle time.

C5. A problem often mentioned on the floor by operators is that the given **processing times are not up-to-date**. The performance of the production shift is monitored by time. This means that if the time on paper is (way) more than the actual production time the production performance is really good. However, it also works the other way around. The floor operators believe, this is the reason that there are days with too much work compared to others.

### 3.1.2 Paint department

The paint department is supported by preferably three operators per shift with a minimum of two. Each operator has its own responsibility in the paint line, which is explained later on. Figure 3-3 shows the steps of the painting process in a schematic way. Be aware that the paint line is a one-piece-flow.

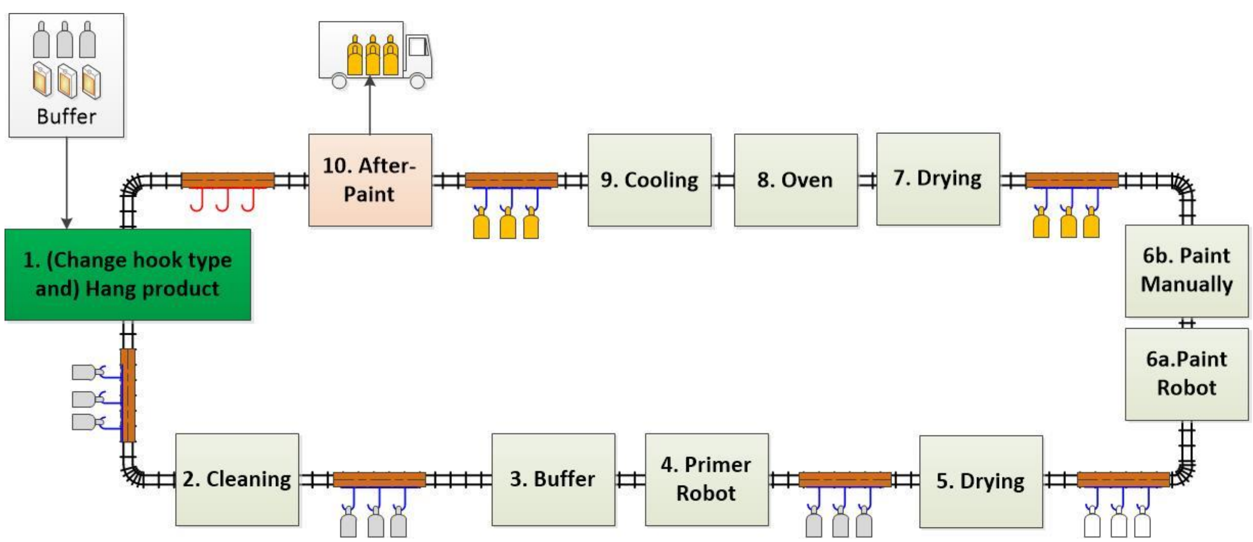


Figure 3-3 Paint department process flow

Step 1 of the process is selecting an order from the buffer, which is the job of the first operator. The operator uses the 200-200 rule as guideline which means that alternately 200 cylinders are followed by 200 pumps or 200 medical items (from the same colour). This mixing strategy is used for the past 20 years. Based on the selection, a certain hook type is required to attach the product onto a transport beam which is actuated by the overhead conveyor. Therefore, based on the incoming beam the hooks need to be swapped by other ones. If the hooks are placed, the product is attached to the hooks.

Step 2 of the paint line is that the product is chemically cleaned from dirt and oil, so that the primer is bonding optimally to the product. A second operator is in charge of this process.

In-between the cleaning and the primer lies Step 3 which is a small buffer that reduces the distance between the transport beams. The primer and paint robot make use of a continuous spray paint, so by reducing the distance between the beams, less paint is wasted. Furthermore, the buffer provides the third operator the time to check if the primer robot is ready for operation.

After the primer is applied (Step 4), it has to dry for a while (Step 5) before the final paint coat is added in step 6a. The third operator sets up the right colouring program for the paint robot and stands by in the manual paint area. In the manual paint area, the products are visually inspected by the operator. The operator manually spray paints the areas that require additional paint, which is step 6b. Afterwards, the beams enter a drying tunnel to remove the air bubbles from the paint (Step 7) this requires a minimum amount of time. To achieve the minimal duration, the transport beams are blocked at the end of the zone and released if the minimal length of stay is passed.

Step 8 is a large oven that heats the product to harden the paint. The product needs to stay here for a while, the length of stay is kept confidential. After hardening, the product is quickly cooled in Step 9. This results in that the operators in after-paint are able to unhook the products without burning their fingers in Step 10. If all products are unhooked, then the beam with its hooks are send back to Step 1.

The paint department does occasionally apply do-overs. For example, if the paint is too thin then the order is refused by the after-paint and send back. The items are sand-down to strip the item from the paint and go back to Step 1.

The following problems were identified by the paint department (P):

P1. **A lack of beams exiting the after-paint department** interrupts Step 1 of the paint process. This indicates a capacity shortage at the after-paint. It occurs that the operator in charge of Step 1, has to wait between 10 and 20 minutes for a beam to arrive. It is unknown how often this occurs. The rate of occurrence is determined in Section 3.2.

P2. The 200-200 rule is used for over 20 years, it is unknown if other strategies result in better solutions. Besides, the **200-200 rule is used as guideline since it is not always**

**applicable** given the buffer mix**.** Furthermore, the 200-200 rule does not provide an actual (day-)schedule since the operators select a new order from the spot.

P3. Hypothetical problem: **Negative impact of paint operators' choice**. The operators are aware of which cylinders take more time to finalize in after-paint and which ones are easier. Considering the man-power in after-paint, the paint operator may choose to only select easy cylinders which results in problems for the next shift. If the next shift only finalizes more 'difficult' cylinders, the more time the paint operator in Step 1 has to wait for empty beams.

P4. **Unbalanced buffer mix**. The available mix in the buffer in front of the paint department is not balanced. For example, one day you receive lots of cylinders in multiple colour-schemes and another day there is a shortage in cylinders.

P5. **Rush orders** are often easy to mix with the other orders if the colour is popular. However, it does occur that they need to setup just for them. Usually, this occurs if the colour is recently painted which is the reason the buffer for that colour is empty. If this is the case, they wait as long as possible in the hope more orders in the same colour arrive.

### 3.1.3 After-paint department

The after-paint department is the last chain in the production process for painted products. This production team finalizes the product and hands (full) pallets over to the logistic team that arranges the shipping to client or warehouse. The overhead conveyor belt runs through the paint and the after-paint department, see Figure 3-4. When a beam, with freshly painted products enters, an **operator decides** to which line the beam is going. Usually, the first two lines are reserved for truck cylinders, where line 3 is smaller and is reserved for pumps and medical products which require less assembly time.

The products are processed by one station, so the product ends up in either: the assembly station, the filling station or the hycab station. To recall, a hycab station combines the cylinder with a pump. **Assembly stations are non-product-specific stations**, thus a product can be assembled at any of the stations. Therefore, it does not matter if the product ends up in line 1, 2 or 3. The assembly stations either **finalize the products** (one at the time), or **palletize products**. Finalizing involves: unhook product from the beam, add the last parts and carefully pack it onto pallets. Palletizing takes place if: (1) the product is finished as is, or (2) the product receives its final assembly later on and is therefore kept as floor stock.

**The filling and hycab stations are product specific**, but usually these stations are supplied through floor stock. Meaning that at some point, at one of the lines (1,2,3) the products are palletized and stored. In the case that the products are palletized for storage there is no necessity to move the beam to either one of the lines, where it would queue up in front of the assembly station. Therefore, the operator can choose to send the beam straight away towards the exit (line 4), so back to the paint department. The result is that while the beam is moving, products are unhooked and palletized in front of the exit. This only occurs if the utilization of the paint department is high enough.

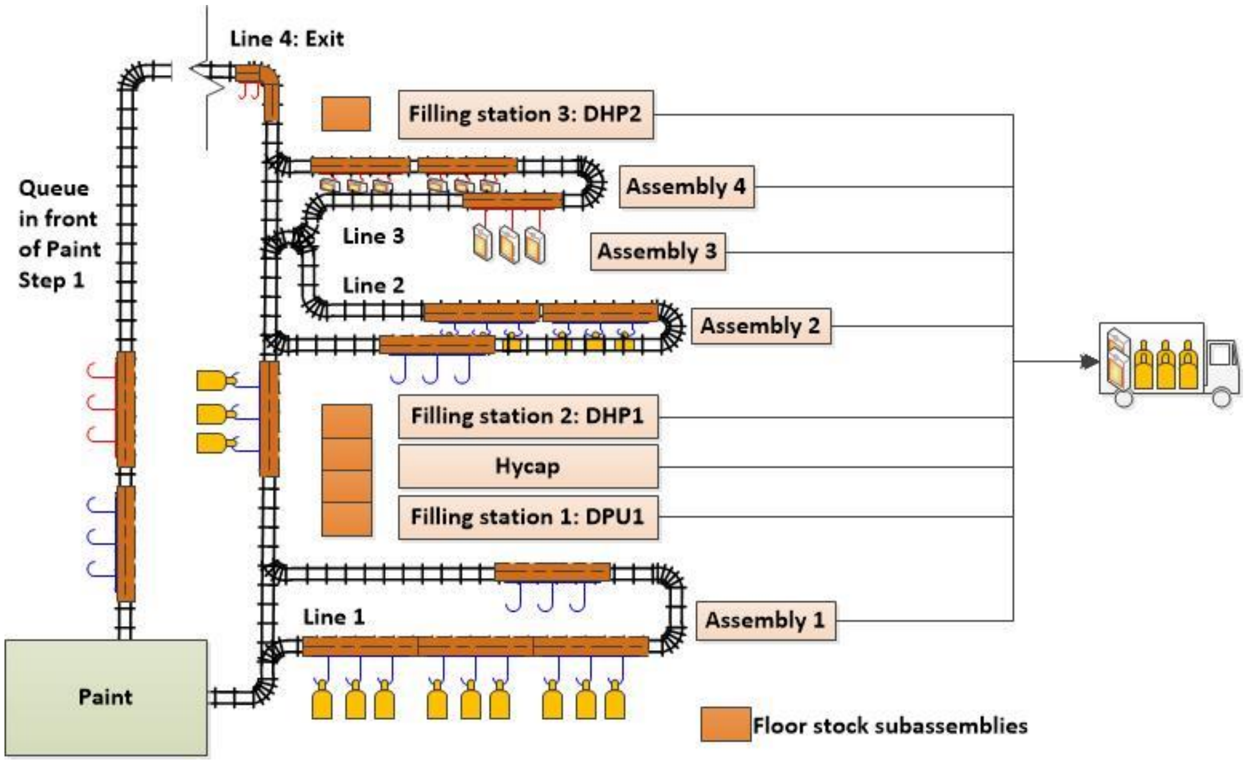


Figure 3-4 After-paint department

The **tasks of the filling station** involve: pick a pallet from floor stock, add the last parts (if required), fill product with oil, pack it onto a pallet and make it ready for shipping. The **hycab station finalizes** specific medical products by combining two subassemblies that are both painted and are kept in floor stock. Afterwards the product is tested and palletized for shipping.

Be aware that the after-paint has no fixed output in pieces per day. The final assembly time per product differs that much that the output quantities fluctuates. The confidential Appendix E contains a histogram showing the output deviation per shift.

The problems described by after-paint operators and shift-leaders are as follows:

AP1. **There are more beams entering after-paint than leaving after-paint in a certain time period**. This becomes visible if:

a. There are **utilization problems**. Absenteeism is a problem occurring in every company. Operators have their own strengths and skills. Not every operator could work at any station. It is not ideal to buffer cylinders like they do for the pumps. Missing an operator at a cylinder station is something they truly miss, because less beams become available per time period for the paint department.

b. The **product mix** contains overall items that take a lot of assembly and packing time.

AP2. **Lack of beams entering after-paint**, **causing idle time in after-paint**. According to the shift leaders: if after-paint is idle than this is usually **due to failures of the paint robot**. Therefore Step 1 contains beams but cannot send them to the next step because the zones after Step 1 are saturated. However, a **product mix with lots of colour changes** in combination with easy products also leads to idle time in the after-paint department. If this would happen the team takes an earlier lunch break.

AP3. **Blockage**. An empty beam leaving line 1, blocks incoming products, since a leaving has precedence over incoming. This is one of the reasons why products with a long packing time are sent to line 1. Another type of a blockage is that the order size (number of beams) is bigger than the line capacity, see Figure 3-4. It occurs that a full beam of products is stuck between line 1 and 2, since there was no room for it on line 2. In this case the operator was too late to stop the track, such that the beam with products where kept in the cool zone.

AP4. **Number of setups after-paint**. Large orders are divided over <u>two buffer lines</u> resulting in setup time for two assembly stations instead of one.

AP5. **The operators collect their own parts and tools for setup** which increases the setup time.

AP6. Every pallet layer is checked on mistakes by an inspector. Mistakes often occurred which is why the inspector is required. All the mistakes made are corrected by the operators who made them. The **correction time is at the expense of production time**.

AP7. Observed: **assembly stations struggle with components and tool sharing**. One assembly station is utilized with two operators. These two operators are facing each other separated by the table. They are sharing components and sometimes tools. Overall, there are enough tools, so they do not have to share, but sometimes they cannot quickly find them. Sharing tools only happens occasionally. The real issue is sharing components. The operators' arms are crossing each other trying to reach the components and fighting over them. Another drawback is that humans unknowingly mirror each other's activities which leads to production mistakes. The casings (component) of cylinders is also an issue. The casings fall out of the boxes while grabbing one to assemble, trying to put them back in the box results in even more mess. To conclude, the design of the station with the component arrangements is up for re-evaluation.

AP8. Observed: The assembly stations are located at the top end of the lines. Meaning that the **buffer space of the lines is not fully used**. Perhaps that using the entire space could prevent problem AP3.

AP9. **Utilization problems**. Lack of manpower (due to absenteeism) or wrong allocation of man to stations.

AP10. Hypothesis problem: **Lack of assembly stations** during peak demand.

AP11. Either the **buffer lines are too small** given some order sizes (number of transport beams) **or** the **order size is too big**.

## 3.2 Quantifying the reason for research

Having clear understanding about the manufacturing systems and production steps described in Section 3.1, it is time to develop a measuring strategy to quantify the reason for research. To recall, management observed idle time at the paint department. They saw (1) that not enough beams entered the paint department and (2) a saturated paint department which could indicated that the throughput at after-paint is too low.

From the interviews and observations, it became clear to the author that there are more factors playing a role in why the first step of the painting process experiences idle time. The first step is to select and order from the buffer in front of the paint department, select the required hook type and hang the product on an empty transport beam. Since it was unknown how often the idle time occurred, the operator is asked to keep track of it for a couple of weeks by using a turve system shown in Figure 3-5.

Table 3-1 Results paint department flow disruptions two-shift system

| | Waiting for empty beams | Strategic waiting | Failures |
|---|---|---|---|
| Minimum amount of occurrences | 0 | 1 | 0 |
| Maximum amount of occurrences | 15 | 8 | 3 |
| Average occurrence rate | 5 | 3 | 0.5 |
| Best guess average waiting time per day | 5*15 min = 1 h 15 min | 3*5 min = 15 min | |

Figure 3-5 Post-it measurement paint

Three things are measured: the **lack of empty beams**, **strategic waiting** and **machine failures**. The lack of empty beams represents that there are no empty beams near the station. The operators' best guess is that the waiting time for an empty beam is on average 15 minutes (10-20 minutes, note that outliers of over an hour occur).

Strategic waiting represents that the operator chooses to wait. For example, the operator sees that the after-paint department is almost finished with order of pumps. This means that empty beams with pump hooks are approaching soon. This hook type is exactly what the operator needs since the next order to hang is pump type. However, they do have a couple of empty beams with cylinder hooks, they decide to wait such that the operators do not have to change the hooks of the beams. The operators' best guess is that strategic waiting takes 5 minutes with the current conveyor speed. A machine failure is a failure within the paint department. This could be the paint robot, but also the cleaning system.

In total 26 days of data is gathered. The operators told us that they sometimes forgot to write it down. This means that the result presented in Table 3-1 is the lower bound. From the result gathered, there is a strong indication that on average 2 hours 15 minutes a day the activity hooking items to beams is disrupted in a three-shift system. However, the operators do not actually wait. They find themselves other activities like cleaning, choosing a next order and prepare it or support a colleague.

## 3.3 The planning procedure

Usually demand is not a controllable factor, but the production output is. The production output is controlled by planning (strategic and tactical) & scheduling (online and offline). The difference between the planning and schedules is explained in the Literature Chapter 04. The case company makes use of a tactical planning and online schedule to decide when to plan the production orders. Note that production orders are unequal to the customer demand in that period. Customer orders may be delivered through stock. In the case the inventory level drops below safety stock a production order is set by the tactical planner.

### 3.3.1 Tactical Production Planning

The work of the production planner starts with the announcement of a sales order or a replacement order (safety stock). The sales order comes with an order quantity and a delivery date which are the fixed constraints for the production planning. The third constraint is the scheduled holidays in which production is closed or has a reduced fixed capacity. Due to holidays the planning horizon differs and can be up to **30 weeks** for fast movers. In this way the production peaks are prevented and the delivery date can be guaranteed. The last constraint is related to non-fast movers and non-holiday fast movers. The time horizon of these products is 5-6 weeks. To explain further, if a client's order is brought in today (week 1) then the order is usually planned in the 5$^{th}$ or 6$^{th}$ week. The first four weeks are required to order and receive the raw materials required for production. The variables in the planning are the start date and the regular week capacity.

Considering the constraints and variables above, a day to day planning is created for the upcoming two weeks. This planning suggests start dates of the various orders. The production sequence is determined by the team supervisor in production.

The **suggested start date** is determined by extracting seven workdays from the **delivery date**. From these seven days, five days are reserved for production and two days for logistics. This means that the **production due date** is two days before the delivery date as is shown in Figure 3-6.

If the production due date is not met (day 5) then the order is manually transformed into a rush order, with the goal to still meet the delivery day (with express shipping). A rush order can be caused by production, but also clients can ask to bring the delivery date forward. Changing the delivery date goes in consultation with the production department. The delivery date remains the same if the production department does not find the time to produce the order earlier.

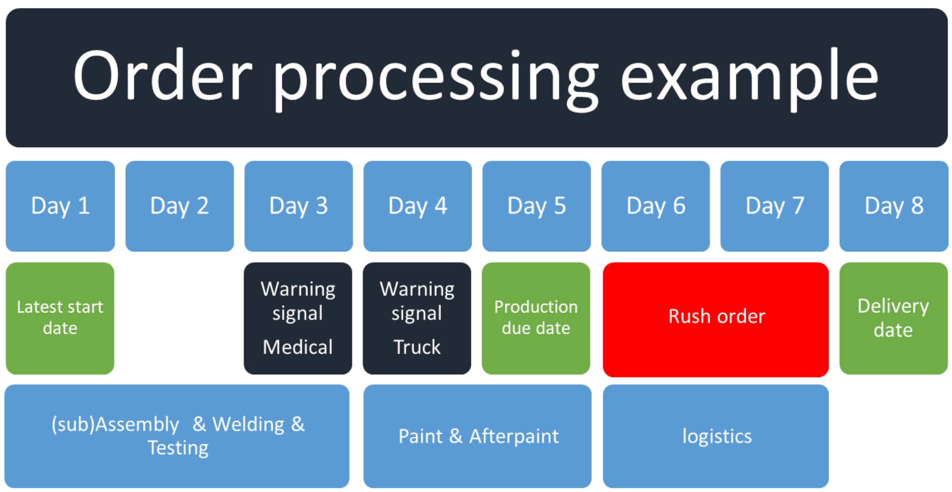


Figure 3-6 Production order processing example

To prevent rush orders, a warning signal is given by the planner to remind the production operators that the production due date is coming up for specific orders. Depending on the product category, Medical or Truck, a warning signal is given five or four days before the delivery date.

The week capacity depends on the product category. The regular truck cylinders and pumps are scheduled together from which a fixed amount is scheduled per day. In the case of electrical pumps or specialized products the capacity is calculated based on their individual production time. For medical items, a fixed number of pieces is scheduled per week.

The planner describes that the tactical planning is a time-consuming activity, since it is done by hand. A planning constructing by hand is not necessarily a problem that could explain the flow disruptions in the paint and after-paint department. Based on the interview the following tactical problems (TP) arise:

TP1. The tactical planning is established based on experience. Basically, the planning contains a little bit of this and a little bit of that product type. There are some guidelines. However, **no experiments are performed to check the performance of the planning**

TP2. The tactical planning is based on **rough approximations**, like the expected number of pieces per day.

TP3. **The planner has a lack of insight** about what machines are required to produce the production order. Therefore, the planner is unaware if the **available capacity** is used or not.

TP4. **Rush orders** do not change the original tactical planning. In the case a client prefers the order earlier, the production department is asked if they can squeeze them in. This put pressure on the production department.

### 3.3.2 Online production planning

The online production planning is the responsibility of the shift supervisor. The shift supervisor receives order tickets through Oracle (utilization report) which are production orders for the upcoming week. These order tickets are first adjusted such that the tickets contain: the item number, the release date, the quantity and the property Kanban if applicable. The Kanban property reveals that the production department has all components on the floor and can start working on this order right away. Not having the Kanban property means that the supervisor has to order parts at the warehouse. Here, the logistic team gathers the components for the order in special boxes which are stacked on pallet(s). Due to the staging mechanism one stack represents one order. In this way, depending on the order size, multiple orders can be stacked on one pallet. Next, the pallets are delivered at the production department in a special receiving area. If too many orders are placed at the logistic department then at some point the delivery area at production will be full. Meaning that the remaining orders are not picked and the supervisor receives a message that he should give logistics a call if there is space available again. In the case that logistics determines that components are out of stock then the order is not delivered.

The sequence in which the orders are produced is the call of the supervisor in charge. Each work shift has its own supervisor. The supervisor of the first shift determines the production sequence for the entire day. However, the second shift supervisor may decide to alter the sequence. The main reason to change the producing sequence are: (1) shortage in parts, (2) the availability of operators and their skills, (3) machine availability and (4) rush orders.

Overall, the first step in determining the order sequence is sorting the order tickets by item type. The benefit of this planning system is that the same products are produced after one another and setup time is reduced. The downside is that orders that are not common are pushed back in the week. To tackle this problem the second sorting step is introduced namely, sorting on release date. The last sorting step is Kanban or not. Orders that require component deliveries results in waiting time. Waiting is not ideal, so in the meantime, a Kanban order is produced. The order sequence is communicated to the operators by using a manual planning board.

In the past, a lot of production time was wasted on finding all the components and to setup the machineries. Today, one operator is responsible to collect the required materials and deliver them to the right production station. The experience of the various team supervisors is that component availability, quality and machine availability is the bottleneck in creating a robust production planning.

Based on observations and interviews, the following online planning (OP) issues affect indirect the paint and after-paint department:

- OP1. Similar to the tactical planner, the online planning is based on experience. After many years of experience, you know most of the products. There is **no matrix of what the setup time is between products** and there is **no manual describing the production path** thus how to move from workstation to workstation. The manuals how to produce the product can be found on the workstations. A new online planner will be lost since they have to check every single station to see what is produced where and to determine the production flow based on the information given there.
- OP2. **Waiting on the parts**. The production team supervisor calls logistics and requests parts for a specific production order. Somewhere during the day, the logistics team delivers them. However, this does not mean that production starts working on this order straight away. Since production had to wait for these items, they started with a different order. This is usually an order which can fully be assembled from floor stock (Kanban).
- OP3. A second observation is that production **orders with small quantities seems to be a problem**. These orders are usually less common, so the production department does not know by head how to produce them. Besides, all parts need to be picked by logistics and production requires space on the floor to receive them. The effect is that these small orders are often postponed to the end of the week. Due to this phenomenon there is a peak of production errors on Friday.
- OP4. **Rush orders are squeezed in.** The impact on the production schedule performance is not evaluated.

OP1. & OP2. & OP3. are all problems related to the offline production planning. There is no blueprint of what an ideal production planning looks like. Where OP4. is part of online scheduling procedure. Chapter 4 provides more insight in these different planning strategies.

## 3.4 Planning & production performance

The goal of this section is to evaluate the production output given the scheduled completion date of the production order. To recall, the scheduled completion date is set by the tactical planning. Section 3.4.1 shows which data is obtained and how it is transformed to be able to evaluate the planning and production performance. Section 3.4.2 determines if the production orders are delivered on time. Section 3.4.3 shows if the scheduled mix, based on the completion date, is equal to the finished mix.

### 3.4.1 Data acquisition

The data collection consists out of 650,000 of data rows representing all transactions of Shop Floor Finished Goods (SFFG) in the period of September 2017 till the moment of extraction November 2019. These two years are found enough because:

- The production mix of September 2018 till August 2019 can be compared with the previous peak of the previous year, so September 2017 till August 2018.
- The production mix of the surrounding non-peak months can be compared to the peak period.

The data list of Shop Floor Finished Goods (SFFG) contains the following information:

- the item number,
- the production order number,
- the transaction date and time representing the booking of finished goods,
- and the transaction quantity.

Be aware that the transaction quantity is unequal to the order quantity, because a part of the order can be finished the next day. Another remark concerning this data list is that it contains all finished production products. Since the scope of this research is limited to products that receive a paint job, the categorization method is applied which is described in Appendix A.

### 3.4.2 Meeting the scheduled completion date

A production **order as a whole** is finished **late** or **on time**. Figure 3-7 shows the scheduled production orders per month and distinguishes how many orders where finished on time and how many were late. In total 78% of the orders are produced on time given the period September 2017- November 2019. The months June, July and August are the months where most production orders are delivered late. To recall the production orders are unequal to customer orders. However, it is interesting that the **customer demand** of July and August is lower than the yearly average customer demand, which is shown in Chapter 2 Figure 2-5. A quick check in the confidential Appendix E shows that production backlog increases rapidly especially in the period of July and August 2018. What happened? According to the confidential logs: the number of shifts changed, but the average shift output remained the same. Besides, there are no records of machine failures. Therefore, it is highly likely that the tactical planning did not considered the reduced capacity.

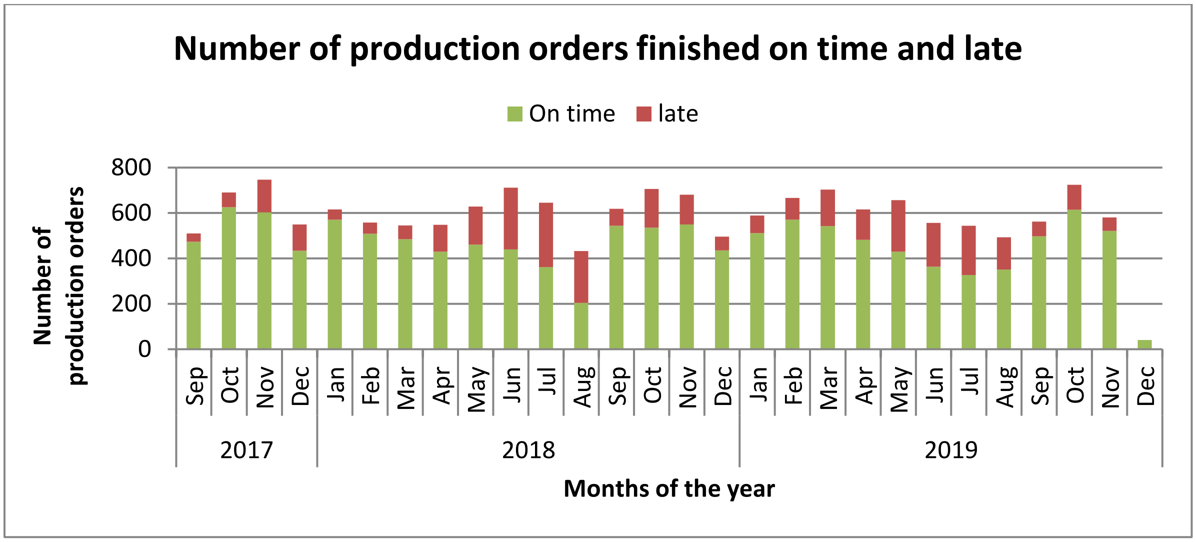


Figure 3-7 Number of finished painted production orders delivered before the scheduled completion date (SFFG file)

Figure 3-8 determines which weekdays deliver relatively the most production orders late given their scheduled due date. Surprisingly, about 100 orders are scheduled with a production due date on Monday in the period September 2017 - November 2019. From these scheduled orders 30% was not finished in time. On the other hand, Saturday is the most scheduled completion day from which 25% is finished after the scheduled due date. After inquiring, it is found that planning Saturdays is a mistake embedded in Oracle. An excel sheet reschedules the scheduled due date. However, rescheduling is done only for production orders with Saturday as due date. The due date is not set to Monday, but one day back, to Friday. The production department just received one day less to complete the order. This explains that from Thursday till Saturday the relatively number of orders late increases.

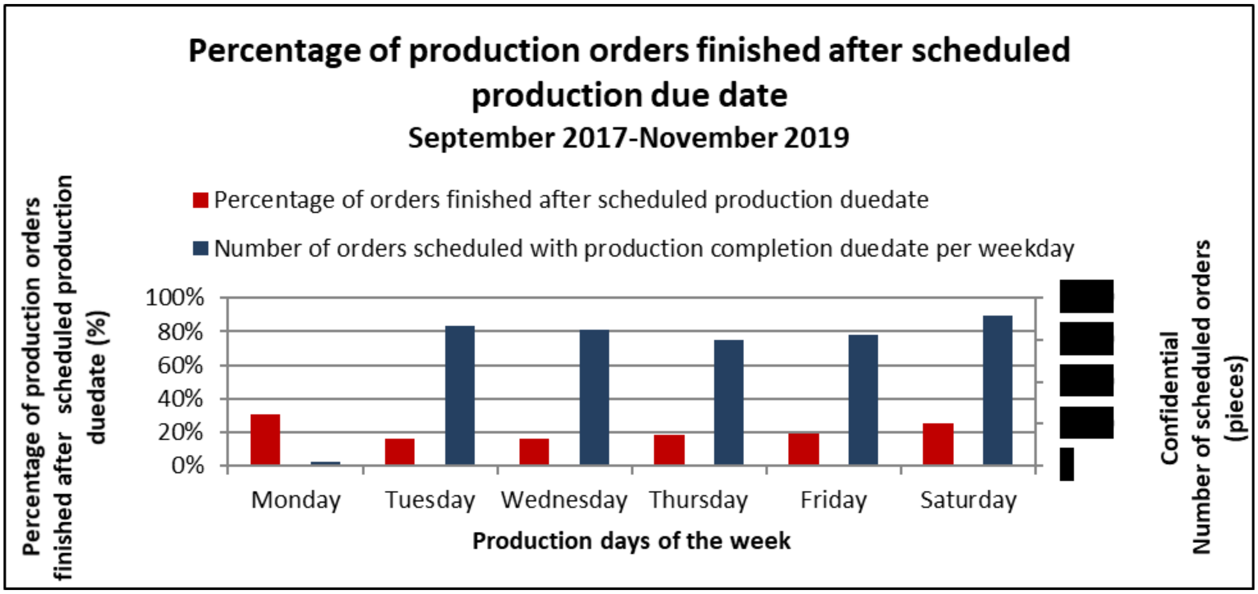


Figure 3-8 Percentage of production orders finished after scheduled production due date.

As stated before, the production order, as a whole, is produced on time or not. However, the company registers finished goods not as a finished order, but per full pallet or even a pallet layer. Hereby, it happens that an order is booked in five transactions and these transactions take place distributed over the day or even multiple days. For this reason, the production performance is analysed from a different angle.

Figure 3-9 shows the scheduled production demand based on the completion day per month in blue. The scheduled completion date is the production target and must be met according to the tactical planning. If the target is not met, it means that the pieces are produced too late. Note that the quantities are left out since they remain confidential. Overall, 94% of the total pieces produced are finished on time in the period Sep 2017- Nov 2019. This is more than the 78% of the order perspective. Perhaps that smaller orders are delivered late or most orders where at least partly finished.

Figure 3-9 shows more interesting findings. The on time produced pieces are split into early-, Just in time (Jit) and scrap. **Jit** represents the produced pieces that are finished at the completions date (light green). **Early** represents the finished pieces any day earlier then the completion day (dark green). The distinguish is made because, if an order is finished too early then the pieces need to be stored in inventory. This is inconvenient, since it adds additional work for the company. Instead of producing and directly loading it into the customer truck, the order is booked as inventory, stored and picked again a few days later. These activities are not value-added processing steps or in terms of lean management: waste. A customer does not pay the company to store finished items.

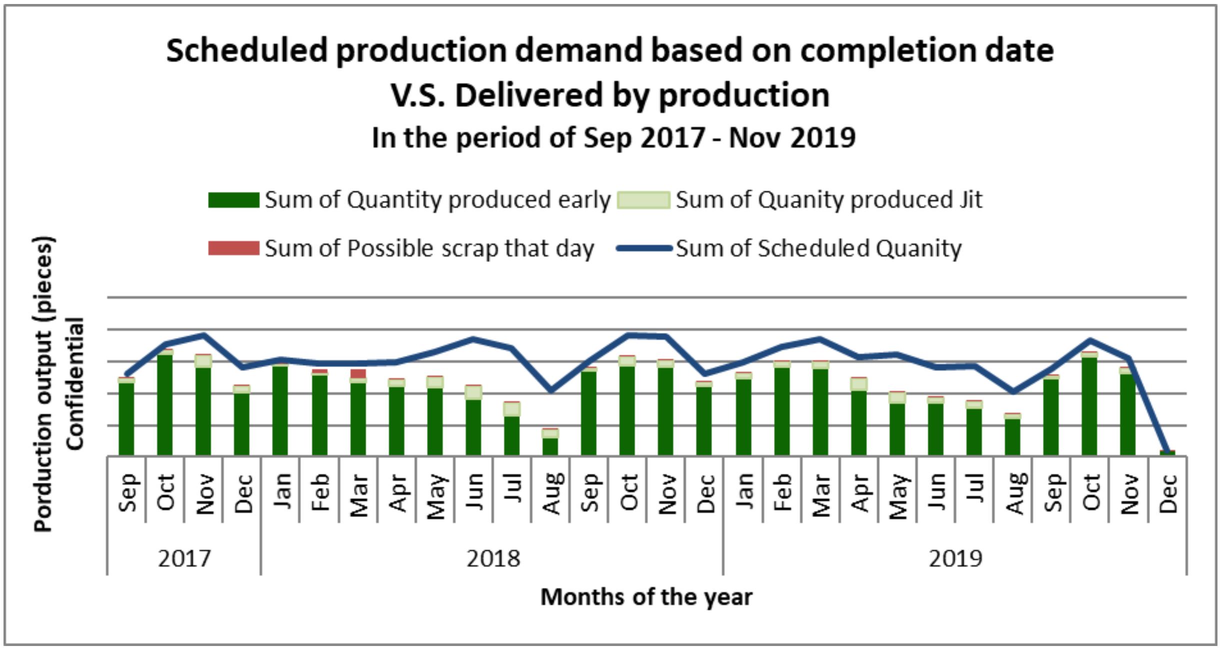


Figure 3-9 Scheduled production demand based on the completion date V.S. Delivered by production (based on SGGF)

Besides the finished early and Jit pieces, **scrap** also plays a significant role and is visualized in red in Figure 3-9. Not all scraped pieces of a production order are replaced. To explain by example: A production order consists out of 100 items. During the production process some scrap appeared, namely 8 pieces. These 8 pieces are (partly) produced, but unfortunately lost. The scrap pieces are usually not replaced immediately, meaning that either the additional 8 pieces are picked from safety stock or a new production order is placed to cover the 8 pieces.

At the end of this data analysis (DA) two problems are identified which has a big impact on production capacity namely:

DA1. **The tactical planning in Oracle does not consider weekends**. This results in many orders that need to be finished on Saturday and almost none on Monday. Instead of fixing the problem in Oracle, the production department reduced the internal lead time with one day. This is done only for the orders that need to be finished on Saturday.

DA2. **The tactical planning did not consider a capacity** reduction in 2018. The number of shifts were reduced due to the holidays. However, the tactical planning showed no reduction in scheduled pieces.

Besides pointing out issues, there is also an opportunity to reduce storage cost by finishing orders just in time instead of early.

### 3.4.3 Production mix vs. scheduled mix

It is known from Figure 2-7, that the average customer demand is annually 46% Cylinders, 45% pumps, 7% medical and 1% others. In our result, a category 'other cylinders' is added. The category other cylinders contains small non-truck orders like agriculture and marine items. This section analyses if the annually customer demand is visible in the tactical planning or scheduled production mix.

There are times that the tactical planner has to deal with high, low and average demand. To provide an indication: High demand is three times the low demand and average is two times the low demand. For each demand volume, it is determined if the tactical mix planning reflects the production output. To explain, the tactical planner sets the production due date of the orders. This results in a planned product mix on a given due date. We compare the planned product mix with the actual production output on the set due date.

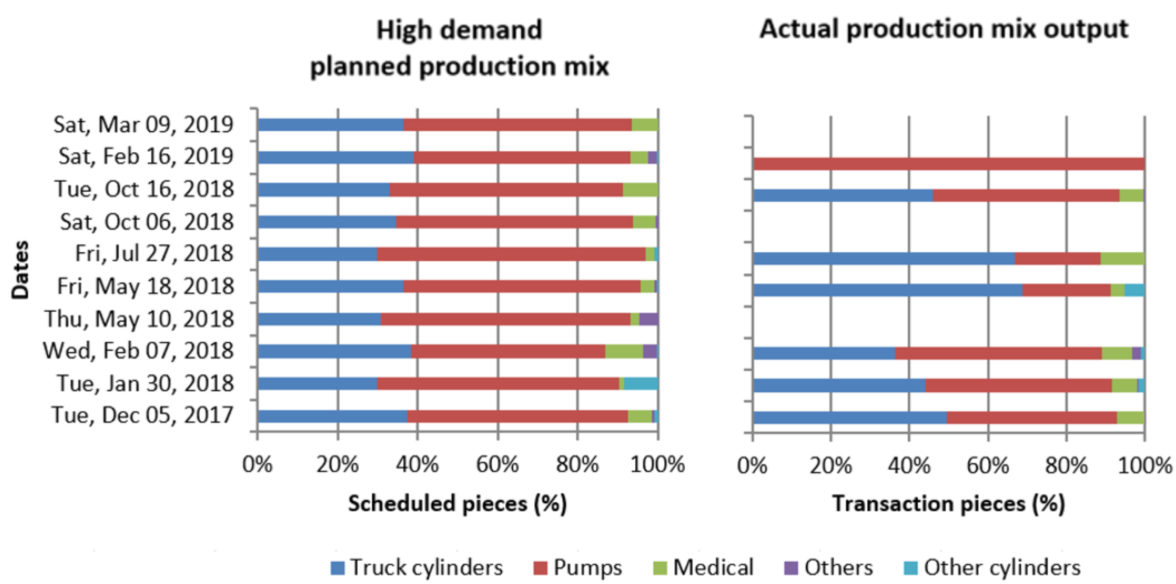


Figure 3-10 High demand planned production mix compared with the actual production mix.

First, the high demand product mix from tactical planning is compared to the actual production output in Figure 3-10. For example, tactical planner planned a production mix output that contains about 38% Cylinders, 54% pumps, 8% medical on Saturday, March 9$^{th}$, 2019. However, the actual production output is zero items that day. This result is explained by the programming error in Oracle which is described in Section 3.4.2. Figure 3-10 also comes with surprising results. The first surprise is that the percentage cylinders and the pumps are out of sync. To explain, usually customers buy a cylinder and a pump, because together they form the hydraulic system. Thus, why is this not visible in the product mix planned by the tactical planner or the actual production output? From the random selected dates, the mix planning contains always less than 38% cylinders and around 60% pumps. The second and last surprise is that planned production mix shows no resemblance with the corresponding production mix.

The same analysis is also performed on the *average* and *low demand* planning and is shown in Figure 3-11 and Figure 3-12. Within the average and low demand production planning contains 40% - 60% cylinders, where the *high demand* planning scores less than 40%. However, the production output mix is close to 40% cylinders, thus less than planned. This is an interesting observation. This could indicate that the online production schedule for the paint and after-paint department is trying to balance the number of cylinders with the other categories. Another observation is that both the low and average planning is overthrown by the production department output. They produce more than scheduled which is perfectly explainable. This is the result of the "Saturday Oracle mistake" as is described in Section 3.4.2.

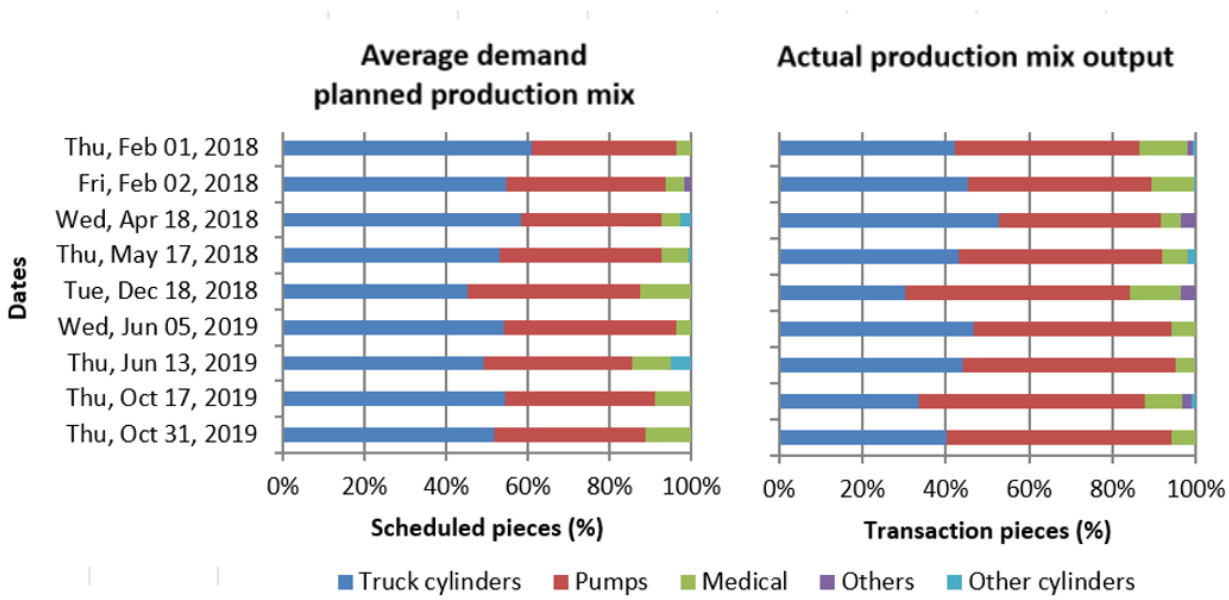


**Figure 3-11 Average demand planned production mix compared with the actual production mix.**

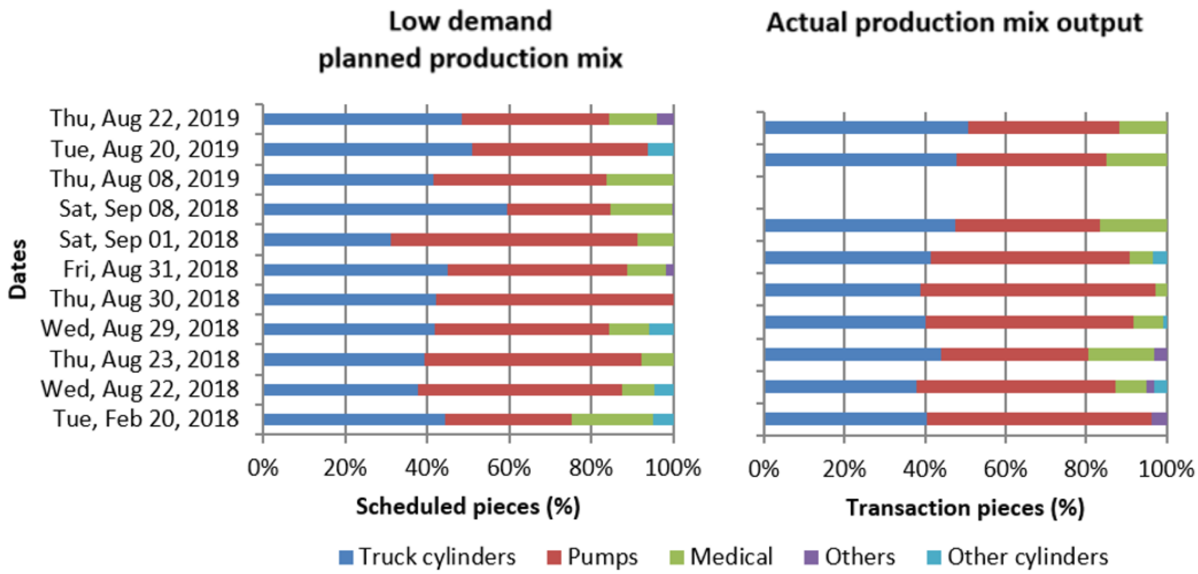


Figure 3-12 Low demand planned production mix compared with the actual production mix.

## 3.5 Problem analysis

The previous sections looked into the production processes and planning procedures with the aim to find issues that result in idle time in the paint department. Through interviews, observations and data analysis, a wide range of problems emerged. This section analysis the problems with the aim to put them in perspective. Section 3.5.1 connects the problems found and positioned them into a problem cluster. Section 3.5.2 describes the problems directly related to the unsuccessful paint schedule. The last Section 3.5.3 reveals how the problems mentioned in Section 3.5.2 are going to be solved.

### 3.5.1 The problem cluster

During the analysis of the production processes and planning procedures, a wide range of problems are found that could have an impact on the idle time in paint department. Some hypothetical problems where stated since they could not be proven or quantified. However, in consultation with management and team supervisors, there is a strong believe that the hypotheses contain a core of truth.

The problems mentioned by the sub-departments turned out to be connected as is shown in Figure 3-13: the problem cluster. It seems that multiple problems caused idle time in the paint department. The main problem, idle time at paint department (P1) is shown at the top of the problem cluster in yellow. The main problem leads back to 8 core problems shown in red(-yellow). The core problems need to be solved before other problems can be addressed. Otherwise you keep firefighting which will only work for the short term. The lack of assembly stations at the after-paint department (Problem AP1) is a potential 9$^{th}$ core problem. It is a potential problem since there no quantified measurement that there is a lack of stations. This is why it is displayed as a hypothetical problem. The core problems in red and yellow are already detected and the company is working on a solution. The problems in green are planning oriented which are of high interest to the company.

The problem cluster shows three topic clusters. The first cluster explains the blocking in the after-paint and how it is influenced by the lay-out of this department and the way of working. The second cluster in the middle concerns all planning oriented problems. The last cluster shows the impact of rush orders on the available orders in the paint mix.

To recall, it is the company's wish to look into the paint scheduling strategy for the paint and after-paint department. Management believes that a new paint scheduling strategy reduces the idle time, improves the flow and increases the production output. Given the interest in the paint schedule, the focus is shifted to the (core)problems of the planning-oriented cluster which will be explained in the subsequent section

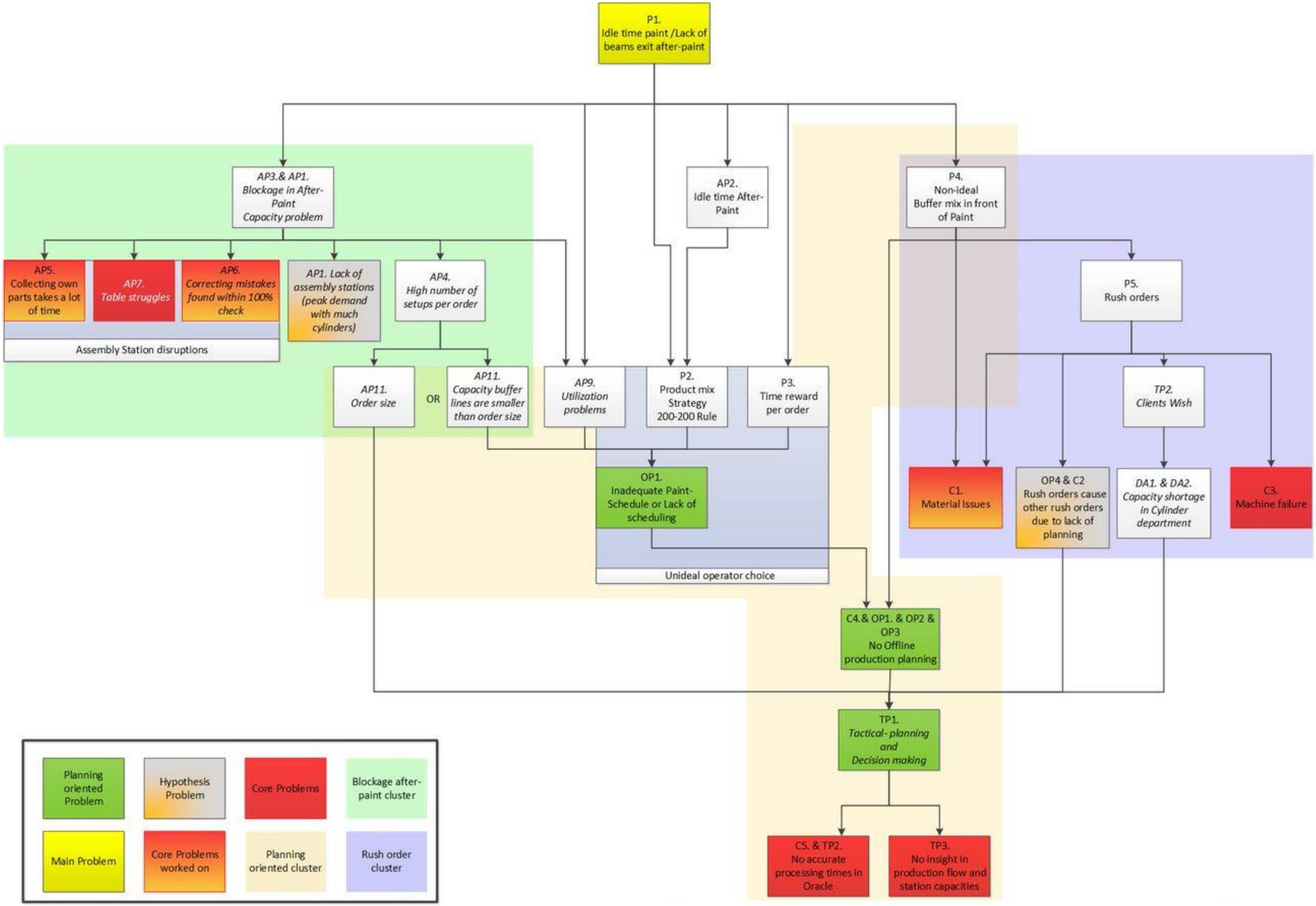


Figure 3-13 Problem Cluster

### 3.5.2 Problems related to paint schedule

The extensive problem cluster revealed many issues causing the idle time at the paint department. Based on the wishes of the company we narrowed the problem cluster down to the problems that have a negative impact on the paint schedule. The relevant section of the problem cluster is displayed in Figure 3-14.

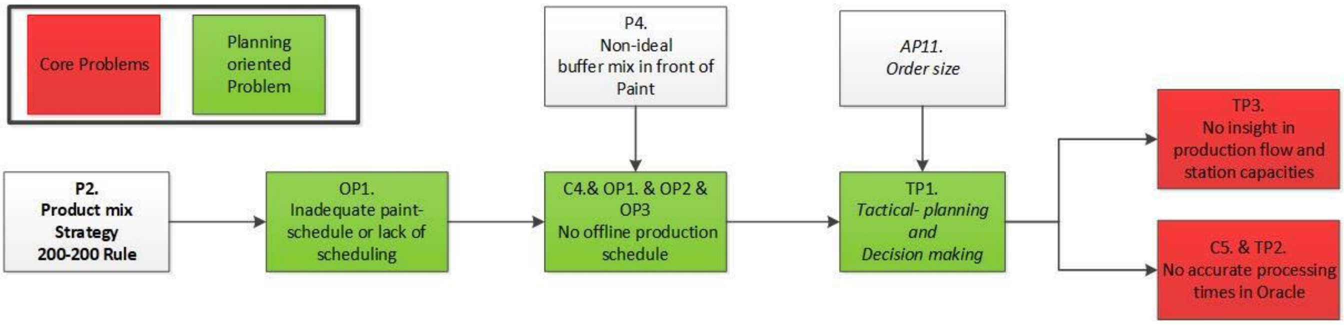


Figure 3-14 Section of problem cluster

The paint order sequence which is chosen by the paint department also decides the packing sequence in the after-paint department. The paint operators make use of the 200-200 rule to select and order from the paint buffer. However, the 200-200 rule is not always applicable given the orders inside the buffer (Problem P2, see Figure 3-14).

Regardless of the applicability of the 200-200 rule, the performance of the rule is unknown. This is mainly the cause of a lack of creating actual schedule (Problem OP1). To explain further, the operators decide along the way which order to paint next. Besides, the operator considers for the order to select also other indicators as shown in the Problem cluster Figure 3-13. The indicators are: the after-paint utilization, the order size and the time reward they receive for finalizing the order. But why would the paint department create a schedule? It is almost impossible to predict which orders are entering the paint buffer. The cylinder, pump and medical department create their 'schedule' also along the way (Problem C4, etc.). These production departments are responsible for what is in the paint buffer mix and therefore the successfulness of any paint schedule.

The tactical planning has also its share in the performance of the operational schedules (Problem TP1). The tactical planner struggles with the creation of the planning due to a lack of valid data on processing times (Problem C5). Furthermore, the tactical planning has lack of insight about the production path of the items and the capacity of the workstations (Problem TP3). For this reason, the planner relies on feedback on the operational department. A balanced demand is therefore a necessity. The moment the demand or available capacity shifts, the tactical planner needs to find with production a new steady state again.

The tactical planner also sets the size of the production order (Problem AP11). Through the problems cluster it is found that the paint and after-paint department is struggling with the order size. The assembly line capacity at after-paint is not large enough to fit an entire order at one buffer line resulting in either a blockage or an additional changeover. The additional changeover is the result of supplying two buffer lines instead of one. These shortage in line capacity, additional changeovers and the relation with the order size is visible in the problem cluster Figure 3-13.

All problems mentioned need to be solved. The next section describes the problem-solving approach.

### 3.5.3 Problem-solving approach

The previous sections showed the problem cluster which distinguished three topics: problems related to after-paint, problems related to rush orders and problems related to planning and organization. The wish of Power-Packer is to develop an adequate paint schedule. For this reason, the focus is put on the cluster section related to planning and organization which was described by Section 3.5.2.

Given the different planning and schedules mentioned in the problems cluster and the lack of measuring the performance of these schedules, we would like to explain the different planning and control activities and how they are imbedded in the different hierarchical levels of an organisation.

The paint schedule is part of the problems mentioned in the problem cluster, but is not a core problem. When we look at the different problems in the problem cluster, we find that there are four problems that should be tackled first before a paint schedule can be developed. The four problems referred to are: invalid data on processing times, a lack of overview about the production path of each item and the required capacity for each workstation, the inadequate tactical planning and last, the lack of an operational planning. Usually, the core problems need to be solved first before other problems can be addressed. However, given the current time frame of this research and the wishes of Power-Packer, a different approach is set.

One of the research goals is to develop an adequate paint schedule and to prevent a third-shift. This can only happen in this time frame if we leave the core problems as is. To develop a paint schedule for Power-Packer the following questions should be answered first:

1. What are the most frequently mentioned planning methods described by literature and which of them may be applicable to Power-Packer's situation?
2. What does literature describe about the implementation of product mix strategies into production schedules and how to form them? Furthermore, could the product mix strategy be applicable to Power-Packer's situation?
3. How does a new planning strategy perform on the paint and after-paint department and what may the benefits be compared to the current scheduling method?

Through literature, suitable planning strategies are identified for the production environment of Power-Packer as well as for the use of a product mix strategy. The planning strategies found are put to the test by implementing them in a case study for which a digital twin is developed. The digital twin makes use of the same tactical production planning used as in the peak period.

<u>The drawback</u> of finding a paint schedule without solving the underlying problems is that the conditions may change. A scheduling method which proves to be adequate today may not work as well in the future. This note should be taken into evaluation when selecting a scheduling procedure from literature to apply onto the Power-Packer case study.

This critical note proves that there is a necessity to solve the *other four problems*. To help Power-Packer overcome the core problems in the future, the need of a generic roadmap is arisen. The paint schedule is not the only planning concern that Power-Packer has. This leads to the following question:

4. How may this research be extended to other production departments?

A roadmap is developed that summarises the steps made in this research. Besides, a small literature study to make it more generic and to provide tips and tricks such that all problems are covered.

*The next chapter is going to discuss literature about the different activities in planning and control and the different planning strategies applicable for the paint schedule. Afterwards the planning strategies will be put to the test in Chapter 5 & 6. Later on, the generic roadmap is developed, but first a summary of this chapter is provided in the next section.*

## 3.6 Summary

The aim of this chapter is to show the causes of the idle time in the paint department and to quantify the idle time. To quantify the observed idleness at the first workstation of the paint department, a new measuring methodology is introduced. Operators at the paint department are asked to turve every time that their work is interrupted. The turve method is ideal since it takes almost no time and is only applied if the operator is already disrupted. It is found that on average, the operator is disrupted eight times a day which is quantified as approximately two hours. The actual average number of disruptions might me higher since the operators mentioned that they sometimes forgot to turve.

To find the causes of the idle time, we looked into production processes, planning procedures and the planning & production performance. Hereby, a broad range of employees are interviewed. The outcomes of the interviews are substantiated with observations and additional data analysis to prove that the causes are real. This resulted in 24 problems affecting direct and indirect the idleness at the paint department. The 24 problems are arranged in a problems cluster and showed 7 core problems. The problem cluster distinguished three topics: problems related to after-paint, problems related to rush orders and problems related to planning and organization. The wish of Power-Packer is to develop an adequate paint schedule. For this reason, the focus is put on the cluster section related to planning and organization.

The paint schedule is part of the problems mentioned in the problem cluster, but is not a core problem. Furthermore, we found that there are four problems that should be tackled first before a paint schedule can be developed. The four problems referred to are: invalid data on processing times, a lack of overview about the production path of each item and the required capacity for each workstation, the inadequate tactical planning and last, the lack of an operational planning. Usually, the core problems need to be solved first before other problems can be addressed. However, given the current timeframe of the research and the wishes of Power-Packer, a different approach is set.

The goal is to develop an adequate paint schedule before solving the core problems. This will be done by developing a simulation model and to test different scheduling approaches. Additionally, to help Power-Packer overcome the core problems in the future, the idea of a generic roadmap is arisen. The aim is to use literature and the results of the paint schedule strategies, to develop a framework with tips and tricks such that the planning problems can be solved in each hierarchical planning level of the organization.

*The next chapter investigate different planning and scheduling approaches found in literature with the aim to find a suitable scheduling method for Power-packer.*

# 4 Literature review: scheduling strategies

The previous chapter showed that planning and scheduling is challenging through multiple hierarchical levels of the organization. For this reason, Section 4.1 explains the basic elements of planning and control. This includes a description of the different hierarchal planning levels of the organization and their activities. Afterwards, the focus is back on creating a paint schedule for the paint and after-paint department. Section 4.2 looks into which planning strategies are suitable for Power-Packer given the production environment at the paint and after-paint department. Section 4.3 provides a review on how product families may contribute to creating a schedule. It provides different techniques to create families. Furthermore, the applicability of the different techniques is discussed given the current situation of Power-Packer. Last, a summary is given in Section 4.4.

## 4.1 Basics elements of planning and scheduling

We have seen in the previous chapter that creating a planning or schedule is challenging. Power-packer's tactical planning strategy is based on experience, mainly due to a lack of data. Over the years some insight was gathered to make a tactical planning, however it is not robust for changes in demand. The operational schedule is a different story. There is a schedule which is established along the way and is also continuously adapted. Not knowing the actual production sequence in advance, makes it challenging to evaluate the scheduling performance. With the aim to create more understanding about planning and control, we provide an overview of the basic elements of planning and scheduling.

Planning and scheduling is part of a decision-making process that deals with the allocation of resources and activities to time periods with the aim to optimize one or more objectives (Pinedo, 2016b). The decision-making process is often referred to as planning and control. The functions activities of planning and control are described in Section 4.1.1. To provide a better understanding about when and who performs the activities, the hierarchical planning and control framework of Hans et al. (2007) is given in the Section 4.1.2

### 4.1.1 Functions of production planning and control

A wide range of functions and activities are involved in planning and control within an organization. (Kiran, 2019) classified the functions of planning and control into three phases: *pre-planning*, *planning* and *control*. **Pre-planning** involves functions concerning the factory planning which determines:

- Product development and design. This involves an overview of the products that are and become part of the company's portfolio. It also contains the characteristics of the product: (i) the type of material to be used, (ii) the machines to be operated on, and (iii) the tools to be used. This function influences therefore the make or buy decision for specific parts.
- The plant layout. This determines the structural units like the positioning of the factory and its lay-out. Furthermore, it describes the design selection of the number

of machinery and equipment required along with its production processes and logistics. Along with the product characteristics this function influences the product mix.

- Selection of control systems. This stage defines the objectives and monitoring strategies for production -, material -, quality -, labour - and financial control.
- At last, the forecast planning. This planning is built up out of forecasts for the long-middle and short term. The forecast provides an estimation of the volume to be produced.

The pre-planning phase determines the production requirements or aggregated planning which is a planning set for the long-term. The *aggregated planning* is part of the strategic decisions which will be explained in the upcoming Section 4.1.2.

The function of the **planning phase** is summarized by planning all available resources (manpower, machinery, methods and materials) with the use of the information and objectives determined in the pre-planning phase (Kiran, 2019). The planning phase involves multiple activities which are explained in Section 4.1.2.

The **control phase** is about monitoring and evaluating all processes that influence the production department (e.g. machine down-time, inventory and logistics). Besides, the control phase responds to dispatching and could lead to adjusting the production schedule. The control phase also contains a feedback loop to the preplanning. In the case that a lot of down time is registered from a machine, it could lead to a project that replaces the machine. This decision to replace the machine is part of the pre-planning.

Figure 4-1 summarizes the classification scheme of Kiran (2019). It shows that the functions are related with activities that need to be carried out in a fixed sequence. It also indicates that there is interaction between the phases. To provide a better understanding about when and who performs the activities, the hierarchical planning and control framework of Hans et al. (2007) is given in the subsequent Section 4.1.2.

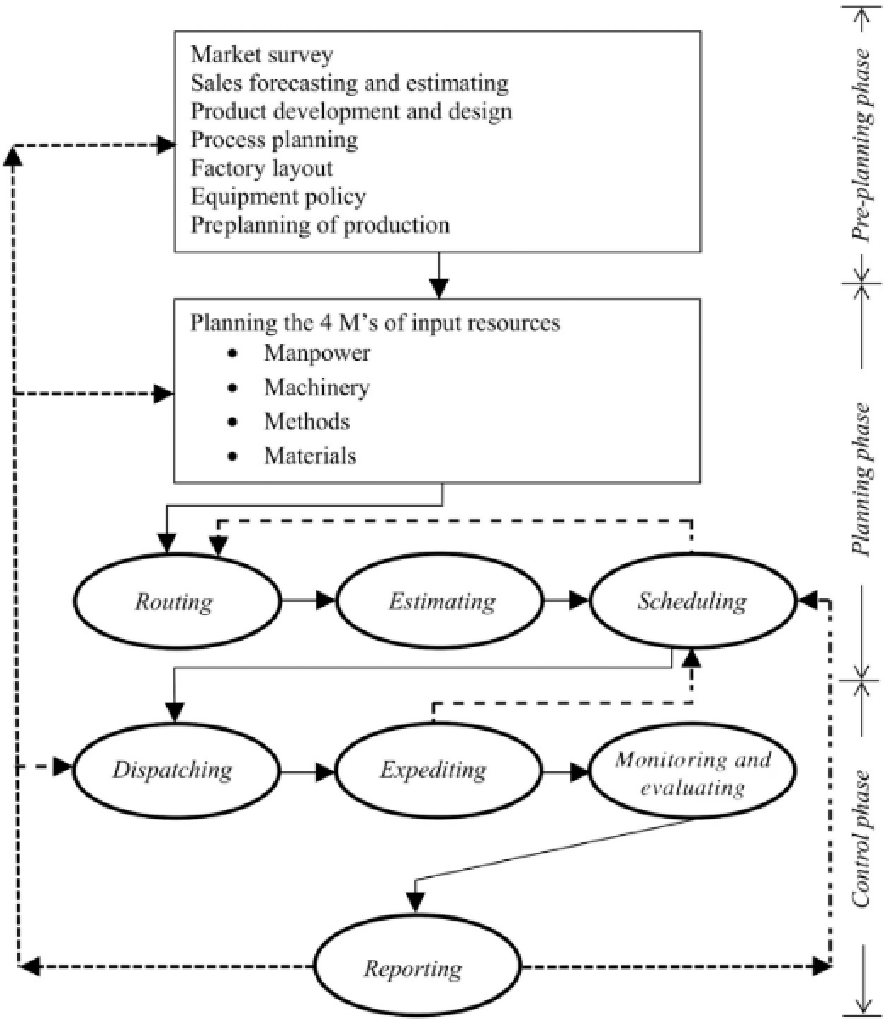


**Figure 4-1 Summary of functions of production planning and control** (Kiran, 2019)

### 4.1.2 Hierarchical planning and control framework

Hans et al. (2007) describe a hierarchical planning and control framework for multi-project planning organizations, shown in Figure 4-2. This framework holds all activities of the production planning described by Kiran (2019) in the previous section.

The hierarchical framework is an extension of the framework of the De Boer (1998) who distinguished three functional planning areas: *technological planning*, *resource capacity planning* and *material condition*. The technological planning holds the information on how products need to be produced. The resource capacity planning involves capacity management (e.g. resource availability of labour and machineries upcoming year). The material condition or material management involves the acquisition and handling of parts and services required for the project. The activities of the functional planning are divided into three hierarchical levels: *strategic*, *tactical* and *operational level.*

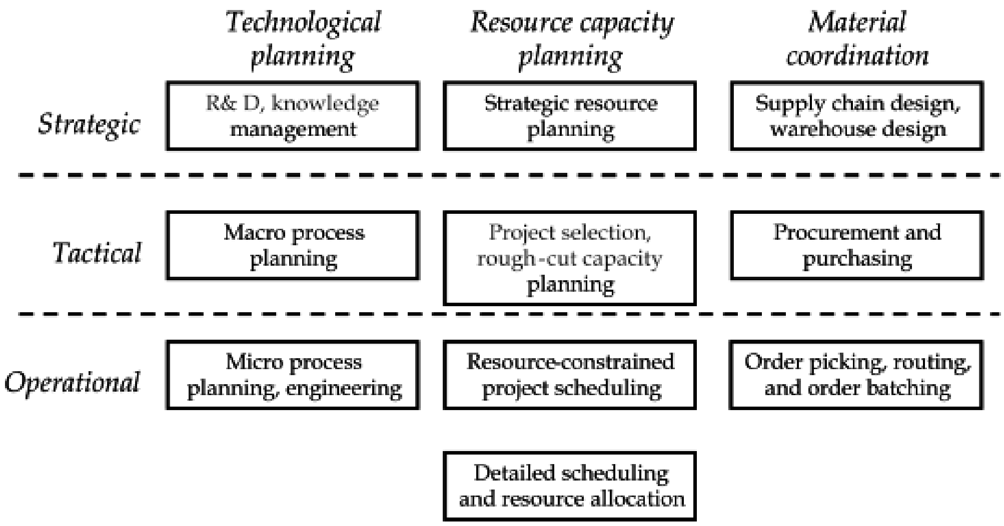


Figure 4-2 Hierarchical project planning and control framework (Hans et al., 2007)

**The strategic level** involves setting and enabling long-term (6-18 months) company goals which are often structural decisions made by the highest management level. Examples of strategic planning are relocating the facility, increase the aggregated capacity by extending the machine park and the introduction of new projects or products.

**The tactical level** supports the operational department by translating the strategic goals or objectives into processes. The planning horizon looks roughly 6 months ahead. The aggregate planning is translated into a *Master Production Schedule* (MPS). The MPS holds all production orders and allocates the orders to the resources at a certain time slot.

The *Rough Cut Capacity Planning* (RCCP) checks the feasibility of the MPS. It addresses level of capacity available in the upcoming weeks or months (e.g. outsourcing of work, the number of work shifts). Basically, the RCCP makes the trade-off between capacity and time flexibility. This trade-off is in literature often described as the loading or order acceptance problem (Hans et al., 2007).

If the MPS is found feasible, then the materials need to be found to produce the order. The M*aterial Requirements Planning* (MRP) keeps track of the inventory. The MPS generated demand for parts or sourcing activities. The parts required to produce the order are found in the *Bill of Material* (BOM). In the case of a material shortage a purchase order should be placed. Nowadays, many software packages, so called ERP systems establish the material requirements planning (Pinedo, 2009).

**The operational planning** addresses short-term decision making related to executing of the production plan (week planning). Usually the capacity planning is fixed and the demand is known. Only rush orders that could arise need to be forecasted and scheduled on occurrence. The hierarchical framework is later adopted by Hulshof et al. (2012) and applied to planning and control decisions in Health Care. In addition, the operational level is subdivided in *offline* and *online* decision making.

The **offline operational planning** reflects the in advance planning operations (Hulshof et al., 2012). Examples of offline planning are: fixing the production sequence of orders, allocate staff to shifts and all material is picked for the orders to produce.

The **online operational planning** is a control mechanism which monitors if all processes are going conform planning and responds to unplanned events (Hulshof et al., 2012).

Having a better understanding about the different planning activities and about how the hierarchy levels work together, it is time to look for planning and scheduling strategies to create a schedule for the paint and after-paint department of Power-Packer.

## 4.2 Planning and Scheduling methods

First, we formulate the scheduling objective, before exploring the various scheduling methods. Next, Section 4.2.2 describes the most frequently mentioned planning and scheduling strategies. With the obtained information, the most promising method is selected in Section 4.2.3 with intend to apply it in our case-study later on. The selected method is explained in more detail in Section 4.2.4.

### 4.2.1 Scheduling objective

To narrow the search range on planning and scheduling methods: (1) we recall the research goal, (2) we identify the manufacturing system on which the scheduling method should be applied and (3) we look into what type of scheduling methods we might be interested in. These topics are described in the flowing sections.

**Research goal**

The aim of this research is to find a scheduling strategy for the paint and after-paint department of Power-Packer that minimizes the idle time of the various stations while maximizing the output. The reason for this objective is to find out if a new scheduling strategy may prevent a third-shift in the future. The planning horizon is one day. All orders coming in today need to be scheduled tomorrow.

**Manufacturing system**

Whether you are looking for a method to develop a tactical planning or operational planning, many methods are available which could be applied in all situations. Not all manufacturing systems are the same. Perhaps this is the number one reason why searching for planning algorithms, the machine environment is often mentioned. Not all planning methods are suitable for all manufacturing system types. We established a list with different manufacturing systems along with observed planning strategies in Appendix F.

The Power-Packer production environment as a whole is best explained as a job shop. Looking to the individual subdepartments of production, then there is a diversity of different manufacturing systems. Paint and after-paint's overhead conveyor belt is an assembly line.

Assembly lines are classified into three classes: single model, multi-model, and mixed-model. The single model line is dedicated to the production of one specific product. The multi-model and mixed-model lines are designed for the assembly of more than one product. A multi-model line produces different products as a batch. A job order contains multiple products which are the same and between different job types a setup is required. A mixed-model line produces the units of different products in an arbitrarily intermixed sequence, and the lot size is one (Liao, 2014).

We identified the paint and after-paint's overhead conveyor belt as multi-model line since the paint department spray-paints batches. The products attached to a transport beam are always the same. Besides, setups are required between orders.

**Type of scheduling method**

Finding an optimal production schedule for a single machine environment is relatively easy compared to flexible manufacturing systems. A schedule for a single machine manufacturing system is often solved to optimality using mathematical programs in little time. Nowadays, companies often invest in developing a flexible manufacturing environment like a job shop or flow shops. In this way, the companies can increase the variation in products such that customers are able to get a tailor-made solution (Pinedo, 2016). The drawback is that due to the flexibility of the machine spark, more sequencing options for scheduling emerge. Having more options to evaluate increases the computation time. Since time is money, a lot of research is performed in developing heuristics that aim to seek acceptable, near optimal solutions.

This latest mentioned is also what we intent to apply in this research. On average 30 to 35 orders need to be scheduled daily at the paint department. To find the absolute optimal result would mean to evaluate the total number of sequencing options which is 35*(35-1)!. We are not comfortable with this number of iterations. This is why we are looking for heuristics that seek near optimal solution in an acceptable amount of time.

***To summarize the aim of this literature study:*** *We are looking for a <u>heuristic</u> that finds an acceptable, near optimal solution for the <u>multi-model</u> paint and after-paint line with the objective to <u>minimize</u> the idle time of the various workstations while increasing the output.*

### 4.2.2 Literature results

This literature review summarises the most frequently used and best rewarded scheduling heuristics for multi-model lines. To be more specific, we looked for optimizing heuristics with a similar objective as our research which is to reduce the idleness of multiple workstations while increasing the production output. Since the hits on multi-model lines where limited the research is extended with result on mixed-model lines. The following sections describe the results.

**Multi-model lines**

Search keywords as multi-model line & planning heuristics did not provide many promising hits. However, one hit is worth mentioning: Dong et al., (2015) have the objective to reduce the tardiness of orders while increasing the utilization rate of the line. They made use of a local search method which perform swaps in multiple iterations with the aim to reduce the tardiness of the orders. The local search heuristics in combination with a tabu-list performed best in reducing the tardiness and increasing of the line utilization. The tabu-list is an addition that remembers specific swaps and prevents that the same random swaps are performed again. Section 2.2.4 elaborates further on the tabu-list and its advantages. Dong's research showed that the Tabu-list implementations work well for their case study, however it makes no remarks about the computation time. Besides, the complexity of their case-study does not come near our circular conveyor belt with transport beams. For this reason, we extend our search with different keywords.

The best results received is from the search terms: mixed-model lines & planning heuristics. Mixed-model lines are similar to the multi-model line, but have the advantage that no setup time is required. These mixed-model lines are often found in the automotive industry. Next, we describe the highlights of our findings about the most frequently mentioned heuristics on mixed-model lines.

**Mixed-model lines**

Kim & Jeong, (2007) aim to minimize the unfinished work of a mixed-model line. They schedule between 5 and 30 jobs. Therefore, they use a mathematical approach to find an optimal solution and compare it with branch-and-bound (B&B) and B&B with a local search procedure as initial solution. The local search method chosen is minimum setup-up time first. The B&B local search heuristic performed on average 15% worser than the B&B optimal solution. However, the computation time of the B&B local search is reduced with 99%.

Tamura et al. (2011) and Xiaobo & Ohno, (1997), propose two algorithms to minimize the total conveyor stoppage time. The conveyor is described as a mixed-model line. Tamura et al. (2011), propose two algorithms to minimize the total conveyor stoppage time. The first is a branch-and-bound method which is devoted to find an optimal solution, but is time consuming. Evaluating possible sequences of 20 jobs took 1 hour to find the optimum

(Tamura et al., 2011). The second method is simulated annealing. This method starts with a solution and aims to improve the solution by repetitively making small changes and evaluates if it is improved or not. Simulated annealing makes use of local search methods to make improvements to the current schedule. This heuristic finds a near optimal solution and is about 100 times faster than the branch-and-bound method (Xiaobo & Ohno, 1997).

Pinedo, p.375 (2016) mentioned that simulated annealing is very generic and is adaptable to various scheduling. The disadvantage is that annealing does not guarantee an optimal solution, but aims to find a reasonably good solution in a relatively short time.

### 4.2.3 Motivation heuristic selection

From the literature review, it is observed that simulated annealing (SA) is the most popular. SA finds a near optimal solution in an acceptable amount of time in comparison with branch-and-bound which finds an optimal solution for small problem sizes, but takes substantially more computation time. Furthermore, annealing is adaptable such that it becomes applicable for a variety of scheduling problems. The computation time along with its flexibility makes annealing more attractive than branch-and-bound. Simulated annealing has proven its effectiveness many times under different manufacturing environments as can be found in Appendix F. These arguments make SA a promising heuristic for our case-study. Besides, if SA proves itself worthy, it can be advised for the other planning problems Power-Packer experiences. This is the main reason for selecting this heuristic to be explored further. The next section will provide more background information on simulated annealing.

### 4.2.4 Simulated annealing (SA)

The simulated annealing finds its origin in the metal industry. Metal is first heated up to a high temperature and then cooled down with a very slow rate until the room temperature is achieved. Cool it too quick and the metal will crack which is why the slow rate is very important. This cooling phenomenon is also embedded in SA. The heuristic generates a solution which is evaluated. The heuristic accepts the solution if the objective is improved. However, accepting only better solutions may result in becoming stuck in a local optimum. The algorithm introduces a probability factor that decides to accept a bad solution in the attempt to escape the local optimum (Mishra et al., 2005). Figure 4-3 shows an example for a maximization problem in which the global optimum is the optimal solution.

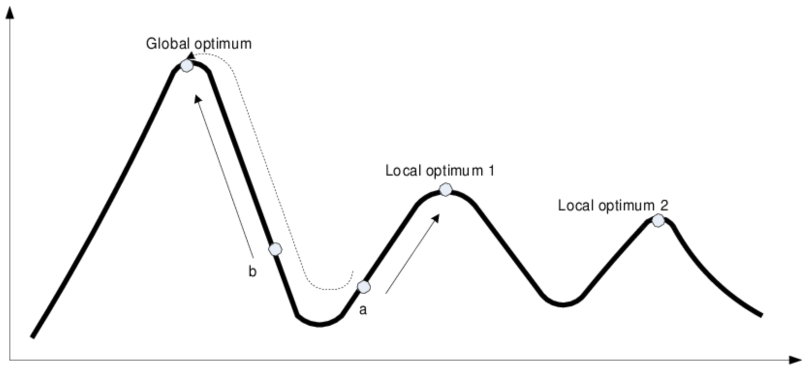


Figure 4-3 Example of local and global optimum, source: Mahama, (2012).

**The procedure of the SA heuristic is as follows** (Mishra et al., 2005)**:**

1. Generate an (random) *initial solution* by using some heuristic. Call it the *current solution* and the *best solution*.
2. Set the start temperature ($T_{start}$), current ($T_{current}$) which is equal to the start temperature and the stop temperature ($T_{stop}$).
3. Execute the following steps until $T_{current} < T_{stop}$
   3.1. Perform the following loop K (*Markov value*) times.
      3.1.1. Generate a *candidate solution which is established by a neighbour heuristic.* This is a small adjustment in the current solution.
      3.1.2. Calculate the performance of the candidate solution by an objective function.
1. If the *candidate solution* is better or equal than the current solution:
   1.1. Save the candidate solution as current solution.
   1.2. Next, evaluate if the candidate solution is better than the *best solution*. If this is true save the candidate solution also as best solution.
*2.* If the *candidate* solution is worse than the current solution, then the candidate solution could still be accepted with the *SA transition probability.*
   3.2. Upgrade the $T_{current}$ by multiply it with the decrease factor *r*
4. *Display best solution.*

**Generate initial solution**

The initial solution is established by using a heuristic. In the example, assign jobs to machines based on a *first come first served* rule. This means that the first job is assigned to the first machine available and is followed up by the second on the list. Note, that there are limitations. Not all jobs could be scheduled on the same machine and often the entire production path of the job has to be scheduled taken into account the precedence constraints.

**Start and Stop conditions**

The start conduction is the initial start "temperature" like in the metal example. The search initially starts with a high temperature, because the higher the temperature the better chance of escaping local optima (Mishra et al., 2005).

There are different options for formulating the stop criteria. There is the option to stop when a certain cooling temperature is reached (Mishra et al., 2005). The effect of the cooling temperature is explained underneath the transaction probability equation. A second option is to let the procedure run for a prespecified number of iterations. Another is to let the procedure run until no improvement has been obtained for a given number of iterations (Pinedo, 2009).

**Generate neighbourhood solution**

The neighbourhood solution is the result of a local search procedure. Local search methods aim to find a better solution than the current solution. There are various methods to generate a solution. The simplest heuristic is to *swap*, for example, two randomly selected jobs in a production sequence or to *move* one job to a different position in the queue. Pinedo (2009), proposes local search methods that searches for the most promising swap or move. These local search methods are also mentioned inAppendix F.

Afterwards, the solution is evaluated by an objective and is either kept or not based on a decision rule. The heuristic keeps generating and evaluating possible solutions until it meets the stop criteria.

**Transition probability equations**

Assuming that the objective $f(\ )$ is formulated for a minimization problem then formula 4.1 is applicable to the situation. The candidate solution ($S_{candidate}$) is always accepted (probability of 1), if the solution is smaller or equal than the current solution ($S_{current}$). If the candidate solution performs worse than the current solution, the transition probability is computed by the exponential equation.

$$P_{S_{current}, S_{candiate}}(T) = \begin{cases} 1, & f(S_{candidate}) \leq f(S_{current}) \\ e^{\frac{f(S_{current}) - f(S_{candiate})}{T_{current}}}, & otherwise \end{cases} \qquad \text{Formula (4.1)}$$

As stated before, accepting a worse solution is an attempt to escape a local optimum. Accepting the bad solution depends on the value of the transition probability and a random number. The random number is drawn from a $Uniform(0,1)$ distribution. If the transition probability is higher than the random number, the candidate solution is accepted.

$$P_{S_{current}, S_{candiate}}(T) > Random\ \ number \qquad \text{Formula (4.2)}$$

The probability transition is based on the current temperature ($T_{current}$).

**Decrease factor r**

The current temperature reduces after N iterations with a decreasing factor $r \in (0,1]$. The larger the factor $r$ is chosen the slower the temperature reduction, so the higher the transaction probability will be. This result in a higher probability to escape a local optimum by accepting a worser solution.

$$T_{current} = T_{current} * r, \qquad \text{Formula (4.3)}$$

**Markov value**

The number of iterations before the current temperature decreases is called the Markov chain length N. Similar to the decrease factor r, the higher the value for N the higher the probability to escape a local optimum. For this reason, the decrease factor and the Markov value need to be chosen carefully.

**Limitations of SA**

The effectiveness of simulated annealing depends on the design of the neighbourhood and on how the search is conducted within this neighbourhood. If the neighbourhood is designed in a way that facilitates moves to better solutions and moves out of local minima, then the procedure will perform well. The search within a neighbourhood can be done randomly or in a more organized way. For example, the contribution of each job to the objective function can be computed and the job with the highest impact on the objective can be selected as a candidate for an interchange (Pinedo, 2009).

SA has no concept of short-term memory list of prohibited neighbouring solutions as in for example the tabu search heuristic. The lack of memory increases the possibility of revisiting a solution that was already evaluated. The evaluated solution could again be a local optimum. This means that SA requires more iterations and thus longer computational time to generate the global optima solution. For this reason, researchers highly recommend to integrate a tabu-list into the SA algorithm (Mishra et al., 2005).

**Tabu-list**

The tabu-list keeps track of the mutations performed by the neighbourhood heuristic. A mutation is for example, two jobs that are swapped. Since these swaps are on the list, these two jobs cannot be swapped back again for as long as this mutation is on the tabu-list. The tabu-list has a fixed number of entries (usually between 5 and 9), which depends upon the application (Pinedo, 2009). Every mutation in the current schedule is positioned at the top of the tabu-list. This means that all other mutations are pushed down one position. If the tabu-list is full, the oldest mutation is deleted.

## 4.3 Forming product families

In the introduction of this research, it is brought up that the company wishes to evaluate the current scheduling strategy of the paint and after-paint. The company currently uses a product mix rule to establish the production sequence. For this reason, they brought up that they are interested in a different product mix strategy. In this literature review, we seek for answer on how to establish an adequate product mix (or product families). The literature review is performed in the online library environment of the University of Twente which has access to millions of (peer-reviewed) publications. The first *search query* used as follows:

title-keyword:(product family OR product families), keyword:(manufacturing, approach) NOT title-keyword:(design, marketing).

Search terms like *roadmap* and *step-wise approach* were additional part of the first query in the hope to find standardized grouping methods. Unfortunately, standardized methods were not found which is why these search terms were excluded. It is observed that product families are often the result of a product design platform. This is a platform that reflects portfolio of the factory. One platform is one family, which consists of different design alternatives. The variety in items is often used in marketing commercials which promise a customized product, (of course given the variety boundaries of the platform). Our interest is not within designing alternative product or marketing strategies. Therefore, the article title's containing the keywords design and marketing are removed from research results.

The *query* resulted in only 12 peer-reviewed articles after removing duplicates. Subsequently, 7 articles were removed based on their title and abstract they did not describe how a family is established. The result of this query is described in Section 4.3.1. A bit disappointed about the number hits, the search is extended to grouping method used in health care which is described in Section 4.3.2.

### 4.3.1 Grouping strategies used in a manufacturing environment

The most mentioned grouping strategy is based on the commonality of the items. Commonality represent the ratio of shared parts. Johnson & Kirchain (2010) tested different strategy of grouping. For example, imagine two almost identical cars. Both cars are assembled form 100 components, but only the colour (which is equal to one component) is different. In this example the commonality ratio 99%. Johnson & Kirchain found that a *simple-piece commonality metric* (commonality ratio between family and item) and the *fabrication-investment-weighted commonality metric* (includes weight or importance the part in a group) provide more fidelity. Although groups with a high demand have less economic advantages, low volume demand pieces do perform better in families. Chowdhury et al. (2013) suggest the *Comprehensive Product Platform Planning (CP3) method* to create the commonality metric. The method is developed to look into design variables and to configure opportunities for modularity.

The drawbacks of these communality matrices method is that it is unclear what the effects on production is. Modularity does not necessarily mean that same fixtures or machines could be used to develop the alternatives. This observation is supported by Zhang & Rodrigues (2010). They observed that successful product family development relies on achieving efficiencies in both designing and producing product families. Product families supports production stability. The investment and development in family process planning are found to be strategic choices**.** Zhang & Rodrigues describe that planning families and deciding on the production sequence is more often part of research than establishing production families. This article elaborates on the importance of a production process overview, because a lack of understanding the link between operations, machines and fixtures result in an inefficient production configuration.

Galan et al. (2007) performed a brought literature study on grouping techniques. They distinguished 5 types of methods: descriptive procedure, group analysis, mathematical programming, artificial intelligence and graph partitioning.

The *descriptive procedure* groups items based on common routings, shared parts or both. The classification is based on the opinion of an expert, or a computer that assigns items to groups based on given properties. *Group analysis,* often referred to as cluster analysis, adds some logic to the grouping. For example, first items are grouped into large families based on common subassemblies. Next, the families are divided into smaller families based on sub-subassemblies. The procedures continuous until the family could not be split anymore into smaller families. This procedure is of the category hierarchical based clustering methods. *Mathematical program approaches* aim to form group items with the highest possible similarity. Compare this to *artificial intelligence.* This method is often based on metaheuristic which is an approach to find an acceptable grouping solution. The most common metaheuristic used are simulated annealing, genetic algorithms and tabu search. The last method is *graph partitioning*. Graph partitioning makes use of a part-machine matrix in which parts and machines are connected by arcs. This matrix provides two options. Minimize the arcs between machine groups such that parts do not have to travel as much or group components that all require the same machine.

Galan et al. (2007) noticed that grouping strategy is often based *on key requirements like: modularity, compatibility, reusability,* and *product demand*. Each requirement is a fair reason for grouping. This is why Galan designed a grouping methodology considering all key elements. The output of the methodology is visualised in a dendrogram suggesting different amount of family groups, Figure 4-4. The dendrogram starts with four product and is read from top to bottom. Product B and C have 95% similarities and is potential one family. The family is accepted based on cost or other decision parameters. If it is accepted, then you continue to look for other potential families or trying the extent the accepted families.

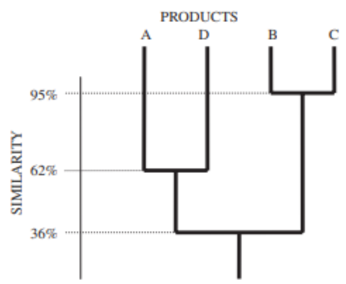


Figure 4-4 Dendrogram (source: Galan et al., 2007)

The advantage of the Galan et al. (2007) methodology is that it considers many aspects to find the optimum. For each key requirement there is a family matrix computed and the methodology combines the matrixes shaping families. Therefore, this is a time-consuming method to implement. Besides, it is not proven if considering all key requirements let to better results that considering only a few key requirements. Furthermore, it is unknown if Galan methodology performs better than a descriptive procedure. The **drawback from** a descriptive procedure is that families are often created based on a single machine instead of the manufacturing flow. *Descriptive methods* and *group analysis* stimulate the implementation of buffers between each operation stage. In this way the machine selects the best successor given the predecessor. The selection procedures are easy to implement, however it increases the work-in-process and the inner lead times (depending on the manufacturing system). The increased work-in-process leads to a lack of overview in the planning.

### 4.3.2 Grouping strategy used in healthcare

Manufacturing seeks families in similar production paths or similar parts, whereas healthcare makes use of a different approach (although it shows similarities) to form families. Although patients can be grouped based on their injuries and could follow the same path like: consult, x-ray, surgery and aftercare; the service time per patient differs. For this reason, the hospital does not have a fixed output of patients. To make sure that the productivity of the hospitals is well balanced given the variety of patients, the patients are grouped according to *acuity levels.* These are patient groups based on a similar expected service time in the hospital (Ozcan, 2009). To balance the annual demand per acuity level, the hospital could reserve for each level time slots.

### 4.3.3 Application to Power-Packer

It is found that families that consist out of items with low volume demand have more economic advantages compared to items with high demand. Power-Packer has a high-variety low-demand product mix, thus the implementation of families becomes attractive.

Furthermore, family groups can easily be embedded into local search methods, like simulated annealing. The use of families in local search methods may lead to more promising swaps and therefore find a better solution in a smaller amount of time. In the previous sections a few options are provided on how to establish product families. However, it is unknown which methods provide the best results in terms of efficiency and cost savings. We believe that the *production processes* and the *commonality* in shared parts are most important to establish family groups. Mainly, because they provide more insight in production and design opportunities with potential cost savings. This means that not only the planning department can benefit from the groups, but also the engineering department.

The only problem Power-Packer has today is that the data available is invalid and the data structure is not user friendly. It is therefore discouraged to (re-)configure product families for this case-study. Besides, it is also possible that a pattern can be found in the results of the most adequate schedule which hopefully will be established in the case study.

## 4.4 Summary

In this chapter, literature is gathered to find the answers to our research questions regarding scheduling strategies:

1. **What is planning and control?**

This topic is addressed to provide the company more insight in when and by who planning and control activities must be executed. Planning and scheduling is part of a decision-making process that deals with the allocation of resources and activities to time periods with the aim to optimize one or more objectives. The decision-making process is often referred to as planning and control. We showed the functions of planning and control can be classified in three phases: *pre-planning*, *planning* and *control.* Each phase comes with its own set of activities. To show how that planning and scheduling is imbedded into different levels of the organization, we showed t*he hierarchical planning and control framework*.

2. **What are the most frequently mentioned planning methods described by literature and which of them may be applicable to Power-Packer's situation?**

First of all, what is Power-Packer's situation? On average 30 to 35 orders need to be scheduled daily at the paint department. To find the optimal result means that all sequencing options need to be evaluated which is 35*(35-1)!. This amount of options are not executable within an hour. For this reason, we have looked into heuristics that are able to provide an acceptable, near optimal solution for the multi-model paint and after-paint line with the objective to minimize the idle time of the various workstations while increasing the output.

It is observed that simulated annealing heuristic is the most popular. *Simulated annealing* has proven its effectiveness many times. Furthermore, is annealing adaptable such that it becomes appliable for a variety of scheduling problems. Thus, if SA proves itself worthy, it can be advised for the other planning problems Power-Packer experiences. This is the main reason why this heuristic is selected to implement in our case-study.

3. **What does literature describe about the implementation of product mix strategies into production schedules and how to form them?**

Literature does not speak about a product mix, but about product families. Family groups can easily be imbedded into local search methods, like simulated annealing. The use of families in local search methods may lead to more promising swaps and therefore find a better solution in a smaller amount of time.

There is *no fixed roadmap* on how to establish product families. It is observed that successful product family development relies on achieving efficiencies in both designing and producing product families. Product families support production stability. The investment and development in family process planning are found to be strategic choices**.**

Different grouping strategies are discussed from which the use of *descriptive methods* and the *commonality matrix* is most observed. Galan et al. (2007) created a grouping strategy which combines costs with the *key requirements like: modularity, compatibility, reusability, product demand*. In healthcare, patients are grouped based on their expected treatment times. Thus, few options on creating product families are provided. However, it is unknown which methods provide the best results in terms of efficiency and cost savings. Furthermore, Power-Packer has invalid data and the data structure is not user friendly. It is therefore discouraged to (re-)configure product families for this case-study up front. It is also possible that a pattern can be found in the results of the most adequate schedule which hopefully will be established in the case study.

*It this chapter is decided to implement simulated annealing in the case-study. The next Chapter develops a simulation model in which the current production strategy and the simulated annealing heuristic are put to the test.*

# 5 Simulation design
To estimate whether or not the three-shift system of the paint and after-paint department may be reduced to a two-shift system by using a new scheduling strategy, a simulation study is conducted. Section 5.1 describes the transformation of the production environment of Power-Packer into a conceptual model. The subsequent Section 5.2 describes the simulation model itself and includes the verification and validation. Afterwards the experimental design is described in Section 5.3. At the end of this chapter the summary is given.

## 5.1 Conceptual model
The conceptual model describes what the simulation model should be able to do. It describes the objectives, model inputs, model outputs, assumptions and simplifications.

**Objective**

To quickly recap the aim of the study. Power-packer dealt with a (gradual) demand increase of 15% in the period 2017 – 2019, shown in Chapter 2. In September 2018, the production departments paint and after-paint are forced to start working into a three-shift system. For these two departments is a three-shift system a new phenomenon. However, management observed that the demand was too high for a two-shift system but not enough to fill an entire third-shift. This is why management is looking into possibilities to increase the productivity of the paint and after paint department with the aim to prevent a third-shift in the future. They found that an operator in the paint department, which is responsible for hooking products to the overhead conveyor, is often idle. In Chapter 3, a problem cluster emerged that shows the root causes of the idle time in the paint department.

Management has a special interest in the root cause paint planning strategy. Chapter 4 showed that simulated annealing is a promising planning strategy. The paint *planning horizon is one day*. Each day, new orders are collected in the paint buffer zone which will be scheduled the next day. Therefore, the first objective of the case study is to evaluate different planning strategies, in particular simulated annealing, with the aim to reduce the make span and idle time in the paint & after-paint departments.

The second objective is to evaluate what the impact is of potentially outsourcing a medical product segment as described in Chapter 2. Reducing the workload for the department might be enough to prevent the third-shift?

The last objective is to find a configuration (e.g. workstation capacity) in which it is guaranteed that the peak demand is produced in a two-shift system instead of a three-shift system.

### Model detail

The focus of the research is on the paint and after-paint department which are connected by the overhead conveyor belt. To be able to simulate the arrival rate of paint orders, previous departments are modelled as well. The pump and medical departments are modelled as a Blackbox. All orders that go through the black boxes receive the same throughput time of three days. Not every activity will be modelled in detail but only the mainstream (at routing level), shown in Figure 5-1. The mainstream represents the production lead time. All parallel activities take less production time than the mainstream activities. The consequence of modelling on routing level is that the pre-assembly and base activity are merged in the simulation model. All other truck activities have their own routings per product(type).

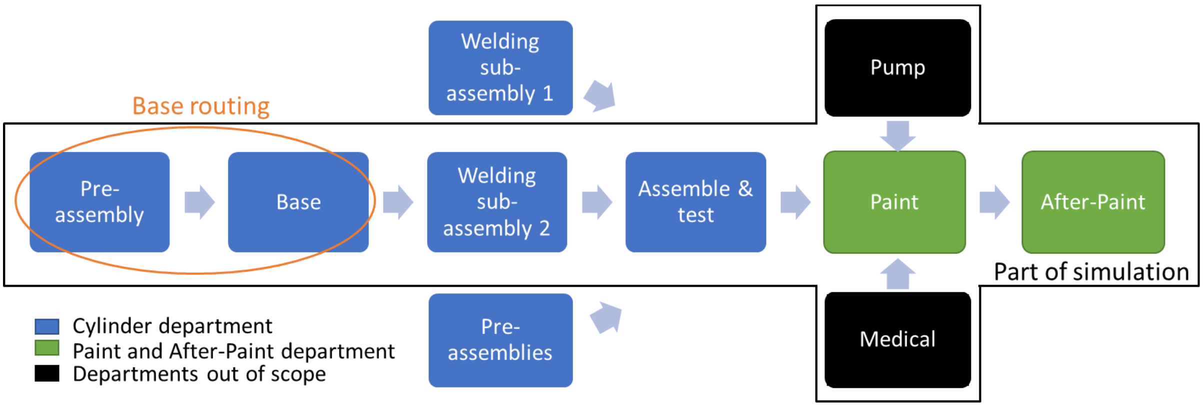


Figure 5-1 Detail in simulation

### Input data

- *Tactical planning*. The production orders are released every single workday day. The result is that there is a fixed arrival rate per day. The aim is to recreate the peak period.
- *Product routings*. The production path of the product
- *Colour setup* time paint department. For each colour change the paint robot is rinsed automatically.
- *Required paint hooks per product.* Each product requires a specific hook type to get attached to the transport beams on the overhead conveyor belt at the after-paint department. The hook type influences the capacity of the beam.

### Stochastic input variable

*Processing time per station per product.* Usually this input data should be covered by stochastic variables. However, due to Covid-19 no people are allowed on the production floor apart from operators and production support staff. This means that the unknown average processing times and standard deviations of the approximately 600 products cannot be estimated, see problem described in Chapter 3. The best available guess are the values attached to the routings. The routing time represents the production path of an item and the time the production required to finish the product per production stage. The routing time includes:

- the processing time of the product per production stage,
- setup time,
- lunch break,
- and unplanned disturbance.

The fraction of time assigned to the processing time, setup, lunch breaks and unplanned disturbance is unknown. Given the additional lunchbreaks and unplanned disturbance the routing time is highly likely to high in comparison with the actual processing time. This means that the routing values are addressed as the *upper bound* of time required for production. Thus, the upper bound represents the worst-case scenario.

**Experimental factors / input variables**

Various experimental factors are part of experimentation. The input range of these factors are positioned underneath Chapter 5.3 the experimental design.

- *Shift schedules.* The work hours involve working in a two- or three-shift system for the paint and after-paint.
- *Workstation capacity*. The number of employees that may support the workstation.
- *Conveyor speed*. In total, there are four zones in the paint and after-paint department with different conveyor speeds.
- *Palettizing or not*. Depending on the product, in the after-paint, products could be palletized and put aside to finish them later.
- *Paint planning strategy.* The *current paint planning strategy* as well as the *simulated annealing* procedure should become part of the models. Simulated annealing may include a *Tabu-list* as described in Chapter 4.5.2. This approach is the third method to implement in the model. The last method to implement is the planning strategy *first come first served*.
- *Possibility of outsourcing medical segment*. Specific products are filtered from the tactical planning.

**Model output**

- *Throughput time per transport beam for each paint zones*. In certain paint zones the transport beams need to stay for a minimum amount of time to ensure the quality of the product. Keeping track of the length of stay proves the validity of the system.
- *The daily idle time per station.* The station is waiting on a production order to arrive.
- *Buffer and processing times per order*. This data support track and tracing of every single order in the system. This works as verification of the routing system.

**Performance indicators (KPIs)**

- Make span of the day schedule. The moment the first order of the schedule is attached to the conveyor the time starts. The moment that all orders are finalized at after-paint the time stops. The difference between the start and stop time is the make span of the day schedule.

- Average weighted idle time after-paint department (AvgIdleAP) of period D.
  The average weighted idle time at after-paint per day $d$ is calculated as follows:

$$\text{Avg weighted idle time AP}_d = \frac{\sum_s^{S=5}(I_{sd} * C_s)}{S} \quad \forall\, d$$

  Where,
  $I_{sd}$ : The idle time of after-paint station $s$ on day $d$.
  $C_s$ : Workstation capacity of after-paint station $s$.

  Consequently, average weighted idle time of period D:

$$\text{AvgIdleAP} = \frac{\sum_d^D \text{AvgIdleAP}_d}{D}$$

- Standard deviation idle time after-paint department (StdvIdleAP) which is calculated as follow:

$$\text{StdvIdleAP} = \sqrt{\frac{1}{\text{D}}\sum_d^D(\text{AvgIdleAP}_d - \text{AvgIdleAP})^2}$$

- Average idle time paint operator (AvgOphangerIdle). The first operator attaches product to the transport beams.
- Standard deviation Average idle time paint operator (StdvOphangerIdle).
- Daily production backlog in orders.

**Model simplifications/ assumptions**

In this case study several assumptions are embedded for simplification purposes:

- No machine failure will occur and all components required for production are delivered in time.
- The yield of the products is 100%.
- The tactical planning is translated by the production planner by scheduling the order with the earliest due date first.
- Incoming paint orders in the paint and pack buffer today must be scheduled for production tomorrow.
- Truck-pumps can only be detached at line 3 in the after-paint department.
- The production process of medical and pump items are modelled as a Blackbox and the throughput for the Blackbox is set to 3 days.
- The performance of the schedule is partly depending on the schedule of the next day. To explain the dependency situation:
  The dependency is the result of the circular conveyor-belt in which transport beams cannot be detached from the conveyor. There is a fixed amount of transport beams in the conveyor which can only move to the paint system when they carry products. Thus, in case that the first paint station has no products in the paint buffer, the

empty beams will accumulate in between the after-paint department and the paint department. This accumulation dominos into the after-paint, resulting in that after-paint becomes saturated with empty beams. Thus, after-paint becomes idle since they can no longer receive transport beams with products from the paint-department.

This dependency cannot be included in the model, since it will affect the independency of the day schedule given the next day schedule. In reality no information is available that predicts the orders delivered the next day. For this reason, we allow the simulation to drain and regenerate the empty transport beams in between the paint and after-paint department. This adaption maintains the independency of the day schedule from the next day.

**Additional wishes of the client:**

- Detachment of DTU items and DPU items takes place outside the after-paint department. In this way it is guaranteed that the operators which finalise the products in after-paint do not interrupt their work, to quickly palletize these two product groups.
- The after-paint makes use of a *cool zone exit strategy*. This strategy allows the production order to split over two after-paint lines. By splitting the orders over two lines results in that two workstations need to changeover. The wish of the company is to prevent this in the future.

## 5.2 Simulation model

The simulation model is built. First the simulation model dashboard is explained in Section 5.2.1. The warm-up period found in Section 5.2.2 and the cooling parameters for simulated annealing in Section 5.2.3. Next, based on the current paint strategy the simulation model is verified and validated in Sections 5.2.4 and 5.2.5

### 5.2.1 Dashboard

The simulation is built in software of Siemens namely Tecnomatix Plant Simulation which is provided by the University of Twente. The simulation is built-up out of different frameworks. The first frame is the dashboard or main frame, see Figure 5-2. The dashboard contains data and methods required to play the simulation. The remainder of this section explains the different elements visible on the dashboard.

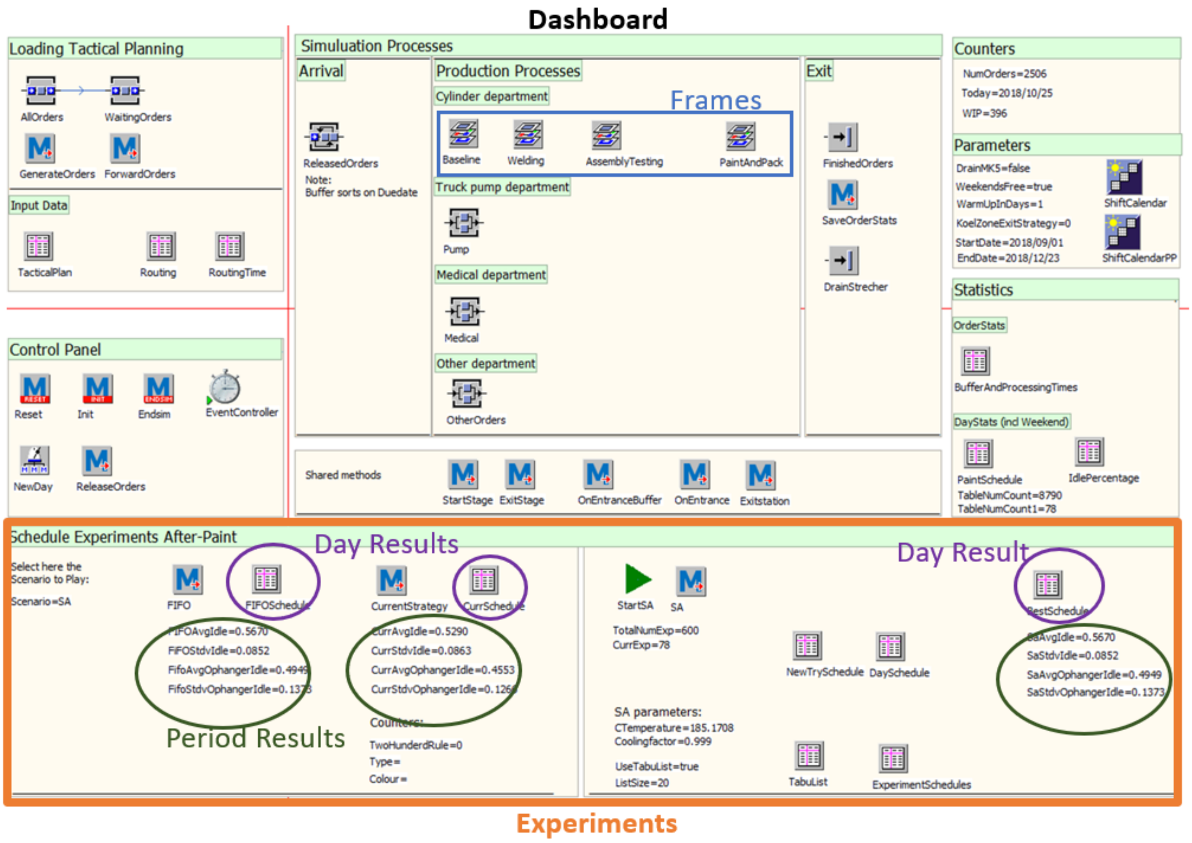


Figure 5-2 Dashboard of the simulation model

**The input data** at the dashboard is required for every production department. In total three data lists can be found here. The first list is the *tactical planning* which contains data of the peak period September 2018 – December 2018 (four months). The tactical planning is responsible for the arrival process of production orders. If the release date of the production order is equal to the date of today, then the order is forwarded to a buffer of *released orders*. This buffer sorts the orders based on the earliest due date and sends the orders to the first station according to their production path. This is in real life the job of the production leader.

The second data list on the dashboard, the *routings*, contains the production path for each item. The last data list, the *routing times*, contains the expected processing time per production activity or production path.

**The production process** is split in different frames that represent the different production subdepartments. The frames can be found in the blue box in Figure 5-3. The production of the truck cylinders is modelled in detail. The first frame or subdepartment is the *base line*. The next frames or subdepartments are *welding* and *assembling & testing*.

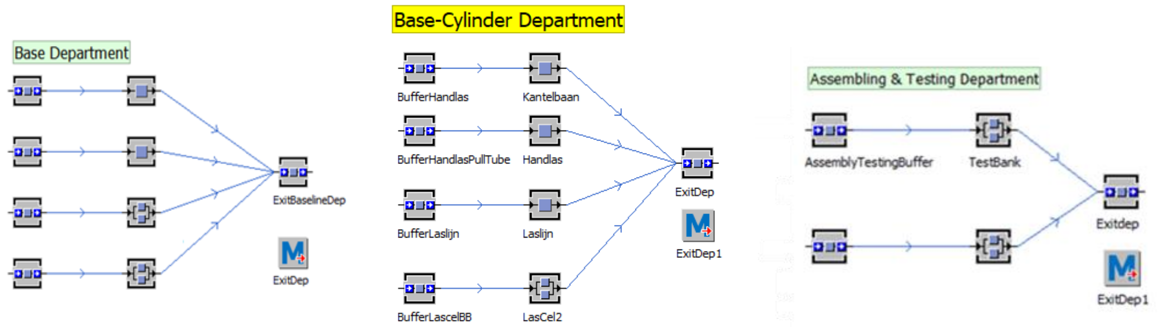


Figure 5-3 Framework of the Base, Welding (yellow) and Assembling& Testing department.

The *medical items*, *truck-pumps* and *others* go each to their own department. However, these departments are modelled as Blackbox. The order exits the department after three days.

The last frame is the *paint and pack* department. Here, all orders that enter de department today are scheduled for tomorrow's paint production. Every day at 6 am, the orders are scheduled according to a chosen paint planning strategy. This framework also contains **input data** for the capacity per transport beam per item. The colours setup time is set to 9 minutes for this case study. The paint schedule strategy and the workstations capacity are part of experimentation. Figure 5-4 shows the simulation framework of the paint and after-paint department.

**The counters** on the dashboard keep track of the simulation date (*Today*), the work in process (*WIP*) in the entire production environment and the number of orders (*NumOrders*) to be scheduled according the tactical planning.

**The parameters** of interest are the shift calendars, the *start* and *end date* of the simulation, the number of *warm-up* days. The start and end date are equal to the first and last release day of the tactical planning. Furthermore, the *weekend free* parameter must be checked if the shift calendars exclude weekends. In this way no weekend statistics are stored. The last parameter determines if the *medical product group* is excluded from production or not.

**The statistics** keep track of all orders. This includes information about the production time on each workstation and the time they spend in a buffer waiting for production. Some statistics are reviewed daily, like the idle time per station per day. Furthermore, the daily paint schedules are saved along with their performance indicators: make span, idle time and backlog.

**The control panel** contains methods to initialize, end and reset the simulation.

The last element visible on the dashboard in Figure 5-3, is the orange box that contains the **experimental paint schedules.** Here, in total three scheduling options are open for review: first come first served method, 200-200 rule which is the current situation and last, simulated annealing with or without Tabu-list. More information about the experiments are explained in the Experimental design Section 5.3.

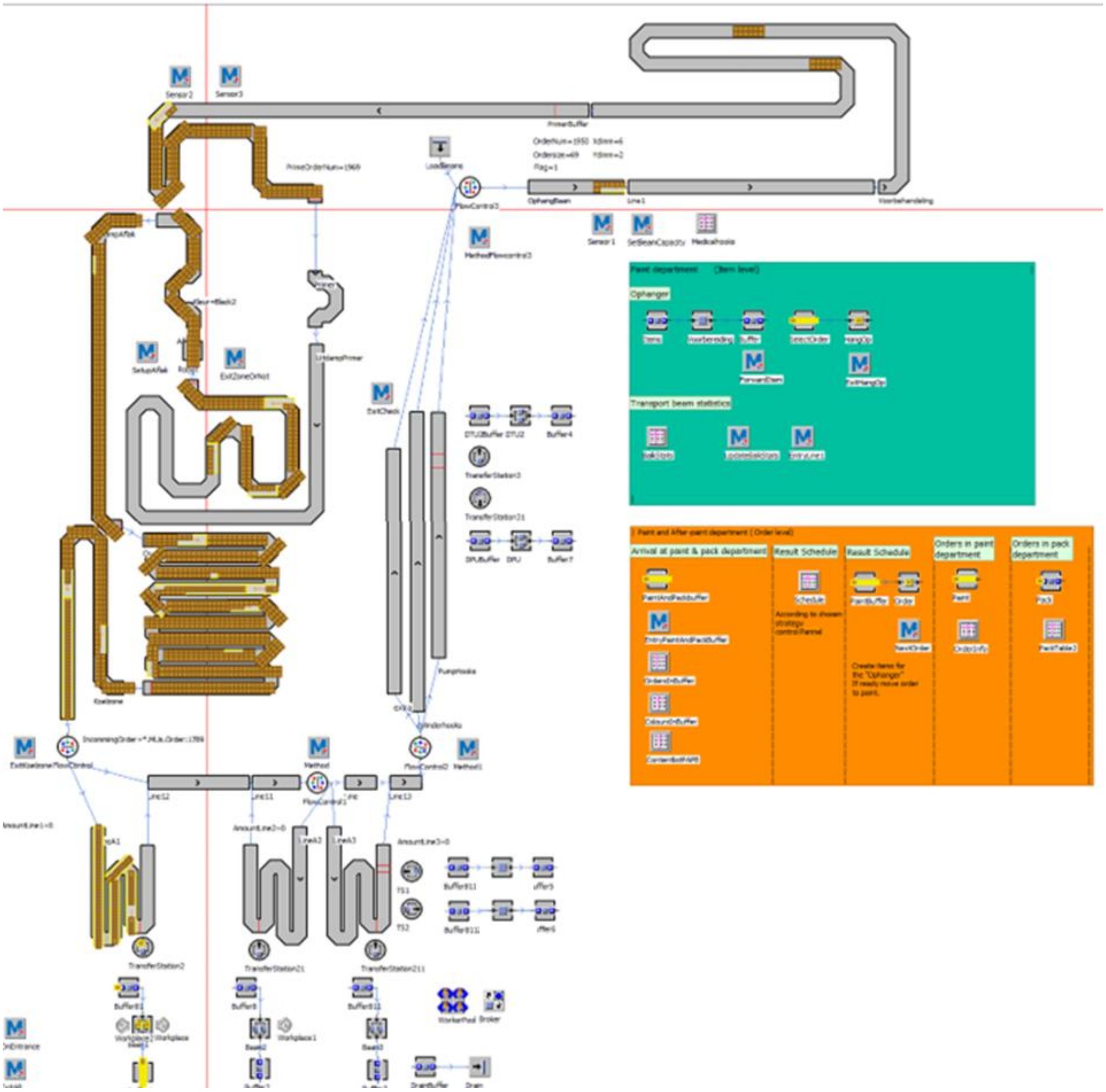

Figure 5-4 Framework of paint and after-paint

### 5.2.2 Warm-up days

The production environment is a continuous or nonterminating process. A change in the production process often affects the short-term however, the interest is in the performance for the long run. This is why the simulation is analysed to see when the behaviour of the model stabilizes or in other words reaches the steady state. The time required to reach the steady state, is the warm-up length. Within the warm-up period no data is collected since it is not representable for a regular production day.

The number of warm-up days is determined through visual inspection. Figure 5-5 shows the result of 80 days simulation and the expected amount of work in hours per workday. The moving averages of 5 days plotted through the graph to smoothen the expected amount of production time over 5 days. This technique is part of the Welch procedure (Law, 2014). Figure 5-5 shows that after 10 days the moving average is stabilizing. For this reason, the warm-up period is set to 10 workdays.

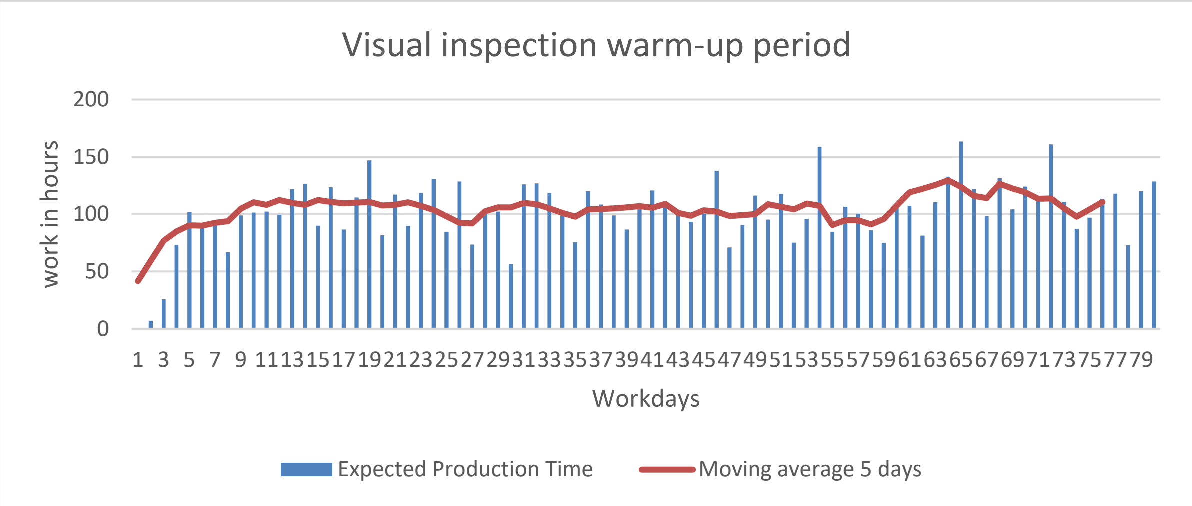


Figure 5-5 Warm-up period

### 5.2.3 Parameter setting simulated annealing and Tabu-list

As was introduced in Chapter 4, the parameter settings for simulated annealing and the tabu-list should be chosen very carefully.

Simulated annealing comes with four parameters: the start temperature, stop temperature, decrease factor and the Markov length each explained in Chapter 4.2.4. The parameter settings have a big influence on the optimization of the paint schedule. Furthermore, the settings have a great impact on the run time of the simulation. A rule of thumb, the size of the Markov length is set to the number of neighbours. In our case study, the number of neighbours is equal to the number of orders scheduled per day, which is on average 30. For the decrease factor 0.9 is chosen. This value could be changed for further experimentation later on.

Our objective is to minimize the make span of a day schedule. In the case that the candidate solution is better than the current solution observed, the candidate schedule is always accepted. However, if the value of the objective is lower, then the transition probability is calculated according to formula 4.1, see Chapter 4.2.4. Figure 5-6 shows the changing transition probability over the number of experiments for different values of the difference between the current solution and candidate solution. The smaller the difference between the best and candidate solution the more likely the worse candidate solution is accepted (in the attempt to escape a local optimum). Furthermore, the figure shows that the transition probability reduces over number of iterations. To explain, after 3000 iterations any worse candidate solution is no longer accepted, see Figure 5-6.

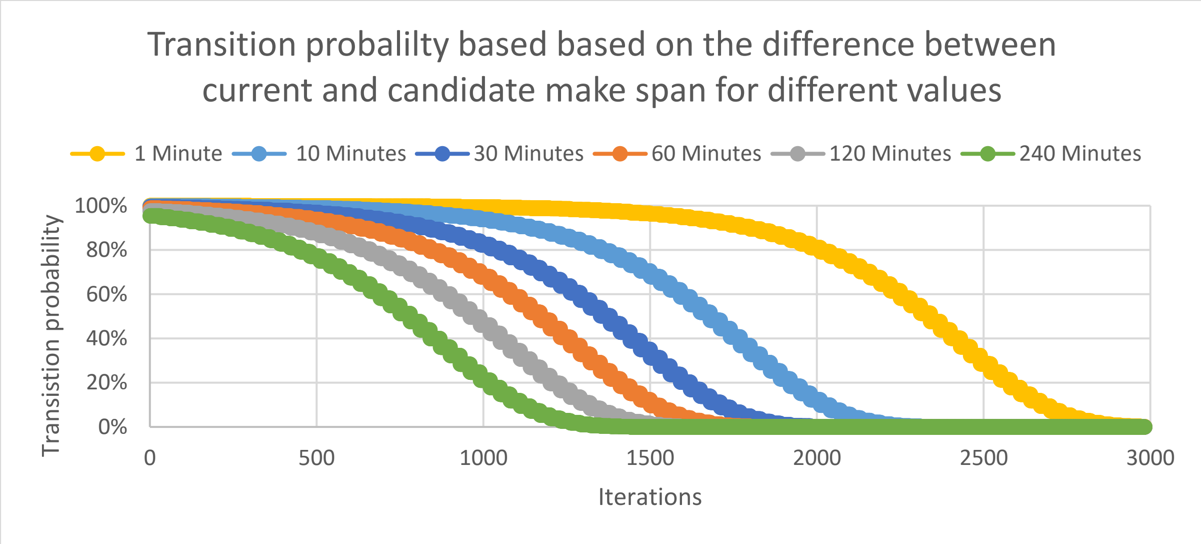


**Figure 5-6 Transition probability based on the difference between current schedule and candidate schedule make span for different values. Parameter settings: Markov length 30, start temperature 5000, decrease factor 0.9**

In Figure 5-6 a start temperature of 5000 was chosen such that the result of the transition probability at the first iterations is roughly 1, thus all worse solutions are accepted. In the case that stop temperature is 5 degrees, the simulation will perform roughly 2000 iterations. This means, that one-minute difference will still be accepted with a high probability (roughly 80%). For one day of simulation the run time is 20 minutes and is therefore not an issue. However, simulating a period of 30 days takes a lot more time. If the days are simulated independently, the run time is linear with the number of days. For 30 days the run time is then 10 hours (20 min*30 days). However, there is a dependency which means that previous days always have to be simulated again. To explain, to get the result of day 3, first the optimized schedule of days 1 and 2 have to be run, before performing experiment on day 3. This means that the runtime is not linear, but increases exponentially with the number of days. The result is that the runtime of 30 days with these parameter settings is days or even weeks, which is not possible within the timespan of this research.

For this reason, experiments have to be performed, playing with the initial temperature and the Markov length and decrease factor, to reduce the number of iterations as much as possible. These experiments are described in Section 5.3 experimental design.

### 5.2.4 Verification

The verification is the process that determines if the production processes and assumptions are correctly translated into the simulation model. Three techniques are used for verification: debugging, visual inspection, measure and safe data to see if the output is reasonable (Law, 2014). Besides, the model is reviewed by the Paint Department Expert and the Manufacturing Engineering Manager.

Embedded in the simulation software is a debugging tool. Debugging is best explained as jumping from code line to code line to see if the code results are correct. Along with the debugging tool also a visual inspection is performed. If the code says “go to the next station” than this should also be visible in the simulation visualisation.

By saving the order data, the production path or routing can be compared with the routings used as input. Another data verification is used for the paint department. The transport beams need to stay in zones for a minimum amount of time. This is the reason that the length of stay is monitored for every transport beam.

The code contains various boobytraps. The simulation model is a discrete event simulation, this means that if an event occurs the reaction on the event should be programmed. Different scenarios are programmed in how the simulation should react under certain conditions. However, if a scenario occurs with unknown conditions the model should debug. In this way the programmer can evaluate the event and respond accordingly to it.

Given the measurements and the model reviews by the experts, the model is found to work as programmed.

### 5.2.5 Validation

After the verification validation takes place. The validation is a critical review of the accuracy of the model. The accuracy is discussed with the Paint Department Expert and the Manufacturing Engineering Manager. During the discussion, the assumptions are reviewed to understand their impact. Afterwards, the model results are compared with reality, and last, we test the model based on assumption data by performing a sensitivity analysis on the routing time.

**Assumptions**

We did not deviate from the assumptions and model simplification, mainly to stay as close to reality as possible. However, one positive assumption will have a negative effect on the performance of the simulation. It concerns the Yield factor of 100%, which means that all assemblies reach the paint buffer. Thus, the paint and after-paint receive the maximum workload. This assumption therefore contributes to the wish of the company to see if all scheduled work can be performed in a two-shift system. The second important assumption concerns the machines failures. Short lasting failures are embedded in the additional 30% routing time, as explained in Section 5.1. About long lasting failures, no data is available but according to the paint expert they were rare in that period.

**Model vs. reality**

It is discussed if the model meets the expectation of the company by comparing the simulation results with reality. Table 5-1 shows the results of reality and the current situation. The Paint Expert had a very positive reaction on the results of the model’s current situation. Which most honestly, the author is surprised about. From our earlier post-it experiment, it is expected that the daily idle time of the paint operator 1 is somewhere between 9% (lower -) and 31% (upper bound). The simulation model showed that the paint station is idle 57% of the time with a deviation of 11%! Additionally, the production backlog at the paint department is roughly 12 times larger than reality, see Table 5-1. The large difference in idle time and backlog between reality and the model can be explained by four observations:

- During the research period five Saturdays are worked to reduce the backlog, where the simulation did not consider the Saturdays shifts. This reduced the backlog by 120 orders. Extract the 120 from the 408 backlog results in 288 which would be still high.
- The routing times used are the upper bound which means that the packing time takes longer and therefore fewer empty beams enter the paint department. This results in an (1) increased idle time for the paint operator and (2) a lower throughput which means that the paint backlog increases.
- The paint department sometimes supports after-paint when the mix in the buffer contains a lot of items that require long packaging time. This reduces in real life the time waiting for empty beams. Operators are not part of the level of detail in the simulation. Thus, additional hands at a workstation are not registered.
- From the visual inspecting the model, it became even more clear what the effect is of a blockage is! As explained in Chapter 3.1.3, the order size is too large (number of transport beams) which is causing a blockage, see Figure 5-7. It shows that the second line at the after-paint is receiving a new order, however the line capacity is reached. This means that part of the order is still waiting in the cool zone of the paint department, blocking the order destinated for line1. This results in that the workstations at the assembly do not receive the order from a long period of time! In real life, the operators at line 1 will relocate to other stations to prevent that the operator becomes idle.

Table 5-1 Validation of the Current strategy in the simulated period September – December 2018

| Scenario | Avg. weighted idle time After-paint | Avg. idle time paint operator 1 | Backlog at 21 Dec. 2018 |
|---|---|---|---|
| **Reality** | - | Expected between 9% and 31% | 34 |
| **Current Situation** | 47.7% | 55.4% | 408 |
| **Sensitivity analysis** Reduced routing time with 10% | 47.4% | 51.8% | 303 |

**Sensitivity analysis**

The last validation technique used is a sensitivity analysis. A sensitivity analysis is performed to observe the effect of large change in the input data, namely the routing times. The routing times are reduced with 10%. Table 5-1 shows the result. Remarkable is that the idle time at the after-paint stayed the same, where the idle time of the paint operator is reduced with 3.6%, compared to the current situation. Besides, the time reduction of 10% results in a backlog reduction of roughly 100 orders. These 100 orders are in the case study the demand of three days. Saving three days in four months is rather small. Perhaps that a new planning strategy may result in higher savings?

In the end, the model meets the wishes and expectations of the stakeholder. This allows us to start performing experiments. The next section described the experimental design.

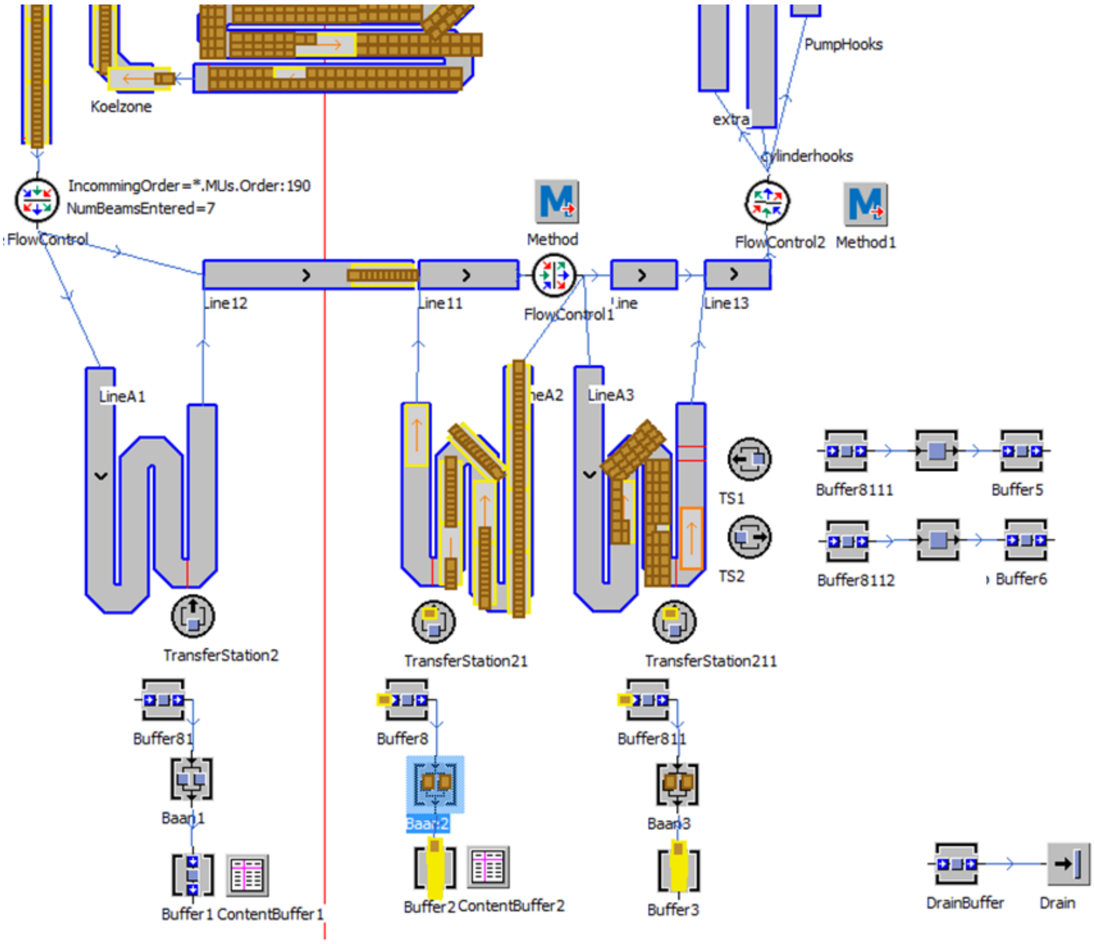


Figure 5-7 Blockage caused by order with too many transport beams

## 5.3 Experimental design

In total three objectives are formulated. The first objective is to evaluate different paint planning strategies with the aim to increase the performance of the paint and after-paint department. Three scheduling strategies are proposed in Experiment 1 in Section 5.3.1.

From a visual inspection of the simulation model, it is seen that the paint department struggles with accumulation of transport beams in the different paint zones resulting in a domino effect. Furthermore, the visual inspection showed blockages in the after-paint department. The blockages are caused by large production orders which do not fit on the after-paint conveyor lines. For this reason, Section 5.3.2 describes experiments with different conveyor speeds and Section 5.3.2 experiments with a reduced order size.

The second objective is to find out what the impact would be, when a medical product group would be outsourced. This experiment is described in Section 5.3.4.

The last objective is to find out which capacity improvement (e.g. workstation capacity) is required to prevent the third-shift. These experiments are described in Section 5.3.5.

### 5.3.1 Experiment 1: Paint schedule strategies

The first experiment is built-up from two experiments. The first experiment evaluates different parameter settings for simulated annealing. The second experiment compares the performance of different paint scheduling strategies.

**Experiment 1.1: Annealing parameter settings**

In Section 5.2.3, it is shown that parameter settings of: a start temperature of 5000 degrees, a stop temperature of 5 degrees, a Markov length of 30 and a degrease factor of 0.9 may provide the most promising schedule solution. However, these settings will result in many iterations when finding solutions for the entire period (Sept -Dec 2018) of interest which takes a run-length of days or weeks. For this reason, the number of iterations need to be reduced drastically while still showing significant scheduling improvements. The parameters which are part of experimentation are: the start temperature, Markov length and decrease factor. The stop temperature and tabu-list size will remain fixed for all experiments. The fixed settings and values part of experimentation are given in Table 5-2. Not all configurations will be tried, since 24 experiments would result in too much computation time. Thus, by playing around, with the settings and based on the results of the previous run, a decision will be made to change the configuration. The start settings are: a start temperature of 500, Markov length of 10 and degrease factor of 0.9.

Table 5-2 Annealing & Tabu-list parameter settings

| Annealing & Tabu parameters | Settings |
|---|---|
| *Start temperature* | 100; 200; 500 |
| *Markov length* | 1; 5; 10; 15 |
| *Decrease factor* | 0.8; 0.9 |
| *Stop temperature* | 5 |
| *Tabu-list size* | 30 |

In the end a trade-off will be made between the run-length of the model and the make span performance of the day schedule, to choose the annealing settings that will be applied in all upcoming experiments. To reduce the run length even more, we use for this experiment a simulation period of four weeks from which the first ten days are part of the warm-up length. Table 5-3 shows the other parameter settings of the model.

**Experiment 1.2: Experiment with different paint schedules**

The current strategy is put to the test. This strategy is in this research often referred to as the 200-200 rule which includes the *cool zone exit strategy* that allows orders to split over two after-paint lines. Two alternative planning procedures are simulated. The first procedure is rather simple, first come first served. The arrival sequence in the paint buffer represents the production sequence. The second method is simulated annealing with Tabu-list. For the two alternative scheduling strategies it is decided by the stakeholders that splitting orders at after-paint is no longer allowed. All other model settings are shown in Table 5-3.

**Table 5-3 Settings Experiment 1**

| ***Paint zones*** | **Conveyor speed (%)** | **After-paint station** | **Station capacity (in num. of operators)** |
|---|---|---|---|
| *1.Hang product* | 100 | *S1. Line 1* | 2 |
| *2.Cleaning* | 19 | *S2. Line 2* | 2 |
| *3.Buffer* | 100 | *S3. Line 3* | 2 |
| *4.Primer* | 38 | *F1. Line 3* | 1 |
| *5.Drying 1* | 100 | *F2. Line 3* | 1 |
| *6.Paint* | 25 | | |
| *7.Drying 2* | 100 | **Produce medical group** | True |
| *8.Oven* | 100 | **Work in the weekend?** | False |
| *9.Cooling* | 100 | **Cool zone exit strategy** | 0 (not allowed to split) |
| *10. After-paint* | 100 | **Number of shifts per day** | 3 |

### 5.3.2 Experiment 2: Tackle zone & conveyor speed

From a visual inspection of the simulation model, it is seen that the paint department struggles with accumulation of transport beams in the different paint zones resulting in a domino effect. The fictive example in Table 5-4 explains the situation. The conveyor is divided into multiple zones with their own speed(limitations). Notice the deviation per zone: the speed, the minimum length of stay and the capacity. The deviations are causing domino effects. To explain further, the zone ‘Drying 2’ only allows three transport beams. The first beam gets to the end of the zone in 11 seconds and has to wait at the end of the zone for an additional 56 seconds to reach their minimum length of stay. The result is that any paint order larger than three transport beams causes the paint activity to stop.

Table 5-4 Fictive example of the Paint bottleneck

| ***Paint zones*** | **Conveyor speed %** | **Minimum length of stay (sec.)** | **length of stay without zone block (sec.)** | **zone capacity (num. of transport beams)** |
|---|---|---|---|---|
| *1.Hang product* | 100 | | | |
| *2.Cleaning* | 19 | | | |
| *3.Buffer* | 100 | | | |
| *4.Primer* | 38 | | | |
| *5.Drying* | 100 | 150 | 30 | 8 |
| *6.Paint* | 25 | | | |
| *7.Drying 2* | 100 | 67 | 11 | 3 |
| *8.Oven* | 100 | 200 | 40 | 11 |
| *9.Cooling* | 100 | 67 | 11 | 3 |

**How to solve the domino-effect?**

Here, we propose a two-step approach to solve the domino-effect.

Step 1: Reduce the conveyor speed to the bottleneck speed, which is in our example 19%. This speed reduction is already beneficial since the period of disruption in the paint zone is reduced. However, it is not solved yet as shown in Table 5-5.

Table 5-5 Fictive Solution example of the Paint bottleneck

| ***Paint zones*** | **Conveyor speed %** | **Minimum length of stay (s)** | **length of stay without zone block (s)** | **zone capacity (beams)** |
|---|---|---|---|---|
| *1.Hang product* | 19 | | | |
| *2.Cleaning* | 19 | | | |
| *3.Buffer* | 19 | | | |
| *4.Primer* | 19 | | | |
| *5.Drying* | 19 | 150 | 160 | 8 |
| *6.Paint* | 19 | | | |
| *7.Drying 2* | 19 | 67 | 58 | 3 |
| *8.Oven* | 19 | 200 | 213 | 11 |
| *9.Cooling* | 19 | 67 | 62.5 | 3 |

Step 2: To eliminate the drying and cooling bottleneck, two options are proposed:

- Reduce the minimum length of stay
- Reposition the zone boundaries, to increase the zone length.

In *the real world* the effect of a time reduction means that the stay time in Drying 2 and cool zone must be reduced with respectively 14% and 7%. This may impact the quality of the product. In consolidation with the process engineers and the paint expert, it is decided to increase the zone length besides the conveyor speed reduction to 19%. The goal of this experiment is to see what the impact of the speed reduction and new zone boundaries are on the performance of the paint and after-paint department.

### 5.3.3 Experiment 3: Reduce order size

The previous experiment aimed to find a solution for the domino-effect. Here, it is found that domino-effect still occurred due the blockages at the after-paint. The blockage is showed before, in Figure 5-7.

Even in the current strategy, where the orders are allowed to split over two buffers lines, blocking occurs at the cool zone. The order size is too large and therefore requires too many transport beams which do not fit on *one* after-paint buffer line. The company is in the possession of a research report of Hoebée (2003), that looks into the ideal order size for the paint and after-paint departments. Hoebée, showed that an order size larger than 14 transport beams results in exponential waiting time in the paint department (domino-effect). However, the 14 beams do not fit on any after-paint buffer line. For this reason, the order size is set to 12 beams, which is the maximum capacity of the after-paint buffer lines.

The tactical planning is reviewed. Every order size larger than 12 transport beams is set to 12 beams and the remaining is placed in a new suborder. Thus, the number of production orders increased significantly. The effect of the order size reduction is evaluated for all paint planning strategies. This experiment uses the same settings as in Table 5-3.

### 5.3.4 Experiment 4: Exclude medical group from production

With the previous experiment the first research goal is answered. Therefore, it is time to address the second objective. What would be the effect of excluding a medical segment on the production performance given the different paint planning strategies. The current scheduling strategy is compared with the best performing scheduling strategies (annealing with and without reduced order size). This means that the parameter 'produce medical group' is set to false. The remaining settings stayed the same as shown in Table 5-3.

### 5.3.5 Experiment 5: From a three-shift system to a two-shift system

Experiment 5 is the last experiment performed and provides an answer on how to eliminate the third-shift during a peak demand. In the previous experiments, we showed the performance of the make span given different planning strategies, but not yet the effect on the number of shifts! The effect on the number of shifts of the various scheduling strategies is positioned in the Appendix E (confidential). Even for the best performing scheduling strategy (annealing with reduced order size in a three-shift system), there is a backlog of 31 orders at the end of the simulated period. This indicates that the after-paint capacity is not adequate for the number of orders received in the paint buffer. Given this result, we experiment with three options in which we aim to find a (profitable) configuration in which the demand can be produced in a two-shift system. The options:

1. Reduce the number of shifts for specific weeks if these weeks show no backlog.

2. Implement a two-shift system and additionally make use of weekend shifts if necessary
3. Increase the capacity of the after-paint stations to make a two-shift system possible as shown in Table 5-6.

Table 5-6 Increasing the capacity at after-paint.

| *After-paint station* | **Station capacity (in num. of operators)** |
|---:|---|
| S1. Line 1 | From 2 to 3 |
| S2. Line 2 | From 2 to 3 |
| S3. Line 3 | From 2 to 3 |
| F1. Line 3 | 1 |
| F2. Line 3 | 1 |

A trade-off will be made to find out, if applying a two-shift system will be profitable. The trade-off is made between the cost of increasing both the workstation capacity and the additional shifts, with the performance KPIs: make span, idle time and backlog.

## 5.4 Summary

In this chapter, we designed a case-study to estimate whether or not the three-shift system of the paint and after-paint department may be reduced to a two-shift system by using a new scheduling strategy. For the case-study, a simulation model is developed. To do so, a conceptual model is developed which holds the objectives of the study, model inputs, model outputs, assumptions and simplifications. Afterwards, the model is constructed and its features explained. The simulation model is verified and validated based on the current strategy. The experts of the company found the model valid to start experimenting. Five experiments are developed which aim to answer objectives of the study.

*The next chapter shows the results of the experiments and the limitations of the research.*

# 6 Results Simulation Experiments

The previous chapter described the developed simulation model of the production environment of Power-Packer. Furthermore, it explained the experimental design which contains the experimental goals and the simulation settings used. This chapter shows the results of the experiments. Experiments described in Sections 6.1 till 6.3 aim to answer the first objective. The first objective is to find an adequate scheduling strategy for the paint department that minimizes the make span, the idle time and the paint backlog for everyday schedule. To recall, the day schedule contains all newly received production orders. The scheduled sequence of these new orders will always be finished in this sequence before the day schedule of a new day can be started. The second objective is to find out what the impact of possibly outsourcing a medical product segment would be on the performance of the paint and after-paint department. This experiment is described in Section 6.4. The third and last objective is to look into options (e.g. weekend shifts, increased workstation capacity) that results in the elimination of the third-shift. The results of this of experiment are described in Section 6.5. Afterwards, the limitations of this case-study are discussed in Section 6.6. In the last section the conclusion is given of this chapter.

## 6.1 Experiment 1: Paint schedule strategies

The paint scheduling strategies given in this research are: a hybrid approach of simulated annealing with tabu-list and a simple heuristic namely, first-come-first-served. Both will be compared to the current scheduling strategy of the paint department in Section 6.1.2. Before the results are compared, Section 6.1.1 shows experimental results of different parameter settings of simulated annealing. From these results, a setting is chosen that will be applied for the remainder of this chapter.

### 6.1.1 Parameter setting for simulated annealing

In Chapter 5.2.3, it was discussed that the following annealing parameter settings are expected to provide the most promising results: Start temperature of 5000, Stop temperature of 5 degrees, a Markov length (k) of 30 and a degrease factor of 0.9. These settings provide many iterations to escape from a local optimum. However, the drawback of these settings is that the simulation will take days to run all iterations. For this reason, we experimented with different settings with the aim to reduce the run-time significantly and still show significant improvement.

Figure 6-1 shows the result of seven simulated annealing experiments relative to the performance of the current situation for different starting temperatures and cooling factors. The performance is determined for each day schedule for the entire simulated period. The *stop temperature* for all experiments is the same, namely 5 degrees and the Tabu-list size is 30. The run-time of these experiments vary between one and ten hours. A few results are pointed out in the subsequent sections.

The first result explained, is the experiment with a Markov length of 1. Here, the improvement is much less compared to the other experiment settings. Some days it even leads to worse results than the current scheduling strategy. This is because it had less chance to escape from a local optimum. This emphasises the importance of choosing the right parameters for simulated annealing.

The best result, on average 28% improvement, comes from the experiment with parameter settings: Start temperature 100 degrees, a Markov length (k) of 15 and the decrease factor of 0.9. The runner-up of best performing experiment has an average make span improvement of 27%. This experiment uses a start temperature of 100 degrees, a Markov length of 10 and a decrease factor of 0.9. The run time difference between the runner-up and the best performing experiment is 3 hours.

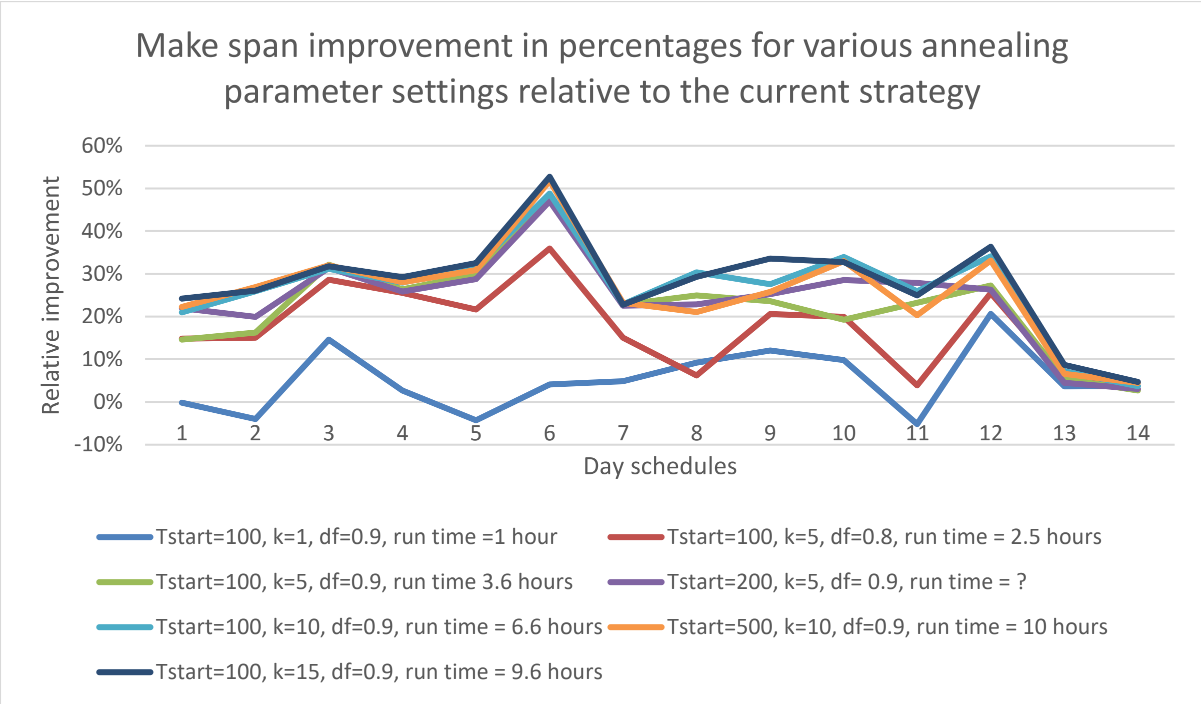


**Figure 6-1 Make span improvement in percentages for various annealing parameter settings relative to the current strategy. All experiments use a stop temperature of 5 degrees.**

Given the great performance of the runner-up and the 3 hour run-time reduction, we decided to continue simulating with the parameter settings of the runner-up: Start temperature 100 degrees, a stop temperature of 5 degrees, a Markov length (k) of 10 and the decrease factor of 0.9.

Additionally, we would like to point out another finding in Figure 6-1. Day 6 shows results with over 50% performance increasement where day 13 and 14 only improve with 5 %. This low increase in performance might come due to the lack of iterations, thus the simulation did not receive enough opportunities to escape its local optimum. Furthermore, we believe that the performance of the experiments highly depends on the product mix received that day. Day 13 and 14 received many pump- and DPU items, which require the most assembly time compared to other items. We performed calculations which showed that the amount of DPUs received on “day 13”, will never be ready within two days in a three-shift system.

This is not entirely the blame of a lack of capacity, it is the lack of smoothening DPU orders over the days.

### 6.1.2 Results different paint scheduling strategies

The first experiment is to compare the current paint scheduling strategy with simulated annealing and the first-come-first-served strategy. The current strategy makes use of the *cool zone exit strategy* that allows a production order to be split over two assembly lines at the after-paint department. The consequence is that two packing stations require a changeover instead of one. The wish of the company is to prevent the additional changeovers. To understand the influence of this assumption additional experiments took place, namely: current scheduling strategy <u>without</u> the cool zone exit strategy and the annealing strategy <u>with</u> cool zone exit strategy.

Table 6-1 Results Experiment 1

| Scheduling Strategy | Make span improvement relative to current strategy | Average daily idle time of the three assembly stations at after-paint | Average idle time first station paint department | Backlog paint department on 5-Oct-2018 (num. orders) |
|---|---|---|---|---|
| **Current strategy** | 0% | 47.1% | 58.3% | 88 |
| **Current strategy without cool zone exit strategy** | -5.9% | 52.2% | 62.0% | 165 |
| **First-come-first-served without cool zone exit strategy** | -14,1% | 55.7% | 64.3% | 231 |
| **Annealing & Tabu-list without cool zone exit strategy** | 22.1% | 43.2% | 49.7% | 45 |
| **Annealing & Tabu-list + cool zone exit strategy** | 24.2% | 40.8% | 40.6% | 36 |

Table 6-1 shows the results of the five scheduling strategies. The current strategy performs rather well in comparison with the current strategy without the cool zone exit strategy and first-come-first served strategy. The first-come-first-served has a 14.1% higher make span than the current strategy and has a significantly higher backlog. The higher the make span, the longer the idle time. To explain, a long make span indicates that the schedule is wrongly balanced resulting in assembly stations waiting for products.

Although the current schedule performs well compared to the other two strategies, using simulated annealing (SA) without cool zone strategy resulted in a dashing make span improvement of 22.1% and a backlog of 45 production orders. This is the direct result of the improved scheduling sequence. Even with SA, the average daily idle time remains high (43.2% for after-paint and 49.7% for paint), so there is still room for improvement. The stations might be idle, this does not mean the operators are idle, since they can be allocated to other stations. In experiment 6, we experiment with the capacity of the assembly stations such that the operators at the idle stations can easily relocate to stations with work.

The assumption that disallows the use of the cool zone strategy, does have a negative impact on the performance of the strategies. The make span of SA is improved with an additional 2% when allowing the cool zone strategy. Furthermore, it reduces the idle time of paint station with an additional 9%. Although the SA with cool zone exit strategy performs better than SA under the conditions in the simulation model, it is decided to remain focused on the regular SA strategy without the cool zone exit strategy. This, to respect the companies' wish and with the prediction that experiment 6 might make up for the 2% make span loss.

## 6.2 Experiment 2: Tackle zone & conveyor speed

From a visual inspection of the simulation model it is seen that the paint department struggles with accumulation of transport beams in the different paint zones resulting in a domino effect, as explained in Section 5.3.2 Here, it was suggested to rearrange the zone boundaries and reduce the conveyor speed such that a continuous flow is established through the entire paint department. It is believed that the new rearrangements prevent the domino effect from the cool zone exit up to the paint robots. To show the effect of the rearrangement, two simulations are performed and compared to the original situation. *The original situation* makes use of the current paint scheduling strategy and the cool zone exit strategy, in which production orders are allowed to split over two packing lines at the after-paint department.

In the first experiment the speed of all conveyer tracks in the paint and after-paint department are reduced. It showed an incredible drawback, the make span increased by 21.7%, see Table 6-2. Furthermore, the idle time in the paint and after-paint department increased as well. This is not according our expectations. Through visual inspection, the simulation shows an increase in blockages at after-paint, compared to the current situation. The blockage is earlier explained in 5.2.4. This blockage is the result of: the used cool zone exit strategy, order size and the lay-out of the tracks. The moment the blockage is gone, the system needs more time to recover due to the lower speed as compared to the original situation. This increased the idle time in both departments. To provide this observation with numerical proof, a second experiment is performed.

In the second experiment the conveyor-speed of all after-paint tracks is changed back to their original speed. However, the renewed zone-rearrangement and speed reduction in the paint department stayed the same as in the previous experiment. Be aware that in real-life the speed deviation between some paint zones and after-paint is tactically not possible since they are part of the same drive chain. The results of this experiment, 'speed reduction paint department', are provided in Table 6-2. Notice that the make span, idle time of both departments and the backlog are a bit worse than the values of the original scenario. This is explained by the increase in lead time at a few zones in the paint department as was expected in Section 5.3.2. The transport beams spend more time in: the buffer, primer, drying, and paint zones than originally. Furthermore, observations show that the flow through the paint department is smooth. However, the domino effect still occurs due to large orders with relative long packaging time in the day schedule and a too low performance of the after-paint department. For this reason, in the next experiment the order size is reduced.

**Table 6-2 Results experiment 2: the effect of the zone re-arrangement and conveyor speed on the scheduling performance relative to original model which contains the current scheduling strategy.**

| **Scenario** | Make span improvement relative to Original model | Average daily idle time of the three assembly stations at after-paint | Average idle time first station paint department | Backlog paint department on 5-oct-2018 (num. orders) |
|---|---|---|---|---|
| **Original speed** | - | 47.1% | 58.3% | 88 |
| **Speed reduction paint & after-paint department** | -21.7% | 58.9% | 66.8% | 254 |
| **Speed reduction paint department** | -0.02% | 47.7% | 58.7% | 91 |

## 6.3 Experiment 3: Reduce order size

The tactical planning is reviewed. Every order size larger than 12 transport beams is set to 12 beams and the remaining is placed in a new suborder. Thus, the number of production orders increased significantly. The effect of the order size reduction is evaluated for the current strategy and the annealing heuristic. We have seen in the previous experiment that the speed reduction did not provide promising solutions. For this reason, the speed and zone configuration remain the same as the current situation.

**Table 6-3 Results experiment 3: reduced order size given current conveyor speed**

| **Scheduling Strategy** | Make span improvement relative to Current strategy | Average daily idle time of the three assembly stations at after-paint | Average idle time first station paint department | Backlog paint department on 5-Oct-2018 (num. orders) |
|---|---|---|---|---|
| **Current strategy** | 0% | 47.1% | 58.3% | 88 |
| **Current strategy + reduced order size** | -10.8% | 52.3% | 62.2% | 186 |
| **Current strategy without cool zone exit strategy + reduced order size** | -10.5% | 52.2% | 62.1% | 186 |
| **Annealing & Tabu-list + reduced order size** | 24.0% | 40.4% | 39.9% | 31 |

The result of the order size reduction is shown in Table 6-3. As expected, the current strategy with reduced order size performs the same with and without cool zone exit strategy. The current strategy is still able to split orders over two lines if the order contains more than 10 beams, but this is no longer beneficial given the additional setup time. This is the reason why the make span of the current strategy with reduced order size is higher than the current strategy without the splitting order strategy. Annealing has a 2% higher make span reduction with the reduced orders size compared to the results found in experiment 1 in Table 6-1. The idle time and the backlog are also reduced. This means that the reduction in order size has a positive influence on annealing as scheduling heuristic. Although the idle time is reduced, there is still room for improvement.

## 6.4 Experiment 4: Exclude medical group from production

This experiment addresses the second objective of the case study, which is to study the influence potentially outsourcing a medical segment on the performance of the paint and after-paint department. Table 6-4, shows the influence of the exclusion of the medical segment on the various scheduling strategies. The exclusion significantly reduces the backlog of all scheduling strategies. It was expected that the make span of all scheduling strategies would improve, since the number of orders is reduced.

**Table 6-4 Results experiment 4: influence of the excluding the medical segment on the various scheduling strategies.**

| Scheduling Strategy | Make span improvement relative to Current strategy | Average daily idle time of the three assembly stations at after-paint | Average idle time first station paint department | Backlog paint department on 5-oct-2018 (num. orders) |
|---|---|---|---|---|
| **Current strategy** | 0% | 47.1% | 58.3% | 88 |
| **Current strategy without medical category** | 18.3% | 44.7% | 36.3% | 7 |
| **Current strategy without cool zone exit strategy without medical category** | 3.2% | 48.9% | 58.6% | 48 |
| **Annealing & Tabu-list without medical category** | 18.3% | 43.6% | 26.6% | 4 |
| **Annealing &Tabu-list without medical segment + reduced order size** | 33.1% | 43.6% | 22.1% | 0 |

Annealing is (again) the best performing scheduling strategy. Additionally, Table 6-4 shows two annealing experiments: annealing with and without reduced order size. Remarkable is the difference between the two. Annealing with reduced order size performs roughly 15% better. The idle time at the paint department is reduced by 4.5%. However, the idle time in the after-paint department remains the same! That the idle time is the same for both strategies, is a coincidence. Looking at the individual day schedules, we observe that annealing with reduced order size is (sometimes) able to eliminate the third-shift, see Appendix E (confidential)! This explains already roughly 33% of the idle time at after-paint. However, the annealing without reduced order size, makes still use of the third/fourth shift, but in an inefficient way. We will take this result with us to the next experiment in which we strive to eliminate the third-shift completely.

When we looked at the individual day schedules, we noticed the high number of paint setups. Trying to explain why annealing allows this number of setups, we observed that this is a response to the domino-effect, which is explained in Section 5.3.2. The additional setups have no (negative) influence on the make span, since the bottleneck is the after-paint department. On the contrary, the additional setups have a positive effect on the paint system, since it provides time to recover from the domino-effect.

## 6.5 Experiment 5: From a three-shift system to a two-shift system

The previous experiments showed: the effectiveness of different scheduling strategies like SA, the effect of reducing the speed of the conveyor, the effect of reducing the orders size and the effect of excluding a medical segment. In these experiments, we showed the performance of the make span, but not yet the effect on the number of shifts!

The effect on the number of shifts is positioned in the Appendix E (confidential). It shows that generally more than three-shifts are required to finish the day schedules for all scheduling strategies. Furthermore, it shows that the number of shifts is significantly reduced by using annealing as scheduling strategy. For example, a day schedule under the current strategy used 6.0 shifts to finish the day schedule, where annealing used 3.0 shifts. The improvement in shift reduction is great, but not enough to finish the day schedule in a two-shift schedule. However, this does not mean that they cannot work in a two-shift system. To explain, Table 6-5 shows the weekly backlog of the case study's best performing scheduling strategies against the current strategy. Using the annealing strategy with reduced order size results in a backlog of zero in weeks 38 and 39. This indicates that the number of shifts might be reduced for these production weeks. Having a backlog of 2 or 3 is still very acceptable. Besides, it indicates that a third-shift is fully required with the given scheduling strategy.

Table 6-5 Backlog per week given a three-shift system for various planning strategies.

| Paint backlog per simulated week | Current strategy | Annealing & Tabu list | Annealing & Tabu list + reduced order size |
|---|---|---|---|
| **week 38** | 21 | 3 | 0 |
| **week 39** | 58 | 2 | 0 |
| **week 40** | 88 | 45 | 31 |

Given these results, we experiment with three options to find out which configuration prevents the third-shift given the **annealing strategy with reduced order size**:

1. Reduce the number of shifts for specific weeks (week 38 and 39), since there the backlog shows we might be able to reduce.
2. Increase the capacity to make a two-shift system possible.
3. Implement a two-shift system with weekend shifts with a maximum of two-shifts on Saturday and one shift one Sunday.

**Two-shift system & weekend shifts**

For the best performing scheduling strategy (annealing & tabu-list with reduced order size), it might be possible to reduce the number of shifts in weeks 38 and 39. To test this theory experiments are performed in which the three-shift system is reduced to a two-shift system. The results are shown in Table 6-6. It is found that a two-shift system would be a bad idea, since the backlog increased massively. Even with three additional weekend shifts, the backlog is still high (139 orders) at the end of the simulated period (week 39). This indicates that the backlog of zero in a three-shift system might be just reached, thus it would not be advisable to reduce the number of shifts under the current conditions.

Table 6-6 Experiment 6.1 results: effect of a two-shift system

| Paint backlog per simulated week | Annealing & Tabu list + reduced order size | | |
|---|---|---|---|
| | Three-shift system | Two-shift system | Two-shift system + three weekend shifts |
| **week 38** | 0 | 123 | 59 |
| **week 39** | 0 | 184 | 120 |
| **week 40** | 31 | 246 | 139 |

**Increased capacity & weekend shifts**

The previous section showed that even with the best scheduling strategy a regular two-shift system is not sufficient. Thus, to be able to realise a two-shift system the capacity of the assembly line workstations must be increased.

The capacity of the three assembly line workstations is increased from two to three (thus, in total nine workstations). Five different experiments with increased capacity were performed, as shown in Table 6-7.

*Three-shift system increased capacity*

The first experiment is to increase the capacity for the three-shift system. Table 6-7 shows that the backlog of the three simulated weeks is zero. Furthermore, the make span improved with 37.1%, see Table 6-8. This is an additional 13% compared to the workstation capacity of two. The idle time of the paint station is also the lowest it has ever been, namely

18.7%. However, the idle time of the assembly stations at after-paint is increased to 59%! Thus, a three-shift system with increased capacity is not efficient for the after-paint department, but effective for the other KPIs.

*Two-shift system increased capacity*

The three-shift system is reduced to a two-shift system. In week 38, 39 the backlog is respectively 15 and 7, see Table 6-7. The backlog is a bit too high for our preference, but acceptable, because week 39 was able to reduce the backlog by 8 orders. However, in week 40 there is a need of additional shifts to bring the backlog of 70 closer to zero.

**Table 6-7 Experiment 6.2 results: effect of the increased capacity and weekend shifts on the backlog**

| Paint backlog in orders per simulated week | Annealing & Tabu list + reduced order size.<br>Increased capacity from two to three workstations per assembly line | | | | |
|---|---|---|---|---|---|
| | **Three-shift system** | **Two-shift system** | **Two-shift system + 1 weekend shift** | **Two-shift system + 2 weekend shifts** | **Two-shift system + 3 weekend shifts** |
| **week 38** | 0 | 15 | 3 | 0 | 0 |
| **week 39** | 0 | 7 | 0 | 0 | 0 |
| **week 40** | 0 | 70 | 42 | 22 | 1 |

Furthermore, the make span, idle time of the two- and three-shift systems are compared as shown in Table 6-8 and 6-9. In a two-shift system, the make span improvement of the schedule is reduced to 23.0%, the average idle of the after-paint department has been halved to a stunning 28.4% and the idle time of the paint station is slightly higher (23.5%).

The decrease in make span improvement is explained by the daily maintenance and inspection work that has to be performed during one of the shifts. This results in different effective working hours for the three-shifts. To explain: Assume the maintenance is performed in the first shift of the day. A day schedule in a three-shift system which would finish in the third-shift, contains only one period of maintenance. In a two-shift system, the same schedule is finished the next day and therefore includes two periods of maintenance, which increases the make span. For this reason, the make span of a two-shift system, will always be worse than of a three-shift system, see average make span as shown in Table 6-8.

*Two-shift system & weekend shifts*

The previous sections showed that only a two-shift system with increased capacity was not enough to prevent a large backlog and the end of the simulated period. Therefore, experiments are performed, where additional weekend shifts are added to the two-shift system. The results of these experiments are shown in Table 6-7 until 6-9.

Adding three weekend shifts results in a backlog of a single order and a large improvement in the make span. However, the idle time (especially of the paint department) is increased to roughly 30%. Furthermore, we observe large differences between the three weeks for the backlog, make span improvement and idle time. This indicates that each week requires a different solution. The next section describes the trade-off for selecting the best solution for each week.

**Table 6-8 Experiment 6.2 results: effect of the increased capacity and weekend shifts on the make span improvement with respect to the current situation (three-shift system)**

| Make span improvement per simulated week | Annealing & Tabu list + reduced order size. Increased capacity from two to three workstations per assembly line | | | | |
|---|---|---|---|---|---|
| | Three-shift system | Two-shift system | Two-shift system + 1 weekend shift | Two-shift system + 2 weekend shifts | Two-shift system + 3 weekend shifts |
| week 38 | 46.1% | 42.7% | 36.9% | 43.0% | 43.0% |
| week 39 | 34.6% | 28.4% | 28.0% | 28.0% | 31.2% |
| week 40 | 30.5% | -2.2% | 4.3% | 19.5% | 32.0% |
| Average period | 37.1% | 23.0% | 23.1% | 30.2% | 35.4% |

**Table 6-9 Experiment 6.2 results: effect of the increased capacity and weekend shifts on the idle time at the after-paint stations (A-P) and paint station (Paint)**

| Idle time per week | Annealing & Tabu list + reduced order size. Increased capacity from two to three workstations per assembly line | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Three-shift system | | Two-shift system | | Two-shift system + 1 weekend shift | | Two-shift system + 2 weekend shifts | | Two-shift system + 3 weekend shifts | |
| | A-P | Paint | A-P | Paint | A-P | Paint | A-P | Paint | A-P | Paint |
| week 38 | 53.4% | 14.4% | 26.1% | 17.5% | 26.2% | 18.3% | 29.0% | 16.8% | 28.9% | 28.7% |
| week 39 | 55.0% | 15.4% | 25.2% | 21.7% | 24.1% | 20.8% | 30.3% | 30.2% | 30.0% | 39.8% |
| week 40 | 53.3% | 26.5% | 33.8% | 31.3% | 31.3% | 26.3% | 35.2% | 27.9% | 31.5% | 25.3% |
| average | 53.9% | 18.7% | 28.4% | 23.5% | 27.2% | 21.8% | 31.5% | 25.0% | 30.1% | 31.3% |

**Trade-off**

Table 6-7 until 6-9 showed the backlog, make span improvement and idle time for the different number of weekend shifts. Based on these results, weeks 38 and 39 would perform well without any weekend shifts which results in a backlog of 7 at the end of the week 39. The make-span of the two-shift system is better (43% and 38%) compared to adding a single weekend shift (37% and 28%).

In week 40, the results show that three weekend shifts are necessary to reduce the backlog to a single order. For additional three weekend shifts the make span improvement is 32%

compared to 20% for two weekend shifts. The idle time for both paint and after-paint stations is also reduced by a few percent when increasing the number of weekend shifts from two to three.

Concluding: the best solution for weeks 38 and 39 is two-shift system with increased capacity. Adding three workstations and three operators to a two-shift system will already save 18% of the cost compared to a three-shift system, see Figure 6-2.

For week 40, the best solution given the three model KPIs, is a two-shift system with increased capacity with additionally three weekend shifts. However, adding three operators and three weekend shifts will result in increase of the cost of 16%.

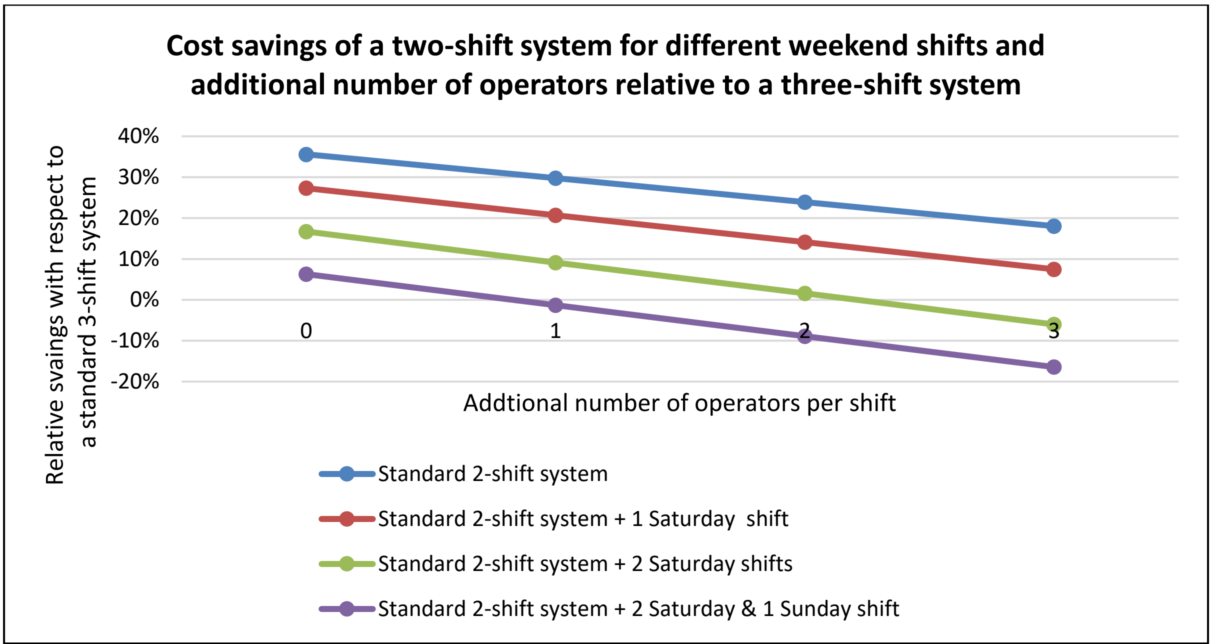


**Figure 6-2 Cost savings of a two-shift system for different weekend shifts and additional number of operators**

Combining the week solutions, result in a positive cost saving of roughly 20%. However, if the orders were better spread over the weeks, then this would have resulted in an additional single shift each weekend and cost savings of 21%. Furthermore, the average make span improvement, after combining the three best week solutions (42.7%, 28.4% and 25.3%) is 33.7%. This is roughly the same make span improvement, as the improvement found in Experiment 4. Here, the influence of excluding a medical segment was evaluated.

The increase in capacity could potentially also be realized without adding three operators, since idle employees can easily be relocated to stations with work. This could potentially lead to an increase of cost savings up to 36% in weeks 38 and 39 (two-shift system) and 6 % in week 40 (two-shift system with three weekend shifts). Thus, the average cost saving is 26% when no extra operators are needed. However, the actual required number of operators should be part of further research.

## 6.6 Limitations of the case-study

Three limitations are found in this case-study. As explained in the model simplification of Chapter 5.1, today's *day schedule* is partly depended on tomorrow's day schedule. This dependency could not be included in the model, since it will affect the independency of the optimization of today's day schedule. Besides, in reality no information is known, about which orders will show up the next day. This deviation from the real situation is the first limitation. How large the actual dependency of next day schedule is on the performance of today's schedule, should be part for further research.

The second limitation concerns the parameter settings of the simulated annealing heuristic. We limited the number of iterations, to reduce the simulation time. The result is that the annealing heuristics did not receive the full opportunity to escape a local optimum. Thus, the found solutions could have been even better with different parameter settings.

The last limitation is about the current scheduling strategy. The current strategy is an online planning in which the operators use the 200-200 rule as guideline. The 200-200 rule is explained in Chapter 3.1.2. In this case study, the 200-200 rule is used to create an offline planning. In this offline planning, no interventions of the operators are allowed. This means that the modelling of the current strategy is a rough approximation of reality. Previously, differences between reality and the model were discussed in Section 5.2.5: Validation.

## 6.7 Conclusion

In this chapter, the results of the five experiments were described to answer the three objectives of the case study. <u>The first objective</u> is to find an adequate operational scheduling strategy for the paint department. The application of simulated annealing with Tabu-list on the paint schedule exceeds our expectations. This hybrid approach reduced the make span by 22% in comparison with the current situation. The average idle time of the paint and after-paint department remained larger than 40%, which indicates that there is a lot more room for improvements. Furthermore, we looked into the influence of reducing the order size. It is found that an order size reduction is only beneficial for the annealing heuristic, which reduced the make span by an additional 2%. To conclude, simulated annealing with order size reduction is the best performing scheduling strategy. Therefore, this scheduling strategy is used for the other two objectives.

<u>The second objective</u> is to find the possible benefits of outsourcing a medical item group. Potentially outsourcing the medical segment brings an additional benefit of roughly 15% in the make span. This means that the use of annealing, with order size reduction and outsourcing, results in a total make span reduction of 33% compared to the current strategy!

<u>The last objective</u> is to reduce the three-shift system to a two-shift system. It is found that an increase in the workstation capacity from two to three at the assembly lines is required to be able to work in a two-shift system. However, this means that some weeks require

additional shifts in the weekend since the backlog becomes too high. For this reason, we provided a solution for each week in the simulation which resulted in a potential cost reduction of 20%. At the end of this chapter, the limitations of this case study were discussed.

*The results found in this chapter and the previous are used in the next chapter, to create a generic roadmap. The generic roadmap guides planners for all hierarchical planning levels in the organization to find suitable planning strategies for their scenarios.*

# 7 Generic Roadmap

The previous chapter showed different paint planning strategies aimed to find the best schedule out of the orders received in the paint buffer. However, the orders in the paint buffer are the result of the operational schedule and tactical planning. Furthermore, the problem cluster in Chapter 3 showed two other core problems that also impact the creation of any planning. It is the lack of valid data and the non-user-friendly database that make it hard or even impossible to create a solid and functional planning. This has led to the pervasive need to develop a generic roadmap on how to establish adequate planning- and scheduling strategies suitable for the various Power-Packer production departments.

The planners of all hierarchical levels of the organization should be able to use this roadmap. The roadmap works as a guideline for planners to kick-off their planning and scheduling projects. The roadmap developed is a visionary document built upon literature research, the reflection of the paint schedule development and extensive work floor experience. We distinguished four key requirements in establishing a planning strategy:

- A clear description of the **problem statement** and its planning objective which involves:
    - The planning environment.
    - The hierarchical organization level and its impact on other hierarchical levels.
    - The planning horizon.
    - Evaluation if product families could be of use.
- **Checklist: data and control** to validate data and to obtain a supporting data structure.
- **Establishing product families** (optional).
- **The selection of planning strategy** which involves experimentation.

Each of the four phases are respectively explained in Section 07.2, 7.3 and 7.4. Subsequently, the benefits of the roadmap are discussed in Section 7.5 and its limitations in Section 7.6.


Figure 7-1 Outline of the roadmap

## 7.1 Problem Statement

Through the problem statement, the planning objective can be formulated. Based on approaches used in Chapters 3 & 4, six steps were identified that contribute to formulating the planning objective for the paint schedule:

- **Step 1**: Describe the motivation for establishing a new planning strategy.
- **Step 2:** Formulate the planning goal.
- **Step 3:** Identify the hierarchical planning level. From this follows the stakeholders and the planning horizon.
- **Step 4:** Identify the manufacturing environment.
- **Step 5**: Identify type of planning/scheduling method.
- **Step 6:** Formulate the planning objective.

These six steps are now part of what is going to be called the problems statement (phase 1 of the roadmap). Along the way, we have gained new insights which is the reason for further specifying the different steps. To stress the importance of each step and to provide some tips, the steps are briefly discussed in more detail in the following sections. This results in the problem statement roadmap which can be found in Appendix G.

**Step 1 & 2: Motivation and goal**

A well written motivation results in more support for starting the project to develop a new planning strategy. The motivation includes detailed descriptions of the reason to develop the planning strategy. It clarifies to which process(es) the planning should be applied. Furthermore, it includes proven issues and over time adapted wishes. In the end, the planning goal should be formulated.

**Step 3: Hierarchical planning level**

The hierarchical planning levels are explained in Chapter 4 Section 4.1.2. Decisions made at higher hierarchical levels have influence on the planning performance of the lower hierarchical levels. It is therefore important to include the stakeholders of lower hierarchical levels into the decision making. Furthermore, the hierarchical planning level also decides upon the planning horizon.

Looking back: We found that the use of product families should be connected to the hierarchical planning levels. In Chapter 4, Zhang & Rodrigues (2010) showed that the development and integration of product families into the planning strategy is a strategic decision. Mainly, because product families are not only applicable for planning purposes, but also for design- and product development. In addition, developing product families is of influence on the time span of your project. Especially, if first new data should be gathered. These reasons made us decide to imbed the use of product families in the objective formulation and integrate it into the hierarchical level step.

We did not show before how product families can be used in the different hierarchical levels, which is why some examples were added in the roadmap. The following sections explain the hierarchical planning levels and examples shown in the roadmap.

*Strategic planning:* It is a long-term planning of 6-18 months and often comes with high investments. An example of a strategic planning is increasing the aggregated capacity by extending the machine park. *To anticipate* what the *role of a product family* may be: instead of extending the machines park, stations may be replaced by a production line that is dedicated to a specific product family.

*Tactical planning*: It is known as a mid-term planning that looks roughly 6 months ahead. Examples of the tactical planning are the development of the master production schedule (MPS). *To anticipate* what the *role of a product family* may be: The MPS holds all production orders and allocates them to time slots. To evenly distribute the demand over the week, product family time slots could be used.

*Offline schedule:* The planning horizon is between one day and a week. An example of an offline schedule is fixing the production sequence of orders. *To anticipate* what the *role of a product family* may be: Even within a family a variety in processing and setup times is possible. The optimal production sequence minimizes the make span of the jobs or lateness of the jobs even within families.

*Online schedule:* It is continuous (re-)planning system and respond to unplanned events. An example of an online schedule is to select the 'best' job from a buffer for a single machine. *To anticipate* what the *role of a product family* may be: If a rush order occurs, then the online planning decides where the rush is squeezed in? It is quicker to identify the rush order's family and only look at the sequencing options of that family.

We end this step with two tips to avoid pitfalls:

**Tip 1:** (online schedule) Do not alter the online planning if this is not strictly necessary! The offline schedule finds the best schedule for the entire production department not just for a single machine.

**Tip 2:** Consider the use of product families. It might save computation time and provide more insight into impact of families on production.

**Step 4: Manufacturing environment**

A good identification of the manufacturing system increases the chance of finding suitable planning strategies for your situation. This is because not all planning methods are suitable for all manufacturing system types. To help identify the relevant manufacturing systems, we established a list with different manufacturing systems with corresponding definitions in Appendix F.

**Step 5: Type of planning/scheduling method**

Answer the question: Does the schedule needs to find the optimum (complete enumeration) or is a near optimal solution (heuristic) acceptable. This decision is mainly based on the problem size as described in Chapter 4 Section 4.2.1.

**Step 6: Formulate the objective**

Summarise step 1 to 5 into the objective.

The next stage of the roadmap is to collect the data and its validity.

## 7.2 The checklist: Data & control

Before planning may be established it is important to gather the required data. To establish *any form* of planning, it is a necessity to:

1. Have a list of production orders,
2. Have valid processing times such that planning is reliable.
3. Given the production orders, know the process plan. The process plan provides insight in all operations and tooling required to assemble the order.

Given these essentials, it is decided that the *second topic* of the roadmap must be a *checklist*. This checklist triggers the user to look into the essentials and to see if the data is legitimate and well structured. The list must guide the user on how missing data could be obtained and shows how a well-organized data structure may look like.

In the appendix, you will find the results of a small literature study. This literature study is the result of providing solutions for two core problems: Lack of valid data on processing times (Problem C5), and lack of insight about the production path of the items and the capacity of the workstations (Problem TP3). Appendix C describes two approaches which are known to provide a good approximation of the processing times. Appendix D describes an approach to setup a structured process planning. This phase of the roadmap is built upon these literature studies and contains two steps.

**Step 1** of the checklist is to confirm if the data is organised well. The checklist suggests a data structure which is inspired by Halevi (2012). Halevi developed a two-dimensional matrix which structures and connects item- and resource properties for the use of process planning. Step 1.1 is the item matrix, step 1.2 is the resource matrix and step 1.3 is an extension of the resource matrix which contains the variable setup times between items.

**Step 1.1** is to create the item property matrix. The following **item properties** are stated by Halevi:

- Operations ID and operation description.
- Priority (hierarchy sequence in which the operations take place).

- Technical details, like workstation ID when fixed, required machine settings and or additional tooling per operation.
- The processing time per operation.
- Design details.

The following optional extensions are proposed:

- Create the possibility to add a column that may tell that a specific operation is part of a family. *The benefit* from this addition is that the family characteristic becomes easily accessible for planning systems.
- Make two columns for processing times. The first column contains the processing time target (Dutch: kale tijd). The second column may contain the experienced average processing time which could be used for planning purposes. *The benefit* from this addition is that the performance of the workstation may be compared. How far is the average processing time from the target, is something wrong?

**Step 1.2** is to create the resource specification matrix with the available resources (workstations, machines, fixtures etc.). This contains the following properties as stated by Halevi:

- The machine ID and machine description.
- Technical details, like machine capabilities, batching or one-piece flow.

The following optional extensions are proposed:

- In the case of identical parallel machines, the machine ID of all machines may be the same for planning purposes. This approach requires an additional column in which the *number of available resources* is stated.
- Add *minimum or maximum number of operators* as workstation details.
- Add *fixed setup time* which is defined as a minimum setup time for every job.

**Step 1.3** is to create a matrix containing variable setup times for each machine.

- The variable setup time is defined as the setup time between product items, excluding the fixed setup time. Later on, the *variable setup time between items* may be replaced by *setup times between product families*. This change reduces the size of the matrix such that the planning software finds the characters sooner.

As stated before, one of the necessities of establishing a planning is the availability of accurate data. Therefore **Step 2** is formulated as follows: make sure no data is missing and check the data to see if it is still accurate for the current situation. In the case that processing times are inaccurate, the literature in Appendix D contains the following useful techniques to obtain these processing times:

- ➔ ***Tip 1***: PERT is useful technique when processing times are not measured before or very limited measurements are available.
- ➔ **Tip 2:** Smart manufacturing software has multiple advantages such as continuous measuring workstation performance. A learning curve becomes visible when operators become more experienced with the product. This means that in the future less time may be reserved for the activity.

For missing item- and resource properties the following tip is suggested:

- ➔ **Tip 3:** Resource and product properties can be obtained by experts, like manufacturing engineers and product developers. It might also be convenient to let them check the data accuracy of the matrices.

The summary of this phase of the roadmap can be found in Appendix G. If all data is structured and found legitimate, then the user of the roadmap may go forward to the next phase of the roadmap. If part of the objective is to include product families then work through the roadmap establish product families as described in Section 7.3. If families are not part of the objective the reader moves on to the optimization strategy in Section 7.4.

## 7.3 Establishing product families

The aim of this roadmap is to establish a better production planning. Chapter 4 Section 4.3 described that successful product family development may achieve efficiencies in both the design and production department. This part of the roadmap aims to form product families using the literature described in Section 4.3. Furthermore, this section also contributes validating existing product families and helps to check if these families are applicable to the objective of the project.

***Step 1.*** *Select grouping characteristics*

Select grouping characteristic(s) based on the objective. To recap, the grouping characteristics found in the literature review:

- Commonality/modularity: the families are established based on the highest ratio of shared parts or modules.
- Technological compatibility: the degree in which items make use of the same operations or workstations.
- Reusability: at a product level, how well could product components be deconstructed and reallocated to other products.
- Product demand.
- Cost.
- Processing time.
- Multi- characteristics: with the support of multi-decision criteria techniques, weights may be assigned to each characteristic to capture its importance.

Keep in mind that there are many more characteristics which are not mentioned in the list, for example grouping based on clients. Therefore, the characteristic *other*s must be added to the roadmap grouping characteristics.

**Tip 1** to select characteristics. Literature showed family groups that consider commonality (shared parts) and the technological compatibility characteristics (machines setting, fixtures etc.), achieve a higher production efficiency.

***Step 2.*** *Select method for grouping*

Recap on approaches to formulate the groups:

- Descriptive procedure: Create groups by hand based on the expert opinions and knowledge. The stakeholders involved may be the design experts and manufacturing experts.
- Group analysis: List the characteristics of each product and compare the products based on the objective. The advantage is that the characteristics are validated in comparison with the expert's opinions found under the descriptive procedure.
- Mathematical programming: The aim is to group items with the highest possible similarity given the grouping characteristic(s). The advantage is that the result may be validated and repeated once in a while.
- Artificial intelligence: This method is often based on metaheuristic which is an approach to find an acceptable grouping solution.
- Graph partitioning: This method makes use of a part-machine matrix. The parts and machines are connected by arcs. The matrix provides two options: (1) minimize the arcs between machine groups such that parts do not have to travel as much or (2) group components that all make use of the same machine.

**Tip 2:** In the case the problem size is too large and the solution space to big, try to consider metaheuristics to find an acceptable solution instead of mathematical programming. Using mathematical programming results in higher computation time. In the case that only one characteristic and only a few products are part of evaluation, consider simple approaches like the descriptive procedure or group analysis.

**Tip 3**: There is little known about what the absolute best method for grouping characteristic is! Be open for experimentation and keep in mind the planning objective!

A **warning** should be added to the roadmap. Literature showed that the selection of the grouping characteristic is a strategic decision. It might be that different hierarchical levels have different grouping wishes. Therefore, keep in mind that created families may have a big impact on all hierarchical levels. Thus, always warn planners in the case of new grouping strategy and try to measure the impact which could be positive or negative.

The summary of this phase of the roadmap can be found in Appendix G. The last phase of the roadmap is to find a suitable planning strategy.

## 7.4 Select the planning optimization strategy

The last phase of generic roadmap is to find a planning strategy, and (optionally) incorporate product families. The reader may notice that planning optimization strategies for families is not that different from a regular planning strategy.

In the previous phases of the roadmap, the user formulated the objective, acquired data and has defined the product families. Recalling the results of the previous sections is therefore identified as **step 1**.

**Step 2.** Given the objective, families and machine environment, select a promising planning strategy. Planners may easily get overwhelmed by the high number of strategy options described by literature. To provide planners a quick start, we conducted a literature study that sorts the most promising and observed planning strategies per manufacturing environment in Appendix F.

In Power-Packers interest, the following strategies are positioned in the roadmap:

a. Single machine environment, and small problem size (< 35 orders a day). Try linear programming to find the optimal production schedule solution! Otherwise try a dispatching rule that fits your objective.
b. Job shop or flex shop environment? Make use of heuristic which aims to find a (near) optimal solution, but does that within acceptable computation time. Like the paint schedule, start with a hybrid approach which combines *simulated annealing* and the *tabu-list*. Later on, the model could be extended: To generate promising alternate solutions (in annealing), use a local search method like *One Step Look-Back Adjacent Interchange.*
c. Parallel machine environment? Similar to job shops and flex shops, make use of the *simulated annealing* and the *tabu-list*. This would be the most obvious selection since, thanks to this research, there is more experience with this method. However, more simple heuristics might provide relatively quicker and acceptable solutions like the use of dispatching rules.

**Step 3:** Experiment with planning strategies before selecting one. It is recommended to use simulation studies (or digital twins) to evaluate the performance and the behaviour of the system. Also, a real-life experiment may part of the experimentations option, but this is not always optional.

**Step 4:** <u>Implement</u> the planning strategy which is the most promising given the objective. <u>Monitor</u> the performance of the planning strategy closely.

**Tip 1**: Keep experimenting with different planning approaches such that the companies find the most efficient solution applied to their situation. Products and tooling change, therefore over time the planning strategy might not be adequate anymore.

## 7.5 Benefits of the roadmap

The aim of this roadmap is to guide planners of power-Packer in establishing a planning strategy. This generic roadmap has three major advantages. Firstly, the roadmap shows how families may be applied to different hierarchically planning levels, to our knowledge this is never done before. Secondly, it is user-friendly due to the many examples, tips and warnings. Lastly, it is generic enough to apply it on any manufacturing company. The checklist for valid data, and the reviewed literature on forming product families is already broadly applicable. The planning strategy for manufacturing systems is currently specified for Power-Packer, but Appendix F provides planning strategies for every manufacturing system.

## 7.6 Limitations

To our knowledge, it is the first roadmap that provides a full outline from gathering data to establishing an efficient planning strategy. The advantage of the roadmap is broadly formulated which makes it applicable to multiple scenarios and other companies. However, this is also a disadvantage. The roadmap does not explain all planning strategies in detail. Neither does it show the performance of the different planning strategies, apart from the hybrid annealing strategy which has proving itself worthy in the paint planning scenario. Proving and explaining all strategies was never the goal of this generic roadmap. The roadmap is a visionary document which needs to be informative and not bias the user to only use methods mentioned in here. It should provide the *lost planner* with ideas on where to start the research and to provide confidence to experiment with the aim to develop an optimal robust planning.

# 8 Conclusion & recommendations

The aim of this study was to answer the following research question:

*'How can the company prevent a third-shift for the paint and after-paint department during a **demand peak** – similar to the one in experienced 2018-2019 - **through productivity improvements**? In particular, to what extent may a **new paint scheduling strategy** reduce the idleness in these departments?'*

This research consists out of three stages. The first stage covers the analysis of the demand peak to predict the likeliness of its return. The second stage discusses bottlenecks which are in(direct) responsible for idleness of the paint department and therefore the third-shift. The problem cluster showed that idle time at the paint department is caused by 24 problems. Amongst the problems, the paint scheduling strategy is one of them. Therefore, the last stage of this research described a case study to find an adequate scheduling strategy for the paint department.

**Demand peak**

This research showed that the demand peak is not likely to return soon. This appears from studying: yearly and monthly seasonality, product mix development and its outstanding items and the forecast. The annual product mix of cylinders, pumps, medical items and others is stable over the last 6 years. This is why economic growth is probably the biggest impulse that caused the long-lasting demand peak. Extrapolating the historical data and combining it with the sales forecast of upcoming year, it is expected that the demand returns to the same level as before the peak. Despite this finding, there is still relevance to research the idle time at the paint and after-paint department and to see if it can be reduced.

**Productivity improvements paint and after-paint department to reduce the idle time**

Management observed idleness at the first workstation of the paint department. A method was developed to measure the idle time. It is found that at least 2 hours a day, the activity hooking items to beams is disrupted by operator choice or a lack of beams. This result is the lower bound, because the operators where in charge to measure the occurrence rate of idleness themselves and admitted that they forgot to turve sometimes.

Through observations, interviews, production output analysis and planning method analysis 24 issues are found that (indirect) caused the idleness at the paint department. Tackling these problems will have a positive effect on the productivity on paint and after-paint department. The problems were positioned in a problem cluster and showed 9 core problems. One of the observed planning problems is the paint schedule strategy, which is not a core problem, but is the topic, the company is highly interested in. For this reason, a case-study is performed with the aim to find an adequate scheduling strategy.

**Case-study: scheduling strategy for paint and after-paint.**

We proposed a hybrid approach of simulated annealing with tabu-list and compared it with the current scheduling strategy and a simple heuristic namely, first-come-first-served. By using discrete event simulation, a digital twin of the production environment was developed to test the different scheduling strategies. The running time of the model with its current setting is for annealing approximately 8 hours for optimizing day schedules of five weeks from which two warm-up weeks.

The case-study contains three objectives. The first objective is to find scheduling heuristics for the *multi-model line (circular conveyer) at paint and after-paint,* with the objective *to minimize the idle time of the various workstations and to minimize the make span* of the *day schedules.* The make span of the simulated annealing with tabu-list with reduced order size performed 24% better than the current scheduling strategy, see Table 8-1. The order size is reduced to a maximum of twelve transport beams. The idle time of workstations in both the paint and after-paint department for all scheduling strategies is >40%. Thus, there is still room for improvement.

The second objective is to find out what the impact would be when a medical product group would be outsourced. The result is incredible! Compared to annealing & tabu with order size reduction is the make span improvement increased with an additional 10%! However, the idle time remained roughly the same for the after-paint department where the idle time of the paint station reduced drastically, see Table 8-1.

**Table 8-1 Best solutions objective 1 and 2 of the case study**

| **Scheduling Strategy** ***Three-shift system*** | *Make span improvement relative to current strategy* | *Average idle time of the workstations at after-paint* | *Average idle time first station paint department* | *Backlog paint department on 5-Oct-2018 (num. orders)* |
|---|---|---|---|---|
| Current strategy | - | 47.1% | 58.3% | 88 |
| Annealing & Tabu-list + order size reduction | 24.0% | 40.4% | 39.9% | 31 |
| Annealing & Tabu-list without medical segment + reduced order size | 33.1% | 43.6% | 22.1% | 0 |

The aim of the third objective is to find a configuration (e.g. increased workstation capacity, additional weekend shifts) that prevents the third-shift in case of a similar demand peak experienced in 2018-2019. It is found that an increase in the workstation capacity from two to three at each assembly line is required to be able to work in a two-shift system. However, this means that some weeks require additional shifts in the weekend, since the backlog becomes too high, see Table 8-2. For this reason, we provided a solution for each week in the simulation, which resulted in a potential cost reduction of 20%.

Table 8-2 Best solutions objective 3: week 38 - 40 work all in a two-shift system with increased capacity. Week 40 requires three additional weekend shifts to prevent a large backlog.

| | Annealing & Tabu list + reduced order size. Increased capacity from two to three workstations per assembly line | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Make span improvement | | Idle time at paint and after-paint (A-P) | | | | Backlog | |
| | Two-shift system | Two-shift system + 3 weekend shifts | Two-shift system | | Two-shift system + 3 weekend shifts | | Two-shift system | Two-shift system + 3 weekend shifts |
| | | | A-P | Paint | A-P | Paint | | |
| **week 38** | 42.7% | 43.0% | 26.1% | 17.5% | 28.9% | 28.7% | 15 | 0 |
| **week 39** | 28.4% | 31.2% | 25.2% | 21.7% | 30.0% | 39.8% | 7 | 0 |
| **week 40** | -2.2% | 32.0% | 33.8% | 31.3% | 31.5% | 25.3% | 70 | 1 |
| **Average period** | 23.0% | 35.4% | 28.4% | 23.5% | 30.1% | 31.3% | | |

To conclude, annealing & tabu-list showed, even with a low number of iterations, incredible improvements in the KPIs which resulted in massive cost reduction. This finding showed that annealing & tabu-list is a very powerful heuristic.

**Generic roadmap**

In the problem cluster, it is found that multiple hierarchical planning levels effect the performance of the paint and after-paint department. To support the planners of Power-Packer in improving their planning strategies a generic roadmap is made. The roadmap contains tips and warnings to address their planning problems. It is developed as a visionary document built upon literature research, the reflection of the paint schedule development and extensive work floor experience. The roadmap consists out of four phases: *problem statement*, *data & control*, *establishing product families* and *selecting the planning strategy*.

**Contribution to practice and literature**

Annealing is a procedure that evaluates neighbourhood solutions. Each iteration, a new *candidate solution* is compared to the *current solution* by means of an objective and is accepted or not to become the new current solution. Typically, in many real-life cases where annealing is applied, the objective of the candidate solution can be computed incrementally. For instance, the small computation time of a swap is all that is required to obtain the objective value of a neighbour. This is not the case in this research. Due to partly dependency of today's *day schedule* on yesterday and tomorrow, the calculation of the objective takes a considerable amount of time. This makes annealing non incremental. Although annealing requires a huge amount of time, annealing still finds impressive solutions and even with a low amount of iterations to reduce the computation time!

**Recommendations**

The first recommendation is to redesign and review Oracle on a yearly base, such that data extraction becomes more user friendly. Make sure to involve data users to ensure that the current data arrangements still work for them and their wishes are considered while redesigning and maintaining the database. Use tips and tricks of the generic roadmap: data & control, to streamline data accordingly.

If the data is in order, it is recommended to optimize the planning and scheduling strategies on a tactical level. The tactical level smooths the production demand over the weeks and months at Power-Packer. The smoothening may prevent large backlogs and therefore cost reduction, because in the end, it might minimize additional weekend shifts or overtime.

The last recommendation concerns the idea of positioning a buffer between the paint and after-paint department as discussed in the introduction of this research. This buffer will be positioned as fourth assembly line at the after-paint. This idea is highly discouraged, since the three existing packaging lines are roughly 30% of the time empty when using annealing as paint schedule strategy! This indicates that the buffer is redundant.

**Recommendations for future research**

The simulation model developed for the case-study can be extended in different ways. Recommendations to increase the performance of the paint schedule:

- Rerun the simulation model with updated processing times for the best performing scheduling strategy. Currently, the data represents the worse-case scenario, therefore the KPIs performance could be improved and cost reduced. Furthermore, run the model for the peak period and non-peak period to evaluate the performance of the scheduling strategy in more scenarios.
- Add operators to the simulated model to have a better cost estimation and to be able to optimize the required number of operators to complete the day schedules.
- Relax the constraints that only certain items can be assembled at certain assembly lines. For example, the pumps always go to line three at after-paint as stated in the assumptions. This assumption is made because this also happens in reality. If this assumption would be relaxed than a more optimal planning solution can potentially be found.

The idle time at the after-paint department is still high and the domino-effect still occurs due to blockages in after-paint. A few experiments for further research came to mind:

- Reduce the order size even further, such that complete orders are (for certain) able to fit on the assembly lines.

- Experiment with a different after-paint lay-out. Think of two large assembly buffer lines instead of the current three small ones. Furthermore, relocate the fill-, DPU- and DTU stations to create more space for the assembly buffer lines.
- Disconnect the after-paint department from the conveyor drive chains that also run through the paint department. This change makes it possible to reduce the conveyor speed in the paint department which reduces the domino-effect.

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# Appendix A: Data acquisition for peak analysis

The data acquisition concerning the demand peak covers two important aspects. First, Section A.1 describes the datasets available and for which purposes they are useful, such as weekly versus yearly demand patterns. Section A.2 describes the data validation which is performed in three phases.

## A.1 The data & creation of the data structure

Currently, the company uses four datasets that could support our research into finding seasonality patterns. Figure A-1 visualizes the data acquisition and is explained later on in more detail. Two datasets are extracted from the company's database Oracle and two datasets are Excels sheets. The datasets and their purpose are explained after another.

1. **Sales order data**

The best representation of historical demand is data containing the clients' preferred shipping date. The *Sales order data* contains order numbers and request dates for shipping which is perfect for determining seasonality. However, the dataset covers only the period January 2018 till November 2019. This time period is too small to determine yearly or monthly demand patterns. Preferably, the dataset should cover at least 5 to 10 years of data. However, the available data of almost two years is useful to determine weekly patterns. The original source of this dataset is the company's database Oracle.

2. **Sales invoice data**

To discover monthly and yearly patterns a new dataset, the so-called *Sales invoice data*, is obtained from Oracle. This data covers the period from November 2013 till November 2019. These six years is also the maximum amount of data that could be obtained, since the database was established in 2013. A sales invoice is a document that lists the quantities and prices of goods the company sells to the buyer. The invoice date, the moment the list is printed, is equal to the shipping date. The invoice date or shipping date does not have to be equal to the clients' preferred shipping date, but it is a good estimate. As a company, you can bargain to send an order earlier or later considering the lead time and plant capacity.

Both the *Sales invoice data* and *Sales order data* contain all products sold to all Lines of Businesses (LOB). In our results, the automotive and emission LOB are excluded. The automotive LOB is excluded, because these items are produced in another plant. The emission LOB is excluded, because these items are not painted and therefore not part of interest. After LOB exclusion, the data files require additional filtering, because they still contain non-painted products. This means that we had to search for files that show which items are actually painted.

Two files are available that contain painted items. It is the *Yield data file* of the After-paint department and the *Paint program data*. Our goal is to combine both files to create dataset *5. the paint file.*

3. **Yield file**

This data file is manually filled in by the supervisor of paint and after-paint department. Yield is defined as the number of product items that are coming out the paint & after-paint process. The *Yield data* contains information about production orders that are processed per shift by the paint and after-paint department. The file covers the period Augusts 2017-September 2019. All items are extracted from the *Yield file* and all duplicates are removed. These items are then saved in the new *Paint file.*

4. **Paint program data**

The *Paint program data* contains for each product item a paint program number. This paint program number is communicated to the paint robots. In this way the paint robots 'know' what to paint, which colour, and how thick the paint layers should be. In Chapter 1, section 1.2.2, it is found that an overhead conveyor belt transports beams through the paint and after-paint department. Products are attached to the beam by using ho oks. The 'Paint program data' informs the operator which hook type should be used. The file is manually maintained by the manufacturing engineers. However, the moment when the file is established is unknown. All product items from this file are added to the *Paint file.*

5. **Paint file**

By combining the product item of the *Yield* data with the items of the *Paint program* data duplicates occurred, which are removed. This Paint file is used as input for the *Sales order data* and *Sales invoice data*, such that only painted items remain to determine seasonality patterns.

Figure A-1 visualizes the data acquisition, using the Entity Relationship Diagram (ERD) as inspiration. The ERD describes the structure of a database and the relations between data sheets. However, in our situation no database is built. For this reason, we show a very simplified diagram that makes clear what datasets are used as input for other data files. Besides, it shows which data fields (or data columns) the datasets contain.

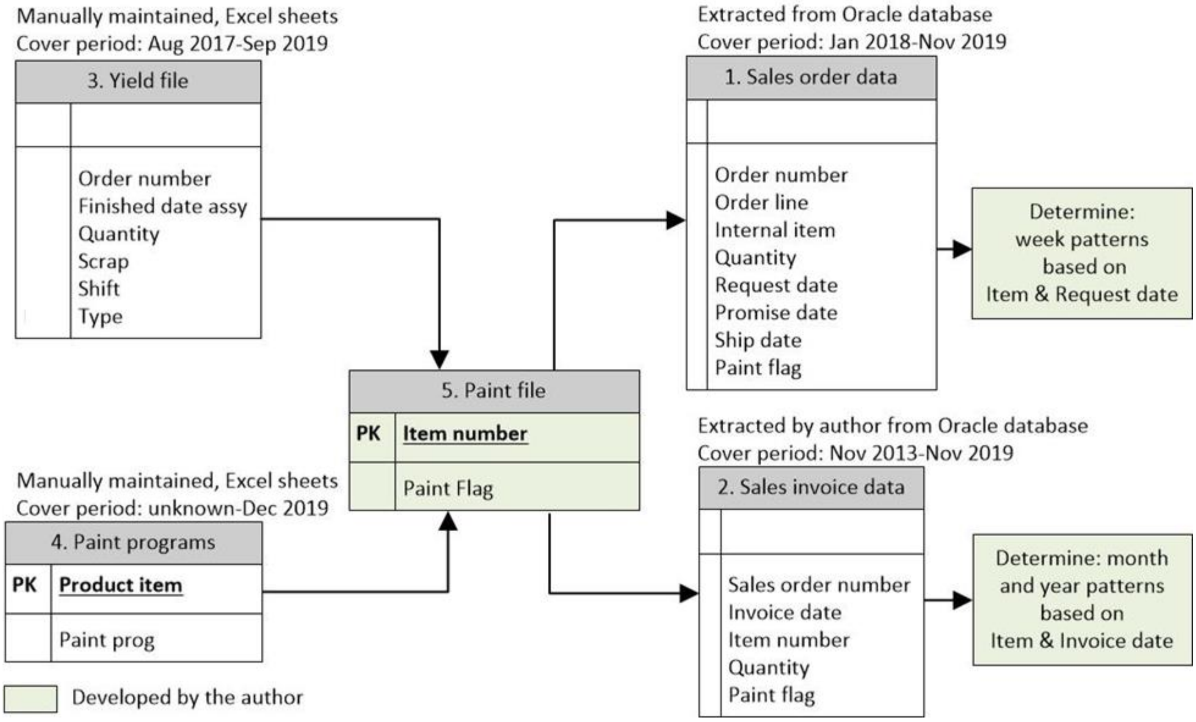


**Figure A-1 Data Acquisition, where PK stands for primary keys in the dataset**

Two data fields contain the property PK which stands for Primary Key, see Figure A-1. This means that this data field only holds unique values. Table A-1 shows an example to explain the PK, all product items mentioned in the *Paint programs* are unique compared to the *Sales order data.* The *Sales order data* contains multiple rows with the same order number and the same product item, thus these two columns are not unique. The *Paint program* file shows only unique product items which makes it a primary key. Keys are an essential element in databases. It helps to establish relationships between the various datasheets and is a must to establish a database (Khillar, 2016). For more information about database process management consult Weske (2012).

**Table A-1 Example explaining primary keys**

| *Sales order data* | |
|---|---|
| Order number | Internal item |
| 1 | Product 1 |
| 1 | Product 2 |
| 2 | Product 1 |

| *Paint programs* | | |
|---|---|---|
| Product item (PK) | Hook type | Paint prog |
| Product 1 | 1 | 10 |
| Product 2 | 1 | 30 |
| Product 3 | 3 | 10 |

Go back to Figure A-1, notice that the product item is named different in each file! Even within Oracle, which is the database of the company. The product item in the *Sales order data* is named internal item, where in the *Sales invoice data*, it is described as item number. Thus, there is inconsistency in terminology.

The *Yield* data of the After-paint department and the *Paint program* data are manually maintained. Therefore, it is likely that painted items are still missing even after combining the two files into the *Paint file*. To test this hypothesis, a validation strategy is introduced in Section A.2.

## A.2 Validation

What is the validity of the obtained data? There is strong belief that the *Paint file* is incomplete. The main reason for this concern is that the incoming data, the 'Yield file' and the 'Paint program file' is manually maintained. This increases the probability on typos and the ability that obsolete items are removed over the years.

To test the hypothesis that the *paint file* is incomplete, we came up with a validation strategy containing three phases which is referred to as the *categorization method*. The **first phase** is to verify if all items in the paint file will actually be painted. The paint file shows many different item numbers. We aim to categorize the number using the first four characters of all product items. An overview of all item categories is included in Section A.3.

The Paint file contains 1,774 finished good items that are categorized in 40 groups. Eight categories are found to be non-paint items and are therefore removed, leaving 32 categories. Three of the removed categories are repair kits. These slipped in through the Yield file, since surprisingly the after-paint department compiles the repair kits besides finalizing the painted items. The other five categories are believed to be typos, because no records are found that these items were ever sold. Here ends the first phase of the validation strategy: verification of paint items.

In the **second phase**, the items of the Paint file are compared with the *Sales order file*. The Sales order file contains 1,534 unique items from which 537 items are an exact match with the paint items. This suggest that from all 1,534 items sold only approximately one third is painted.

The **third phase** is built on Assumption 1:

*"All 32 product categories found in the Paint file, so DCD1 & DCD2 etc., are automatically items that are painted*." A1

By using this assumption, we verify if some items are missing from the Paint file. Under the assumption, additionally 87 unique items are identified as a paint item in the *Sales order file*. To verify if these 87 items are truly painted, the bill of materials (BOM) is consulted. From these 87 items, only 11 product items are actually painted.

**It is proved,** the Paint file is incomplete and therefore our hypothesis is confirmed. 11 Items are missing in the Paint file, which means that the file is 2% off in the period January 2018 – November 2019. A coverage of 98% is very good, but at the same time it should have been 100%. Especially, because the files used for validation are established in the same time period. This makes us wonder, what would happen if the time span increases?

Assumption A1 works for most product categories, but covered also non-painted items. A full overview is given in the Confidential 0. After validation, 6.44% is found not to be painted (74 items). It is observed that the assumption is not working for the categories DCD1, DSC's and DMI3 which represent 6.38% out of the 6.44% of the non-paint items. Off the remaining non-paint categories, the DCD2 and DPE2, the mismatch found is acceptable. They were delivered to the client as prototypes. A second argument why the mismatch is acceptable is that the number of non-painted items sold is only 0.016 % of the combined DCD2 and DPE2 categories.

The previous analysis shows that DCD1, DSC's and DMI3 product categories are the bottlenecks of why the assumption A1 is not working. However, it is observed that the product items have similar product descriptions meaning that by using a text constraint, assumption A1 can easily be improved. By implementing these constraints, it is found the assumption covers 99,9% of the painted items in the Sales order which is better than the 98% Paint file. For this reason, we apply the assumption A1 with the following text constraints for the remainder of this research to identify painted items:

- Exclude DCD1-XXXXXX-S items and 'Cylinder double acting.'
- Exclude DMI3 with the item description 'Medical installation' and 'MC.'
- Exclude DSC3 & DCD4 with the item description 'Roof lift' and 'Stretcher.'

### A.3 Product item categories (confidential)

# Appendix B: Specific product growth at item level

The demand growth with respect to the previous year in 2017 was 9%. This had a big impact on the production department. They went from a two-shift system to a three-shift system which the company wants to avoid in the future. For this reason, we focus on the items sold in the period 2016-2017. The production department has three major subdepartments, Truck cylinder-, Truck pump- and the Medical department. It is crucial to analyse for each of these departments, which product items had the most impact on the overall demand growth in 2017 and which product items had the most impact on the production. Section B.1 describes the methods used to determine the impact on the production department and demand growth. Subsequent Sections B.2, B.3, B.4 give respectively the results of the truck cylinders, truck-pumps and medical items.

## B.1 Methods to calculate impact on production and demand growth

Impact on production is defined as the products that occupy the resources the most. This is easy to determine because this will be the products that are sold the most. The demand for each product item is translated into a Pareto diagram. This diagram shows the frequency of occurrence, as well as their cumulative impact. However, showing a chart with hundreds of items is undesirable. Our interest is in the products with biggest production impact, for this reason only the top 5 is provided.

The impact of a product item on the overall demand growth of the corresponding product category is a bit more difficult to obtain than the top 5 of most sold items. To explain the required steps a simple example is given. Imagine, three trucks: a red, a blue and green one which are all part of the product category Trucks. Of the red truck 8 pieces were sold in 2017 and 14 in 2018, of the blue truck 2 pieces in 2017 and 6 pieces in 2018. The demand of the green truck is declining, 5 pieces were sold in 2017 and 3 pieces in 2018, see Table B-1.

Table B-1 Example to explain the impact of product i on the demand growth of the corresponding category

| **Product item $i$** | **Number of items sold in 2017** | **Number of items sold in 2018** | Growth of item $i$ in pieces (Formula B.1) | Weight factor of product $i$ (Formula B.2) | Demand growth caused by product $i$ (Formula B.4) |
|---|---|---|---|---|---|
| Red truck | 8 | 14 | 6 | 0.75 | 40.00% |
| Blue truck | 2 | 6 | 4 | 0.5 | 26.67% |
| Green truck | 5 | 3 | -2 | -0.25 | -13.33% |
| **Total** | **15** | **23** | **8** | | 53.33% (Formula 2.3) |

*The first step* is to calculate the demand growth of each individual item using Formula B.1, resulting in a positive growth for the red and blue truck of respectively 6 and 4, and a negative growth of -2 for the green truck.

$$Growth\ of\ item\ i\ (pieces)\ =\ pieces\ sold\ in\ 2018 - pieces\ sold\ in\ 2017 \qquad \text{(Formula B.1)}$$

Step two. The growth in pieces for each item is divided by the total demand growth in pieces to get the so called, weight factor of product i, see Formula B.2  In the example the weight factors of the red, blue and green truck are respectively 0.75, 0.5 and -0.25 meaning that 75% of the growth can be contributed to the red truck and 50% can be contributed to the blue truck. The green truck has a negative contribution of -25%.

$$Weight\ factor\ of\ product\ i = \frac{Growth\ item\ i\ in\ pieces}{Total\ demand\ growth\ in\ pieces} \qquad \text{(Formula B.2)}$$

*Next*, the relative total growth of the product category truck is calculated using Formula B.3. In the example, the result is a total growth of 53.3%.

$$Relative\ total\ growth\ of\ product\ category\ Z\ (\%) = \frac{total\ pieces\ 2018 - total\ pieces\ 2017}{pices\ 2017} * 100 \qquad \text{(Formula B.3)}$$

*Finally*, the impact of each item on the total demand growth is obtained by using Formula B.4. The weight factor of each item is multiplied with the total growth of the product category in %.

$$impact\ of\ each\ item\ i\ on\ demand\ growth\ of\ category\ Z\ (\%) = Weight\ factor\ of\ product\ i * Total\ growth\ of\ product\ category\ Z \qquad \text{(Formula B.4)}$$

In our example, the product category had a growth of 53.3%, where 40% is caused by the red truck, 26.67 % is caused by the blue truck and -13.3% is caused by the green truck. Notice that the blue truck had an individual demand growth of 300%, but since the quantities are lower than the red truck, its impact on the total demand is lower.

The methods to calculate the impact on the production departments and demand growth were given in this section. These methods are applied on the Cylinder-, Pump-, and Medical department. The results are given in the subsequent sections.

## B.2 Results truck-cylinders

A quick check shows that 71 out of the 238 are cylinders produced for the aftermarket. The aftermarket is a group of retail companies that sell spare parts. The overall demand of the spare parts is quite low, but is definitely rising. Due to the fact that there is a wide range of aftermarket cylinder products with a relatively low demand, it is decided to group them. In this way the group can ‘compete’ in the top 5 most sold items and top 5 impact on demand growth. Besides the aftermarket group, the portfolio of client X is also grouped. Client X replaced their old portfolio into a new one in the period 2016-2017. By grouping the data of the cylinders of the two portfolios the actual growth becomes visible. The last grouping strategy used is combining obsolete items with their replacement cylinders, these groups can be recognized by two cylinder numbers. In the end, 177 items or item groups are left to analyse.

Figure B-1 shows the top 5 most sold items or item groups for the product category Truck cylinders. To our surprise the aftermarket cylinder group has large impact on the production department. They are responsible for 4 % of the truck cylinder sales which is huge compared to 177 other items or item groups. In total sixteen items/groups are responsible for 80% of the sold items from which the top 5 is good for 53% of all cylinders sold in 2016 and 2017.

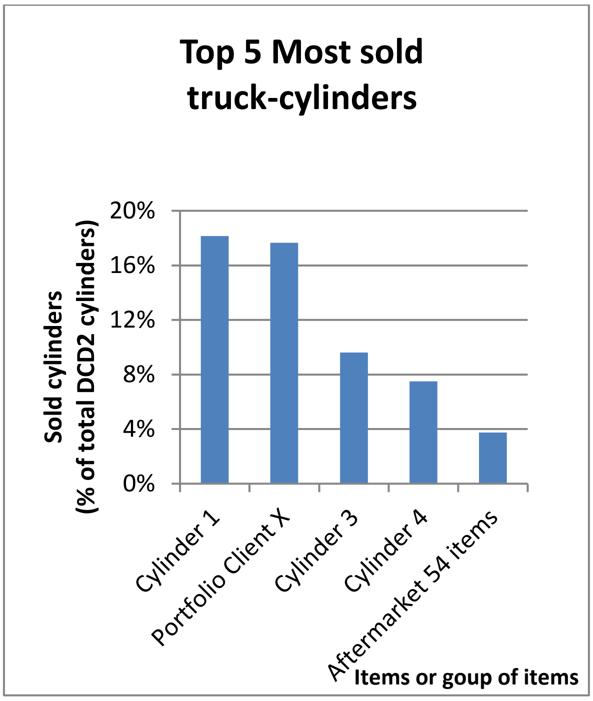


Figure B-1 Top 5 most sold truck-cylinder based on *Sales invoice data* of the year 2016-2017

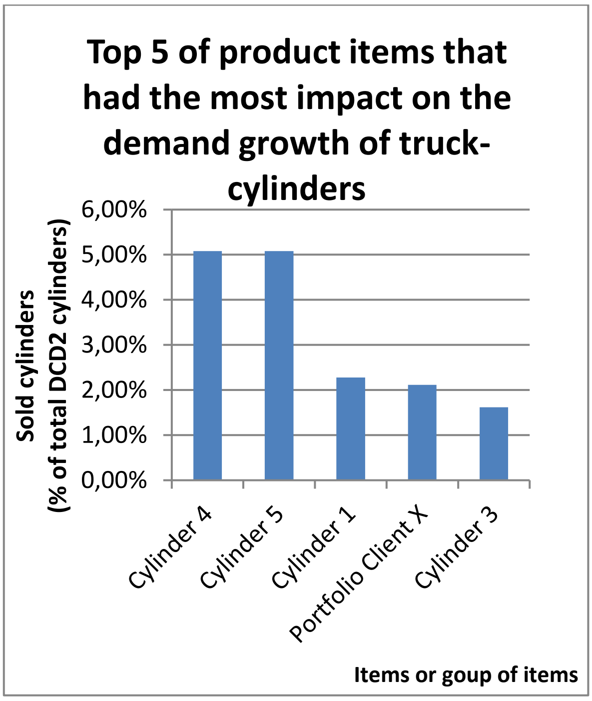


Figure B-2 Top 5 items with the most impact on the annual demand growth of the product category truck-cylinders of the year 2017 based on *Sales invoice data* of the year 2016-2017

The demand growth for the product category cylinder is 10.0%, which is bigger than the 9.2% total annual growth of the year 2017, as was shown in Chapter 2 Figure 2-6. The top 5 items or item groups that have the most impact on the demand growth of the cylinder category are shown in Figure B-2. The top 2, the Cylinder 4 & 5 are apparently new cylinders, sold as a duo. The DCD2-123459 and its replacement cylinder and the portfolio of Client X is also in the top 5 most sold items.

## B.3 Results truck-pumps

A quick check shows that 75 out of the 256 are cylinders produced for the aftermarket. Similar to the truck-cylinder category the aftermarket pumps are combined in one group and the pumps of client X are combined in another group. In total 213 pump item/groups remain to be analysed.

Figure B-3 shows the top 5 most sold items or item groups for the product category Truck-pumps. To our surprise, the aftermarket cylinder group has large impact on the production department. It is responsible for 8 % of the truck pump sales which is huge compared to 256 other items or item groups in the list. Other interesting findings are: (1) the significant impact of 18% of the portfolio of clients X and (2) the fact that the third item in ranking, Pump 2, is a new item released in 2017.

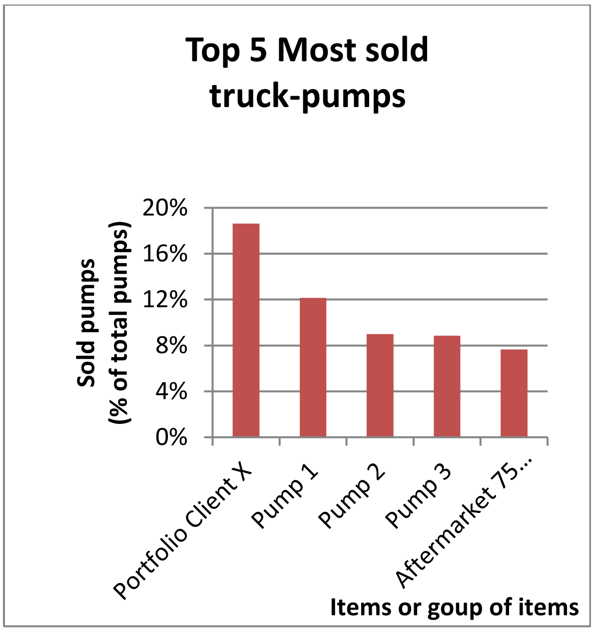


Figure B-3 Top 5 most sold truck-pumps based on Sales invoice data of the year 2016-2017

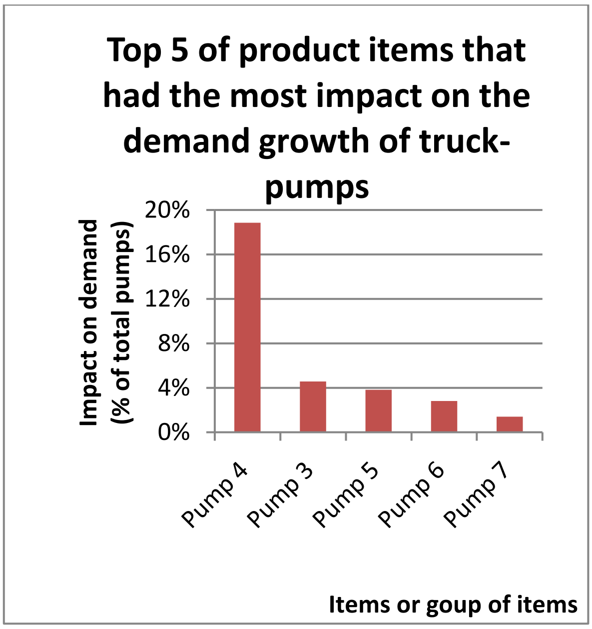


Figure B-4 Top 5 items with the most impact on the annual demand growth of product category truck-pumps based of the year 2017 on *Sales invoice data* of the year 2016-2017

The demand growth for the product category truck-pumps is 9,4%, which is bigger than the 9.2% total annual growth of the year 2017, as was shown in Chapter 2 Figure 2-6. The top 5 items or item groups that have the most impact on the demand growth of the pump category is shown in Figure B-4. The first item had a significant impact on the pump demand of 19%. This seems high, but when you put it in perspective and say that 65 items had a negative growth, then it might make more sense. Thus Pump 4 compensates considerably for the declining demand of other items. Remarkable are items Pump 5 & 7 which are both part of the DPU2 sub-category. DPU2 is a combination of hand and electric pumps. It seems that the market is interested in these hydraulic solutions and become more popular.

## B.4 Results medical items

In total, 106 different medical items were sold in the period 2016-2017. These product items are not sold to the aftermarket industry, so no grouping of items has taken place. The top 5 items are all part of the sub-category DSC, which is known by the company as MK5, see Figure B-5. The top 28 items are 80% of the total pieces sold.

The demand growth for the product category truck-pumps is 6.1% which is smaller than the 9.2% total annual growth of the year 2017, as was shown in Chapter 2 Figure 2-6. The top 5 items that have the most impact on the demand growth of the medical items' category are shown in Figure B-6. Only one item is in the top 5 most sold as well as in the top 5 of biggest impact on the growth, namely item Medical 3. The remaining items have no overlap with the most sold items.

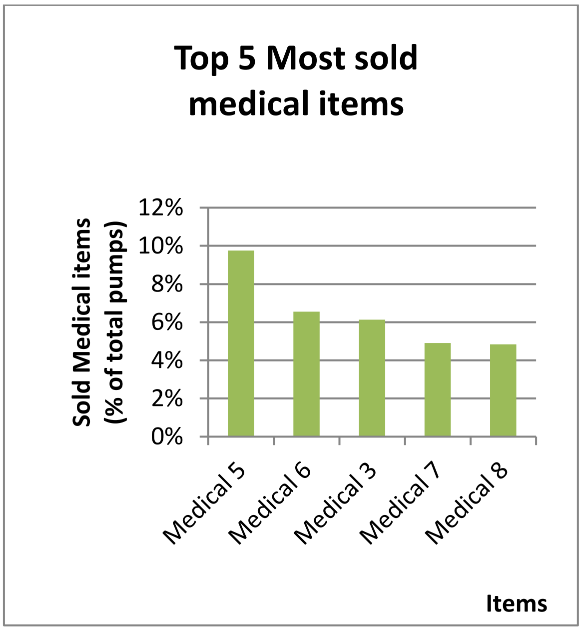


Figure B-5 Top 5 most sold medical items based on *Sales invoice data* of the year 2016-2017

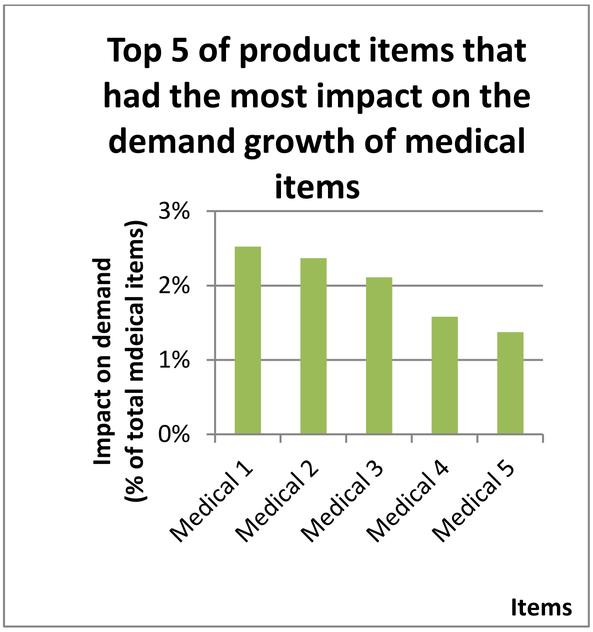


Figure B-6 Top 5 items with the most impact on the annual demand growth of product category medical items based on the year 2017 on *Sales invoice data* of the year 2016-2017

# Appendix C: Processing times

This chapter aims to provide solution to solve the core problem: Invalid processing times. Two approaches are discussed which are known to provide a good approximation of the processing times. The first method is PERT which is discussed in Section C.1. PERT is applied when production- or project times are hard to determine. The second approach is applicable when production times are live measured and saved. Section C.2 describes the advantages of industry 4.0 solutions like having a digital twin of the production environment to measure and predict processing times.

## C.1 Programme evaluation and review technique (PERT)

PERT is developed by the US navy in 1958 for the use of project management. The timeline of projects is often uncertain which made it hard to determine the project costs. To predict the expected project duration, probability theory plays an important role (Simpleman et al., 2001).

PERT makes use of the assumption that these time estimates are consistent with a beta probability distribution. The expected time (mean) for the project is estimated as follows (Slack et al., 2013):

$$t_e = \frac{t_o + 4t_{t_1} + t_p}{6} \qquad \text{(Formula C.1)}$$

Where,

$$t_e = \text{ the expected time for the activity (project)}$$

$$t_0 = \text{ the optimistic time for the activity (project)}$$

$$t_{t_1} = \text{ the most likely time for the activity (project)}$$

$$t_p = \text{ the perssimistic time for the activity (project)}$$

The variance (to indicate the deviation) is estimated as follows:

$$V = \frac{\left(t_p - t_o\right)^2}{36} \qquad \text{(Formula C.2)}$$

The complex one-of-a-kind project suits PERT the best (Simpleman et al., 2001). Therefore, PERT is a good algorithm to estimate the processing time for new items in the production industry. The advantage of the production industry is that there is the possibility to measure production times. Although not all operators actually like to be timed, some operators might be up for the challenge. The operator could be asked to produce: one item in a relaxed (pessimistic) tempo, one item as fast as possible (optimistic), and a few items at normal speed from which you take the average.

The downs side of this theory is that the estimation only works for an average day in the production industry. Especially in the beginning, operators are not experienced and produce below the estimated time. Later on, operators are too experienced and produce above the estimated time. PERT is not a self-learning prophecy. For this reason, the production performance must be remeasured once in a while, to see if the estimated production time is still applicable.

Nevertheless, the PERT algorithm is broadly adopted in planning system and is often applied in Simulation studies to determine the bottleneck in the production system (Ahuja & Thiruvengadam, 2004; Pinedo, 2009)

## C.2 Industry 4.0 & Digital Twins

The development high performance computer processors and computational methods, opened the door to address manufacturing problems and to look at a variety of solutions (Karkalos et al., 2019). Industry 4.0 is described as the technological development that visualizes the manufacturing enterprise (Ghobakhloo, 2018).

A Digital twin is a virtual copy of the manufacturing plant which is developed with the aim to experiment with planning and control decisions. The most efficient and effective solutions are then embedded in the real plant. Digital twins are used for offline-experimentation which is an important step to smart manufacturing. Today, real time (online) performance monitoring of production processes takes place like: product quality, energy use and real time considering planning and control decisions (Fei Tao et al., 2019).

The advantage of measuring real time is that the expected production time is updated after every job order. The more measurements, the more accurate the production times become. Besides, a learning curve in the production times is observed with the introduction of new items and or assigning new employees to workstations. The learning curve is visualized in Figure C-1. Putting more weight on the lasted measurements provides more accurate estimated production time. The result is that the production schedule is better forecasted and potentially resources better utilized.

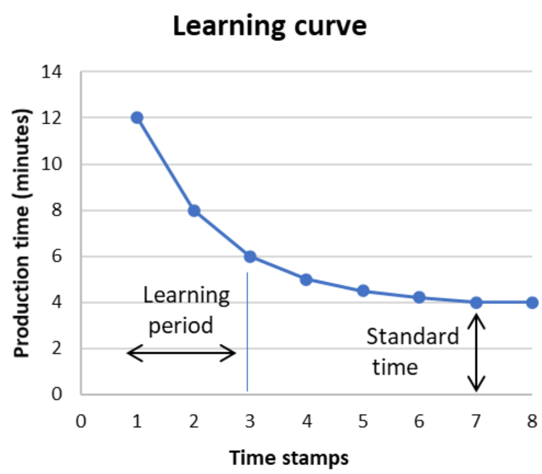


Figure C-1 Learning curve

# Appendix D: Processing operation planning

This chapter aims to provide solution to solve the core problem: lack of insight in production flow and station capacity. Here, an approach is provided to develop a process planning. The process planning structures data containing information of all products and workstations or machines, like the production paths of items and machine capacity. Moreover, the process planning could fixate resource to item types given certain constraints, like a fixed sequence in which operation takes place.

Section D.1 proposes a two-dimensional matrix in which the process planning data could be organized. The subsequent Section D.2, a for the company adapted version of the matrix is developed.

## D.1 Two-dimensional routing matrix

Gideon Halevi (2012) developed a roadmap consisting out of three stages to find an optimal process plan. The first two stages are dedicated to construct the two-dimensional matrix which is the cope of this research. The sections below, describe the first two stages.

**Stage 1 - Technology stage: Create process operation table**

The process operation table holds the engineering and technological constraints. Especially the technological constraint could be relevant to determine change overs between jobs. An example of a process operation table is given in Table D-1. To explain the example: an object requires nine operations to transform into its final form. Each operation receives a (random) number. Behind every operation the priority or predecessor is located. In the example, operation 020 cannot start before 010 is finished. The remaining columns contain the technological requirements the tooling must meet and the basic processing time (Dutch: kale tijd). Based on the priority column the execution sequence of operations may be: 010; 020; 030; 040; 050; 060; 070; 080; 090; **OR** 010; 020; 030; 070; 080; 090; 040; 050; 060; **OR** any other combination (Halevi, 2012).

Table D-1 Process operation table (source: Gideon Halevi, 2012)

| No. | Operation | Priority | Tool Dia | Length mm | Depth mm | Feed mm/min | Speed m/min | Power KW | Time min |
|---|---|---|---|---|---|---|---|---|---|
| 010 | Rough milling | 0 | 125 | 378 | 4.4 | 808 | 100 | 20 | 0.47 |
| 020 | Rough milling | 010 | 125 | 128 | 4.6 | 735 | 100 | 20 | 0.17 |
| 030 | Semi-finish milling | 020 | 125 | 278 | 0.4 | 905 | 148 | 2.2 | 0.31 |
| 040 | Finish milling | 030 | 125 | 378 | 0.2 | 200 | 165 | 0.39 | 1.89 |
| 050 | Rough pocket milling | 010 | 80 | 150 | 4.0 | 1,093 | 102 | 20.6 | 0.24 |
| 060 | Finish pocket milling | 050 | 12 | 472 | 0.4 | 120 | 24 | 0.33 | 4.16 |
| 070 | Center drill | 020 | 3 | 3 | – | 0.05 | 14 | 0.025 | 0.03 |
| 080 | Twist drill | 070 | 7 | 21 | – | 0.16 | 15.7 | 0.3 | 0.22 |
| 090 | Core drill | 080 | 12 | 21 | – | 0.19 | 23.5 | 0.5 | 0.20 |

To summarize the tasks to obtain the process operation table:

1. List the operations required to produce an object.
2. Assign each operation with a (random) unique number.

3. Determine priority by finding the predecessor of each operation.
4. Provide constraints on tooling.
5. Provide production time

**Stage 2 - Transformation: specification of available resources**

This stage connects the operations table with the resources by creating a two dimensional-matrix. First a resource specification one-dimensional table should be developed like, Table D-2. In the example, a resource is only applicable for an operation in the case the minimal power constraint is met. In the case of operation 010, who request a minimum power of 20 KW, it could be produced on Resource 1 or 2. From the one-dimensional table a two-dimensional matrix can be made. The link between the tables is in this example the resources. Thus, the two-dimensional matrix provides an overview of which operation could be produced on which machine and what the processing time and cost would be.

Table D-2 Specification of available resources (source: Gideon Halevi, 2012)

| Resource Number | Resource specifications | Power KW | Speed RPM | Handling Time min | Relative cost $ |
|---|---|---|---|---|---|
| 1 | Milling Machining Center | 35 | 1,500 | 0.10 | 4 |
| 2 | Large CNC milling | 35 | 1,200 | 0.15 | 3 |
| 3 | Manual milling resource | 15 | 1,500 | 0.66 | 1.4 |
| 4 | Small drill press | 1 | 1,200 | 0.66 | 1 |
| 5 | Old milling resource | 15 | 2,400 | 1.0 | 1 |
| 6 | Small CNC milling | 10 | 3,000 | 0.25 | 2 |

## D.2 Application for the case company

The case company has not as many resource options as in the example of Gideon Halevi (2012). Their process operation table could therefore include a column with the fixed workstation if applicable as in shown Table D-3.

Table D-3 Example operations table case company

| **Nu.** | **Operation** | **Priority** | **Fixed Work-station** | **Work-station** | **Technical details** (tooling, fixtures, paint colour, family etc.) | **Basic processing time (min)** |
|---|---|---|---|---|---|---|
| 010 | Operation 1 | 0 | Yes | Station 1 | .. | 0.5 |
| 020 | Operation 2 | 010 | Yes | Station 2 | .. | 0.8 |
| 030 | Operation 3 | 0 | No | Station 1 | .. | 1.5 |

An example of the resource specification table for the case company is shown in Table D-4. A relevant specification is the availability of a workstation. In the example, station 1 is available for 8 hours, has an uptime of 90% and requires 2 operators. The uptime could be used for scheduling purposes. This means that 90% of the available time, so a bit more than 7 hours, is filled with jobs. Furthermore, the example contains setups times. A fixed setup is always there for every job change. Flexible setup is depended on the previous job or the jobs family. For example, machines setting must be altered, or fixtures changed. Note, the number of specific fixtures is limited. In the case of flexible parallel machines, it is recommended to develop a 'fixture resource table' showing how many fixtures are available per fixture type.

Table D-4 Example resource specification for the case company

| Station nu. | Station | Availability (h) | Uptime (%) | Fixed Setup (min) | Flex setup Fixture change | Flex setup Colour change | Number of required operators |
|---|---|---|---|---|---|---|---|
| 1 | Station 1 | 8 | 90.0 | 5 | 5 | 1 | 2 |
| 2 | Station 2 | 8 | 75.0 | 5 | 0 | 1 | 2 |
| 3 | Station 3 | 8 | 80.0 | 0 | 0 | 1 | 1 |

## Appendix E: Confidential

# Appendix F: Manufacturing systems and observed planning strategies

Not all manufacturing system are the same. Perhaps this is the number one reason why searching for planning algorithms, the machine environment is often mentioned along with the optimization issue. This appendix provides an overview of the different *manufacturing systems, manufacturing characteristics* and *observed planning strategies per environment*.

**Manufacturing systems**

It is possible for a factory to have different types of production process and therefore different types of workstation and machineries. For example, a chair is produced in the following sequence: sawing (A), assembling(B) and painting (C). The sub process could be arranged in series as shown Figure F-1. However, the sawing process contains multiple unique workstations, a job shop which is shown in Figure F-2. Process B has a different machine arrangement and is built-up in parallel mixed model lines. The painting process (C) is a single workstation. The multiple different machine arrangements or manufacturing systems is called and *integrated system* (Kiran, 2019a).

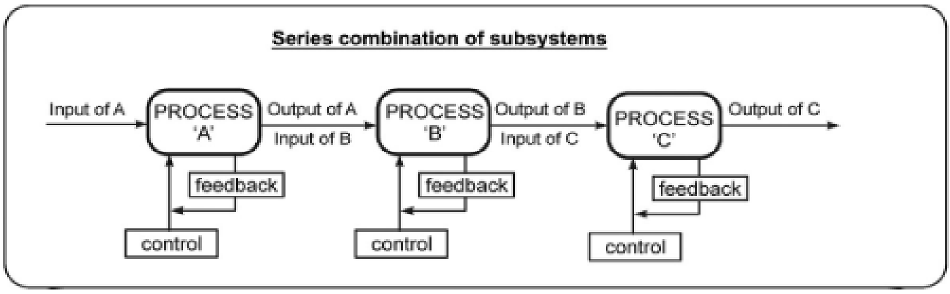


Figure F-1 Three production processes arranged in series (Kiran, 2019)

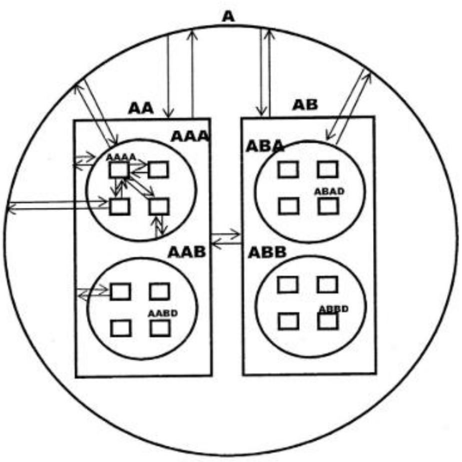


Figure F-2 Process A is identified as a Job Sop System (Kiran, 2019)

**Manufacturing characteristics**

The different manufacturing systems have their own processing methods. Some machines can process only *one job at the time* where others work with *batches*. The next distinguish of a system is that it produces *continuously* or *discrete.* An example of continuous production is the (one-piece-flow) conveyor belt of a car manufacturer. The conveyor transports the assemblies from one workstation to another with the intention to never stop. Discrete production involves that a job moves if an operation or event has taken place.

**Planning strategies per manufacturing system**

A list of different types of manufacturing system is established along with appliable planning strategies

***Single machine***

Definition: Identical (multiple) single machines (Pinedo, 2009)

Planning strategies

- Schedule bottleneck machine first (Pinedo, 2009)
- Dispatching rules are easy to implement and often provide an optimal solution (Pinedo, 2009)
    - Earliest due date first (EDD)
    - Shortest processing time first (SPT) or longest (LPT)
        - LPT finds only in 33% of the cases an optimal solution
    - Weighted Shortest Processing Time first (WSPT)
        - Generates solutions within 22% of optimality
    - Minimum Slack first (MS)
    - Apparent Tardiness Cost first (ATC) rule
- Time-based decomposition (Pinedo, 2009)

***Parallel Machine***

Definition One operation can be performed by many single machines available. The machines do not have to be identical. They can vary in speed or are only able to process specific items. (Pinedo, 2009)

Planning strategies

- Time-based decomposition (Pinedo, 2016)
- Bidding and pricing rules (Pinedo, 2016)
- Dispatching rules mentioned underneath single machine

***Job shop***

Definition Is a generalization of a flow shop. A job typically consists of a number of operations that have to be performed on different machines but do not follow a fixed route. It is possible that a job visits the machine multiple times which is called recirculation. In a job shop each job has a fixed route that is predetermined. (Pinedo, 2009)

Planning strategies
- Shifting Bottleneck Heuristic (Pinedo, 2009)
- Constraint programming (Pinedo, 2009)
- Branch-and- bound (Pinedo, 2009) (Kiran, 2019)
- Machine-based decomposition (Pinedo, 2016)
- Time-based decomposition (Pinedo, 2016)
- Hybrid: Simulated Annealing- tabu list (Pinedo, 2009) (Kiran, 2019)
- Generic algorithms (Kiran, 2019)
- Local search (Kiran, 2019)

***Flow shop***

Definition

A job has to undergo multiple operations on a number of different machines. All jobs follow the same routes which is why the machines are setup in series. The producing sequence of the jobs are determined by the machines. (Pinedo, 2009)

Planning strategies
- Time-based decomposition Pinedo, 2016)
- Machine-based decomposition = Schedule first the job with the longest path (or the jobs that are the hardest to schedule). (Pinedo, 2016)

**Flex shop**

Definition

A job has to pass different stages. Each stage has a number of parallel machines. It is possible to skip a machine (or stage). All jobs follow the same routes and, but the sequence is determined by the machines. (Pinedo, 2009)

Planning strategies
- Unpaced system: no machines are skipped.
    - Cyclic schedules: an identical set is repeated over and over
        - Minimum Part Set (MPS) in combination with (weighted) Profile Fitting heuristic (Pinedo, 2009)
- Paced: The machines connected by conveyors with a fixed speed
    - Grouping and Spacing (GS) heuristic (Pinedo, 2009)
- Bypass machine
    - Flexible Flow Line Loading (FFLL) algorithm (Pinedo, 2009)
- Machine- based decomposition (Pinedo, 2016b)
- Time-based decomposition (Pinedo, 2016b)
- Bidding- and pricing rules (Pinedo, 2016b)
- Annealing- tabu list

**Open shop**

Definition

Where a jobs shop has a fixed route. In the open shop the routings are not fixed. (Pinedo, 2016b)

Planning strategies
- Time-based decomposition (Pinedo, 2016b)
- Dispatching rule: Longest Alternate Processing Time first (LAPT) rule (Pinedo, 2016b)

**Mixed model/ flex model (assembly lines)**

| | |
|---|---|
| Definition | Similar model can also be produced here, there is no setup process (Pinedo, 2009) |
| Planning strategies | - Toyota *goal chasing method* to balancing output (Pinedo, 2009)<br>- Artificial bee colony algorithm (Kucukkoc et al., 2019)<br>- Local search methods (Kucukkoc et al., 2019)<br>- Time-based decomposition (Kucukkoc et al., 2019)<br>- Cycle improvement strategy which is Local search Tabu algorithm (Dong et al., 2015)<br>- Simulated annealing  (Tamura et al. 2011), (Xiaobo & Ohno, 1997)<br>- Branch-and-bound (with local search initialization) (Kim & Jeong, 2007) (Tamura et al. 2011), (Xiaobo & Ohno, 1997) |

**Multi model**

| | |
|---|---|
| Definition | Multiple type of products are assembled in same line (Dong et al., 2015)<br>Setup is needed in multi-model lines. (Pinedo, 2009) |
| Planning strategies | - Time-based decomposition (Pinedo, 2016b)<br>- Cycle improvement strategy which is Local search Tabu algorithm (Dong et al., 2015)<br>- Simulated annealing & tabu search (Pinedo, 2016b) |

## Appendix G: Roadmap Summary

This appendix provides the visionary roadmap to support planners on all hierarchical levels to develop a suitable planning strategy. It contains four stages: The problem statement, the checklist, establish product families, choosing the planning strategy.

### Problem Statement

1) **Describe the motivation for establishing a new planning strategy.**
2) **Formulate the planning goal.**
   a) Which KPIs do you wish to optimize?
3) **What is the hierarchical level of the planning application?**
   a) Identify stakeholders
   b) Identify the possible impact of the planning mix on other levels
   c) Identify planning horizon

| Strategic planning | Tactical planning | Offline schedule | Online schedule |
|---|---|---|---|
| • 6-18 months<br>• Formulate goal based on family groups.<br>• Investments in the machine park | • ± 6 months<br>• Fixate machines to families<br>• Smooth(family) demand over the weeks | • Daily /weekly<br>• Sequence of jobs (within families) given available resources<br>• Sequence between family groups | • Real time<br>• Job selection procedure from buffers<br>• Rush orders<br>• Disturbances: machine failure shortage in parts |

**Tip 1:** (online) Do not alter the offline planning if you do not have to! The offline schedule had found the best schedule for the entire production department not just for the single machine.
**Tip 2:** Identify if the use product families might be beneficial. It might save computation time and provide more insight into impact of families on production.

4) **Identify the manufacturing environment.**
5) **Identify <u>type</u> of planning/scheduling method.**
   **a)** Does the schedule need to find the optimum (complete enumeration) or is a near optimal solution (heuristic) acceptable?
6) **Formulate the planning objective**.

## Check list: Data and control

**1) Check if process data is well-organized**

1.1) Process operation table per item:

i) Operations ID and operation description
ii) Priority (hierarchy sequence in which the operations take place)
iii) Technical details, like workstation ID, which is where the operation should be performed, required machine settings and additional tooling. The processing time per operation
iv) Design details: dimensions, size, weight
v) (Optional) Add a column that may tell that a specific operation is part of a family.
vi) (Optional) Create two columns with processing times. (1) ‘Expected’ processing time for each operation = target time without disturbance (2) The ‘real’ average processing time for planning purposes

1.2) Resource property table:

i) Workstation ID and description
ii) Technical details, like machine capabilities, batching or one-piece flow
iii) Optional: For identical resources use one ID and add a column with the number of resources.
iv) Optional: Fixed setup-time
v) Optional: add the minimum and maximum number of operators as workstation detail.

1.3) (Optional) Variable setups times per workstation between items or families

**2) Check the data on accuracy**

**Tip 1:** Use PERT when operations are not measured before or very limited data is available.
**Tip 2:** Obtain smart software package which saves and measures continuously the production times per workstations. This is highly recommended for large production facilities with high-mix low-volume demand and flexible. manufacturing systems
**Tip 3:** Resource and product properties can be obtained by experts, like manufacturing engineers and product developers.

## Establish product families

**1) Investigate if product families are beneficial for your company**

**Tip 1:** manufacturers may benefit the most from establishing product families if they have the following characteristics: high-variety low-demand products, and a flexible manufacturing facility.

**2) Select grouping characteristics**

**Tip 2:** Literature showed family groups that consider commonality (shared parts) and the technological compatibility characteristics (machines setting, fixtures etc.), achieve a higher production efficiency.

**3) Select grouping method**

**Grouping characteristics**

- Commonality/Modularity
- Technological compatibility
- Reusability
- Product demand
- Cost
- Processing time
- Multi-characters
- Others

**Methods for grouping**

- Descriptive procedure
- Group analysis
- Mathematical programming
- Artificial intelligence: metaheuristic
- Graph partitioning

**Tip 3:** Families can be created by experts who select family criteria. Families could also be formed by using mathematical formulations. However, the more details to consider the longer the computation time.

**Tip 4:** There is little known about what the absolute best method or grouping characteristic is! Be open for experimentation and keep in mind the planning objective!

**Warning:** keep in mind that created families may have a big impact on all hierarchical levels. Thus, always warn planners in the case of new grouping strategy and try to measure the impact which could be positive or negative.

## Select the planning strategy

1) **Recall the planning objective**
2) **Given the objective, families and machine environment, select a promising planning strategy.**
   a) Single machine environment and small problem size? Try linear programming to find the best planning solution!
   b) Job shop or flex shop environment? Use of heuristic which aims to find a (near) optimal solution in acceptable computation time. Think of simulated annealing in combination with a tabu-list. Use a local search method like One Step Look-Back Adjacent Interchange to generate alternative solutions.
   c) Parallel machine environment? Similar to job shops and flex shops, make use of the simulated annealing and the tabu-list. Use a local search method that swap or move jobs to generate alternative solutions.
3) **Experiment with different planning strategies.**

**Tip 1:** It is recommended to make use of digital twins or other type of simulation models to evaluate the performance of the planning strategies.

4) <u>Implement</u> the planning strategy which is the most promising given the objective. <u>Monitor</u> the performance of the planning strategy closely.

**Master tip** keep experimenting with different planning approaches such that the companies find the most efficient solution applied to their situation.