MASTER THESIS
BMS: Industrial Engineering & Management

Optimization of the high consumption logistic process at Scania Production Zwolle

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SCANIA

UNIVERSITY OF TWENTE.

Management summary

This thesis is about the optimization of a part of the internal logistic process at Scania Production Zwolle.

Scania is a global leading company that produces and sells trucks, buses, industrial engines, and marine engines. Scania's largest assembly unit is located in Zwolle, where a wide variety of trucks are produced on two assembly lines. The Unit Supply Pallet process is the process that supplies high consumption parts on pallets to the two assembly lines using fixed routes and fixed takt times and is the focus of this research. Two means of transportation are used for this process: pallet trailers and tugger trains. Pallet trailers bring the pallets to decentralized locations in delivery zones in the production hall, and from there, pallets are supplied with reach trucks to the consumption locations. Tugger trains supply pallets directly to the consumption location at the assembly line. Scania uses a two-bin Kanban system that creates, together with the wide variety of trucks, a lot of variation in the process. This leads to fluctuating fill rates of pallet trailers and tugger trains. As a result, the capacity is not properly utilized, which is a loss of productivity.

Furthermore, due to the increasing number of parts, Scania no longer expects to have enough space at the assembly line in the future to store the extra pallets required for them. The main research question of this thesis is as follows:

"How can we increase productivity and reduce the number of pallets per part number at the assembly line of the Unit Supply Pallet process by redesigning the current method in the short-term, at the lowest possible cost?"

We divide our research into different phases to answer our main research question. First, we analyze the current situation of the Unit Supply Pallet process. We found that the pallet trailer process had the most potential for improvement given the low utilization rate (32%) and the high number of pallets per part number at the assembly line (on average 2.4 pallets per part number). Therefore, we focus on the pallet trailer process. More specifically, we focus on the location-allocation problem of the decentralized locations in a delivery zone and their consumption locations.

Using a literature study, we show that the location-allocation problem of the decentralized locations at Scania has similarities with the capacitated p-median problem and the supermarket location problem. There are three practical elements where the problem at Scania deviates from the theory. First, at Scania, the demand is delivered in cycles, which is not discussed in the literature. The pallet is not directly requested when the pallet becomes empty, but according to the fixed schedule at fixed times. Second, pallet trailers (supermarkets) have no stock and contain already requested pallets. Finally, models in the literature make use of deterministic demand,

where the demand is known in advance without stochasticity; this is not the case at Scania. Therefore, we propose a model that copes with these elements.

We classify our problem as a Discrete Supermarket Location Problem with Stochastic Demands. The problem is classified as NP-hard. Therefore, we are not able to find an optimal solution for a real-world problem within a reasonable time. We use the metaheuristic Simulated Annealing to solve the problem. The objective of our model is to minimize travel time, as well as balancing the volume per delivery zone while maintaining a required service level. In addition, we use simulation techniques to estimate the objective value of a solution by evaluating the impact of stochastic demand while using a high level of detail. Furthermore, we manage to calculate realistic distances and travel times based on the layout of SPZ using Dijkstra's algorithm.

We experiment with the model by evaluating different scenarios. In the current situation, 6.4 reach truck FTE and 3 pallet trailer FTE are needed per shift. We distinguish different scenarios in which we experiment with reducing the number of delivery zones, increasing the number of cycles in a day, and varying the number of pallet trailer locations per delivery zone. Furthermore, we solve different experiments by optimizing the pallet trailer locations, the consumption locations, or both. The service level in the current situation is 99.2% and must be at least 99% to be feasible.

Table 1 shows the characteristics and output parameters of the alternatives we propose for Scania to increase productivity and/ or reduce the lead time compared to the current situation.

	Experiment:	**Exp. 6**	**Exp. 14**	**Exp. 15**	**Exp. 22**
Input	Number of delivery zones	9	7	6	9
	Number of cycles	12	12	12	24
	Number of pallet trailer locations per delivery zone	2	2	2	1
Output	Travel time per pallet	-11.7%	-3.1%	8.4%	-18.9%
	Reach truck FTE (pallet trailer FTE)	-0.3 (0)	-0.1 (-0.7)	+0.2 (-1)	-0.5 (0)
	Service level	+0.7 p.p.	-0.1 p.p.	-0.2 p.p.	+0.1 p.p.
	Utilization rate	+0 p.p.	+14 p.p.	+25 p.p.	-1 p.p.
	Surface pallets (m^2)	0.0%	0.0%	0.0%	-13.4%

Table 1 Characteristics of alternatives and output parameters compared to the current situation

Experiment 22 has the best performance in terms of travel time per pallet and the reduction in reach truck FTE needed, followed by *Experiment 6* and *Experiment 14*. *Experiment 15* leads to an increase in travel time. However, 1 pallet trailer FTE less is needed to supply the pallets per shift. This leads to the highest increase in the utilization rate, increasing productivity. In *Experiment 22* the lead time is shortened. As a result, the number of pallets per part number decreases, which also decreases the pallet surface at the assembly line.

We advise Scania to not reduce the number of delivery zones as less than 1 pallet trailer FTE can be eliminated per shift without an increase in travel time. Therefore no significant cost can be saved. We advise Scania to implement *Experiment 22* to decrease the pallet surface needed at the assembly line and improve the productivity of the process. It has the best performance overall and there is still space left to cope with higher demand. As a secondary solution, we advise Scania to optimize the current situation and reallocate consumption locations and pallet trailer locations according to *Experiment 6*.

The condition for implementing *Experiment 22* in the current situation is that the pallet recorder must be able to record all empty pallets within a cycle. This should be tested in reality, otherwise, another pallet recorder must be added or a replenishment signal must be used. Furthermore, we advise Scania to use our model in the future to check if the delivery zones are optimally divided when the production rate increases or decreases.

Preface

In front of you, I present my master's thesis 'Optimization of the high consumption logistic process at Scania Production Zwolle'. This thesis is the final part of my study Industrial Engineering and Management at the University of Twente. I would like to thank several persons who contributed to this thesis.

First of all, I would like to express my gratitude to my colleagues at Scania Production Zwolle. Although I had to work a lot from home due to the Covid-19 pandemic, they were always open to help me further in my project, both on location and via online meetings. I appreciate the great working environment they offered me. In particular, I would like to thank my company supervisor, Gerben Stoffers, for his professionalism, enthusiasm, advice, and critical view during my graduation project.

Furthermore, I would like to thank my supervisors Peter Schuur and Marco Schutten from the University of Twente for their good guidance and support. The provided feedback from both of you helped me to bring my thesis to a higher level.

Finally, I would like to thank my family and friends for their support. During this graduation project, I learned a lot about myself and I look forward to the future in which I can continue to improve myself and keep learning.

I hope you enjoy your reading.

Tom Wolfkamp,
August 2021

Contents

List of Abbreviations

Abbreviation	Definition	Introduced on page
CPMP	Capacitated P-Median Problem	38
FLP	Facility Location Problem	37
ILP	Integer Linear Problem	40
JIS	Just In Sequence	35
JIT	Just In Time	1
KL	Koude Loods	8
KPI	Key Performance Indicator	25
LC	Location Classification	63
NP	Non-deterministic Polynomial	39
SA	Simulated Annealing	41
SLP	Supermarket Location Problem	39
SPZ	Scania Production Zwolle	1
USP	Unit Supply Pallet	2

1. Introduction

This chapter describes the background of the company and the assignment. Six sections divide the chapter. First, Section 1.1 introduces Scania after which Section 1.2 describes the research motivation. Then, Section 1.3 describes the problem analysis which shows the problem cluster and identifies the core problem. Section 1.4 discusses the research questions. Finally, Section 1.5 describes the research approach.

1.1. About Scania

Scania is a global leading company that produces and sells trucks, buses, industrial engines, and marine engines. Scania was founded in 1891 and produced its first truck in 1902 and its first bus in 1911. In 2014, the Volkswagen Group took over Scania for a stronger position in the truck market. Globally, Scania has approximately 50,000 employees, has factories in Europe and Latin America, and is represented in more than ten countries with the headquarters in Södertälje, Sweden.

Approximately 4,000 employees work in the Netherlands, spread over Zwolle, Meppel, Breda, and forty sales and service offices. Scania's largest assembly unit is located in Zwolle, which accounts for 60% of the annual production. The location in Zwolle employs 2400 employees, where trucks are produced on two assembly lines.

Scania Production Zwolle (SPZ) works according to the Scania Production System, which focuses on continuous improvement by putting the customer first, respecting each individual, and eliminating waste by creating a situation where there are as few deviations from the standard as possible. Scania's vision is to be the leader in sustainable transport by applying the Scania Production System.

1.2. Research motivation

SPZ produces trucks based on customer demand, which leads to high product variability in the production process. This variability is also reflected in the demand for parts supplied by the logistics process. To cope with this variety in the production process, SPZ has designed a modular production system. In this system, the same parts are used in different types of trucks as much as possible. Scania uses the Just in Time (JIT) principle, which means that parts are delivered to the right location at the right time.

SPZ uses both line feeding and factory feeding in its internal logistics. Line feeding is the supply of parts by using an intermediate storage facility. At SPZ, line feeding is used to supply parts from the warehouses to the assembly line. Factory feeding is the supply of parts without using intermediate storage. Factory feeding is used for larger parts such as engines, cabins, and bumpers.

One of the logistical processes for supplementing parts at the production line is the Unit Supply Pallet (USP) process. In this process, frequently used pallets with parts for the trucks are brought to the production hall from a warehouse located outside the production hall. This process uses two different flows to bring the pallets to the production hall. With one flow, pallets are brought directly to the consumption location at the line; with the other flow, the pallets are brought to decentralized locations in the production hall, and from there to the consumption location.

SPZ is not satisfied with the current USP process. The current process consists of two different flows, which are based on all independent choices. SPZ suspects that the two flows do not work optimally together and wants insight into how the flows can be optimized in the short-term and which flow of the two flows is best to choose for certain circumstances and when one outperforms the other. Also, SPZ suspects that the capacity utilization of the flows is low. Section 2.5. elaborates more on both of these flows. Another problem that SPZ faces is the increasing number of part numbers at the assembly line. Soon, SPZ no longer expects to have enough space at the assembly line to store the extra pallets. Based on this, SPZ expects that there is great potential for improvement in the USP process.

1.3. Core problem

The core problem can be found using a problem cluster. The problem cluster contains problems that are classified as problems. To identify the core problem, we analyze the chain of problems to the problems that no longer have a cause themselves, which are potential core problems. What cannot be influenced, cannot become a core problem. When more than one core problem remains, the core problem is chosen which has the most potential to solve the experienced problem (Heerkens & van Winden, 2012).

Figure 1.1 shows the problem cluster. The orange-colored boxes contain causes that are difficult to influence or cannot be changed according to SPZ. The yellow-colored boxes are causes that may be a core problem and can also be changed. The red-colored boxes indicate what the losses are, which have a lot of potential for improvement. A diamond shape is used to indicate a collective name of several core problems.

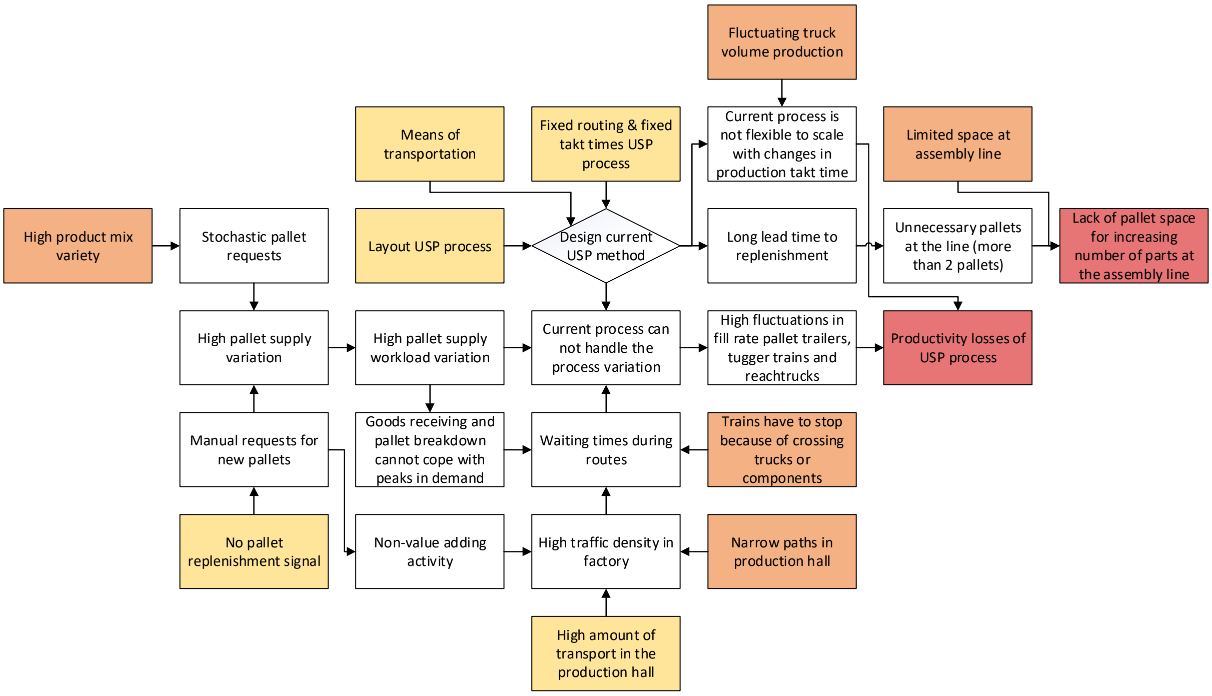


Figure 1.1 Problem cluster Unit Supply Pallet process

1.3.1. High pallet supply variation

The stochastic pallet requests of parts create a lot of variation in the demand for pallets, mainly due to the variable product mix of trucks at the assembly line. Furthermore, there is no signal indicating that a pallet is empty, so an employee has to drive past the pallets to check whether a pallet is empty. This leads to extra variation in the requests for pallets. This transport is also a non-value-adding activity, waste, which contributes to productivity losses.

1.3.2. High traffic density in factory

The high amount of transport in the production hall, in combination with the narrow paths, results in a high traffic density. This, in combination with stops caused by crossing trucks or components, leads to even more variation in the process.

1.3.3. Design current USP method

Two different flows are part of the design of the current USP method, which is used to transport pallets from the warehouse to the production hall. One flow uses tugger trains and the other flow uses pallet trailers and reach trucks. In addition to the last flow, there is also a pallet recorder driving on a single-person vehicle. A pallet recorder is someone who continuously drives through the production hall to record empty pallets. The two different flows have fixed routing and fixed takt times. This method with fixed routing, fixed takt times and the current process layout leads to long replenishment lead times for the pallets. As a result, for fast-moving part numbers, more than 2 pallets are placed at the assembly line. This is at the expense of the limited space available and causes a lack of pallet space at the assembly line.

Another experienced problem is that the current USP process cannot handle the high variation in pallet requests, which leads to fluctuating fill rates of pallet trailers, tugger trains, and reach trucks. As a result, the capacity is not properly utilized, which is a loss of productivity.

Also, the current method is not flexible to scale with the fluctuating truck volume production, when the takt time changes and more or fewer trucks are produced per day, the process must be partly redesigned.

1.3.4. Conclusion

The following possible core problems emerge from the problem cluster in Figure 1.1.

- No pallet replenishment signal
- High amount of transport in the production hall
- Design current USP method
    - Fixed routing & fixed takt times USP process
    - Layout USP process
    - Means of transportation

By solving the problem that there is no pallet replenishment signal, no more pallets need to be requested manually. This leads to less variation in pallet requests and a shorter lead time, since pallets can be requested directly after the last part on the pallet is used. It removes non-value-adding transport, which reduces the traffic density in the production hall. SPZ indicates it is already developing a pallet replenishment signal but does not see it being implemented in the short term. This part is therefore out of scope and it is given that there is no pallet replenishment signal.

By reducing the amount of transport in the production hall, waiting times can be reduced, which leads to less variation in the process. This would require several supply methods to be redesigned, leading to a drastic change in multiple logistic processes. In consultation with SPZ, it is decided that this problem is out of scope.

By redesigning the current USP method, a method can be designed that reduces long lead times, accommodates the fluctuating pallet demand leading to higher utilization rates, and scales more flexibly with the pallet demand. Also, the current means of transportation will be evaluated. Therefore, we define the core problem as follows:

"The current USP method with fixed takt times, fixed routes and the process layout suffers from the variation in pallet requests, leading to fluctuations in fill rates of vehicles and long pallet lead times, causing a loss in productivity and a lack of pallet space at the assembly line."

The core problem is translated into a research goal, which is can be found below.

"Redesign the current Unit Supply Pallet method such that the productivity increases, the number of pallets per part number at the assembly line reduces, at the lowest possible cost"

Figure 1.2 shows the three objectives of the research.

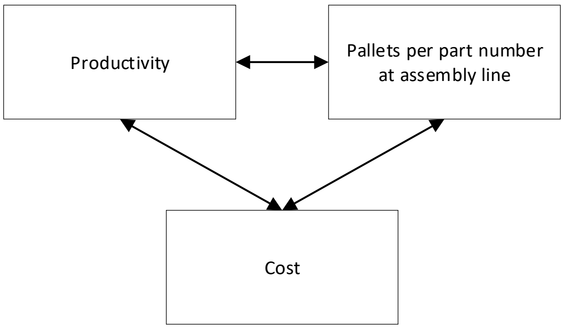


Figure 1.2 Schematic representation of the three objectives of this research

1.4. Research questions

To solve the core problem and achieve the research goal, we define the following main research question:

"How can we increase productivity and reduce the number of pallets per part number at the assembly line of the Unit Supply Pallet process by redesigning the current method in the short-term, at the lowest possible cost?"

This main question is divided into several research questions which are shown below. Each research question is answered in a separate chapter.

Research question 1: What does the current situation of the Unit Supply Pallet process look like? – *Chapter 2: Analysis of the current situation*

- What does the production process look like within SPZ?
- What does the internal logistics process look like?
- What does the current USP process look like?
- What are key figures for the current USP process?
- What is the performance of the current means of transportation used?

Research question 2: Which methods are described in the available literature regarding internal logistics processes? – *Chapter 3: Literature review*

- How can the USP process be positioned based on literature?
- What methods are described in the literature to increase productivity and reduce lead time in internal logistics?
- What are similar optimization problems described in the literature?
- What methods are described in the literature to solve similar optimization problems?

Research question 3: How can the Unit Supply Pallet process be modeled to improve productivity and reduce the number of pallets per part number at the assembly line? – *Chapter 4: Modeling*

- How can literature contribute to improve productivity and reduce the number of pallets per part number at the assembly line?
- Which alternative methods can be designed, based on literature, that fit the current USP process?
- How can the performance of the alternative methods be modeled?

Research question 4: What adaptations at the Unit Supply Pallet process ensure improved productivity and reduced number of pallets per part number at the assembly line? – *Chapter 5: Experimental results*

- What should the experimental design look like?
- What is the modeled performance of the proposed alternative methods?
- Which parameters ensure improved productivity and a reduced number of pallets per part number at the assembly line?
- What adaptions should be made to the current USP process to achieve the modeled performance?
- How can these adaptions be implemented?

Finally, we present the conclusions and recommendations in Chapter 6. Deliverables of this research are:

- Analysis of the current situation.
- Model to evaluate options (e.g. simulation model, mathematical model).
- Thesis with solution design and recommendations.

1.5. Research approach

The research approach shows the research design, elaborates on the scope and stakeholders, and discusses the previous research done.

1.5.1. Research design

The core problem and research questions have already been defined in Sections 1.3 and 1.4. We consider only the core problem regarding the current method of the USP process. The research goal is to redesign the current method such that the productivity increases, the number of pallets per part number at the assembly line reduces, at the lowest possible cost.

Figure 1.3 shows the research design, which we use to achieve the research goal. The research design shows the relationship between the input, the research chapter, and the deliverables. We use a feedback loop for continuous improvement to update results based on progressive insight.

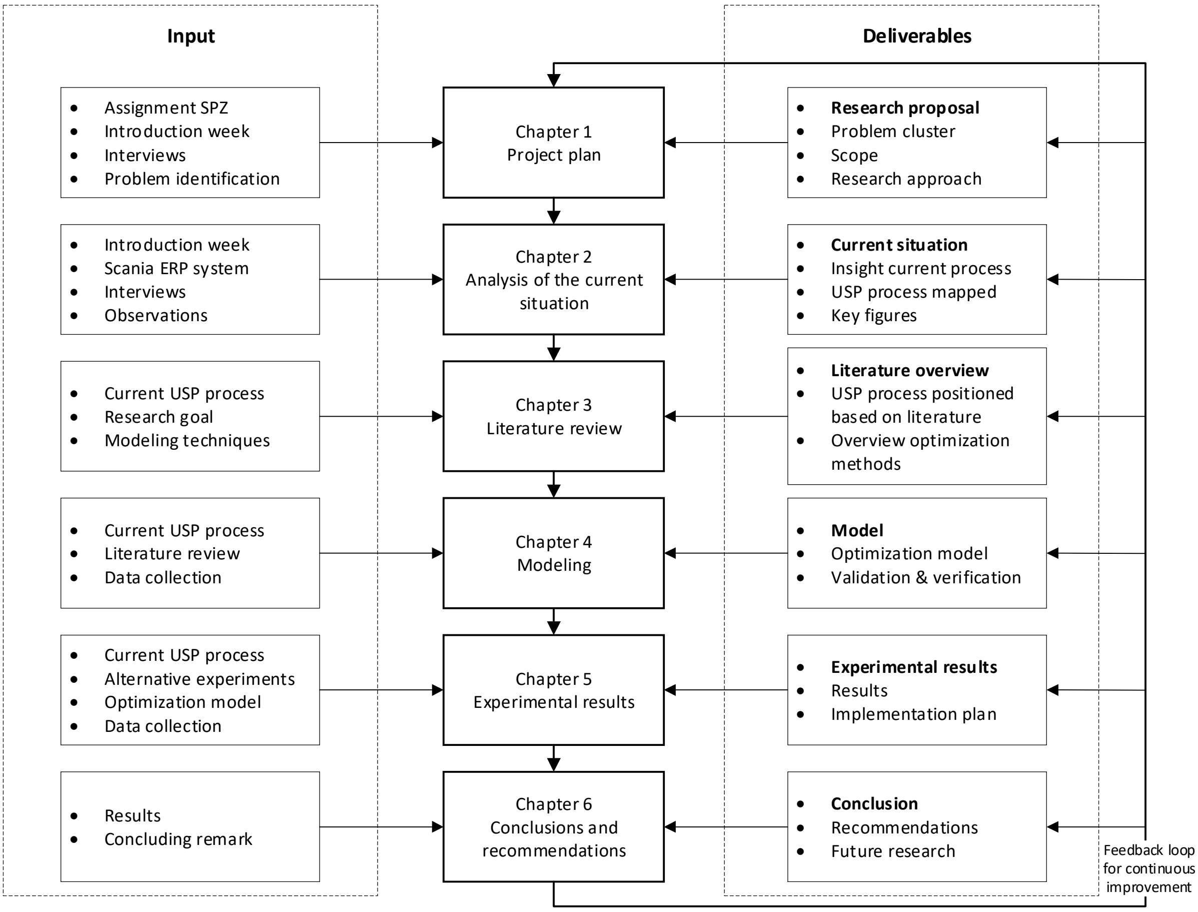


Figure 1.3 Research design. Adapted from (Sileyew, 2019)

To summarize, in Chapter 2 we gain insight into the current process through interviews, observations, and data analysis. Then we build the theoretical framework using a literature review in Chapter 3. Subsequently, we combine the knowledge about the current situation and the theoretical framework to build a model to analyze scenarios in Chapter 4. In Chapter 5, we define experiments and use the model introduced in Chapter 4 to predict intended results, resulting in experimental results and an implementation plan. Chapter 6 presents conclusions and recommendations.

Data collection

Most of the data is available in Scania's systems. This includes data such as pallet requests information, information about line locations, and the layout of SPZ. Key figures can be made with this data to get insight into the current performance of the USP process.

For the modeling of the current situation, some of the data is not available or is no longer up to date. This includes data such as loading and unloading pallet trailers and tugger trains. This data is collected during the data collection phase.

1.5.2. Research scope

SPZ uses line feeding and factory feeding as described in Section 1.2. Different supply methods are used for this, which are divided into roughly four categories. We present a brief overview of the different supply methods used to supply parts to the assembly line below. We elaborate more on these methods in Section 2.4.

- Batch Supply: the supply of parts on fixtures in batches to the assembly line. The batches are replaced at fixed times.
- Kitting: the supply of parts on special fixtures or pallets at the assembly line. All parts are chassis bound and are delivered in the production sequence.
- Sequencing: the one-by-one supply of parts in the production sequence to the assembly line. These parts are chassis-specific and have a low consumption rate or are too large for other delivery methods. Examples are parts such as axles and tires.
- Unit Supply: the supply of parts that are frequently used. The parts are delivered to the assembly line with pallets and boxes.

This research focuses on the Unit Supply flow within SPZ. This flow is divided into the Unit Supply Boxes and the Unit Supply Pallet flow. The problem focuses on the USP process, which already partially demarcates the research. The USP process covers the flow of parts of pallets that are originating from the warehouse "Koude loods" (KL), delivered to the assembly line, and ends when the empty pallets are delivered at pallet breakdown.

The research is further demarcated to properly complete the research within the time allotted. The solution of the research should be able to be implemented in the short term. Therefore, the layout of the production hall is fixed and the means of transportation are limited to the means of transportation currently used. The amount of pallet picks, in the warehouse KL, is also an important indicator of this research since the fluctuations in the process can lead to large peaks with waiting time as a result. The pallet breakdown is out of scope as it is outsourced to an external party, but is an important control parameter. Furthermore, the research does not take into account the traffic flows of other flows, the solution found could be tested with a pilot.

After consumption, empty pallets must be returned to pallet breakdown. The return of empty pallets is, therefore, part of the scope. The empty pallet returns from other logistic flows, which are currently collected by the USP process, are also part of the research but will not be optimized and will be used as a control parameter.

1.5.3. Stakeholders

There are multiple departments involved in this research, which are internal stakeholders. All these departments fall under the Logistics and Industrial Engineering departments within Manufacturing Zwolle, see Figure 1.4. The problem owner is the Logistics Engineering department who initiated this research, it is a support department whose goal is to engineer the logistics process efficiently based on the Scania Production System.

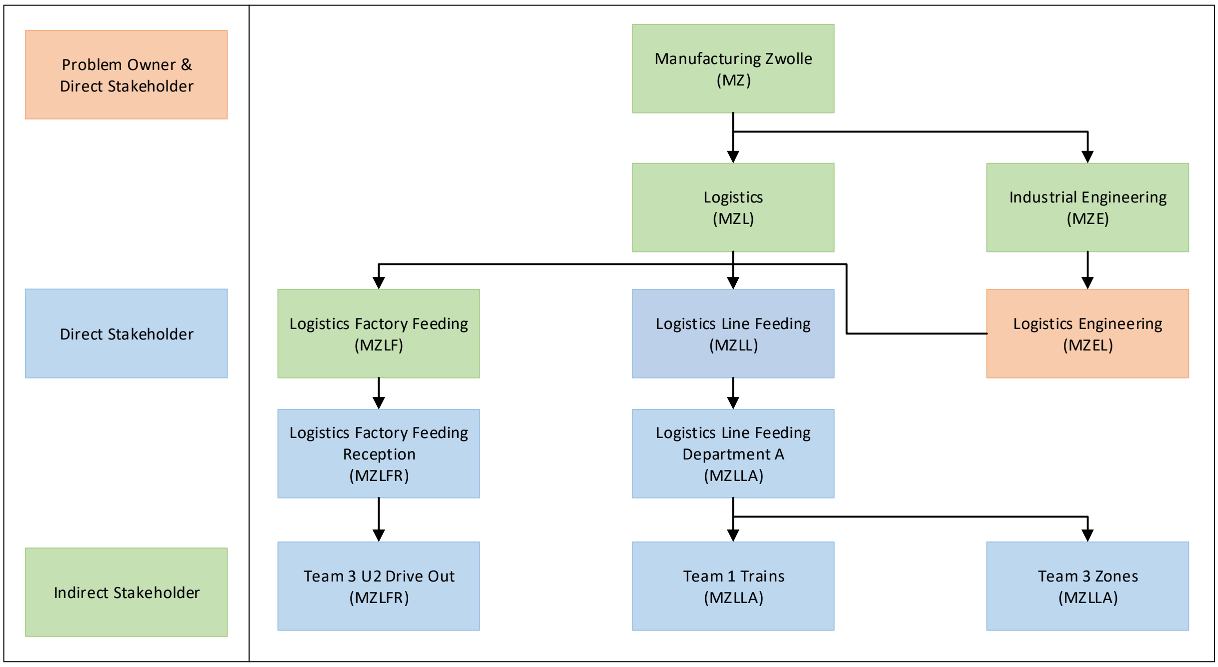


Figure 1.4 Stakeholders of the research, departments that are not stakeholders have been omitted

The other stakeholders are part of the Logistics department, which is divided into Logistics Factory Feeding and Logistics Line Feeding. Logistics Line Feeding is a direct stakeholder in this research since the USP process is part of this department and benefits from an efficient process. The Logistics Factory Feeding department is an indirect stakeholder as only a sub-department prepares pallets for the USP process. The Reception department is the sub-department that benefits from an efficient USP process and is, therefore, a direct stakeholder. The specific team that prepares the pallets is Team 3 U2 Drive Out.

The direct stakeholders of the Logistics Line Feeding department are part of sub-department A of Logistics Line Feeding and are Team 1 Trains and Team 3 Zones. Team 1 Trains is the team that transports pallets from the KL to the production hall and takes empty pallets to pallet breakdown. Team 3 Zones is the team that transports the pallets in the production hall to the location of consumption.

1.5.4. Previous research

In the last three years, two master theses were focused on Scania's logistics process. Kortenhorst (2019) focused on the internal sequencing process, which is a different, low-consumption, sequencing process, and therefore irrelevant for this research. Grit (2018) focused on the USP process, as this research does. The objective of the research was to level workload, looking at the number of pallets to supply per cycle by pallet trailers and tugger trains. The research also investigated how supply zones could be divided differently such that the workload was more balanced. The research did not focus on the method of supplying pallets to the assembly line, as will be done in this research.

Postponing pallets

The concept of postponing pallets when there is peak demand, advised by Grit (2018), is implemented within SPZ. This means that when too many pallets have to be supplied to the assembly line in a cycle, pallets are postponed to the next cycle when this is possible, taking into account the production demand of that certain part number. Therefore the capacity is better utilized and less exception transport is needed.

2. Current situation

This chapter describes the current situation within SPZ with all processes related to the USP process. First, Section 2.1 elaborates on the location of SPZ with the most important buildings that are part of this research. Second, Section 2.2 explains the production process. Section 2.3 describes the current planning process. After that, Section 2.4 looks further at the current internal logistics process of which the USP process is part. Section 2.5 zooms in further on the current USP process. Section 2.7 describes the key figures of the current USP process. Finally, Section 2.8 summarizes and concludes the chapter.

2.1. Map of Scania Production Zwolle

This section gives an overview of Scania's production location in Zwolle.

Figure 2.1 shows a photo of SPZ. The dark blue building represents the production hall where the trucks are assembled on two assembly lines. In the green building, trucks are tested and parts, which could not be added at the assembly line, are added to the truck. The orange buildings indicate the logistics buildings from where parts are brought to the assembly lines. The “Koude Loods” (KL) is the warehouse from where pallets, which are part of the USP process, are brought to the assembly line. The light blue building “Suez” is the building where the pallet breakdown takes place.

Figure 2.1 Map of Scania Production Zwolle

2.2. Production process

This section describes the production process at SPZ.

The production process is closely aligned with the logistics process. SPZ assembles trucks on two U-shaped production lines (Castor and Pollux). Figure 2.2 shows the schematic layout.

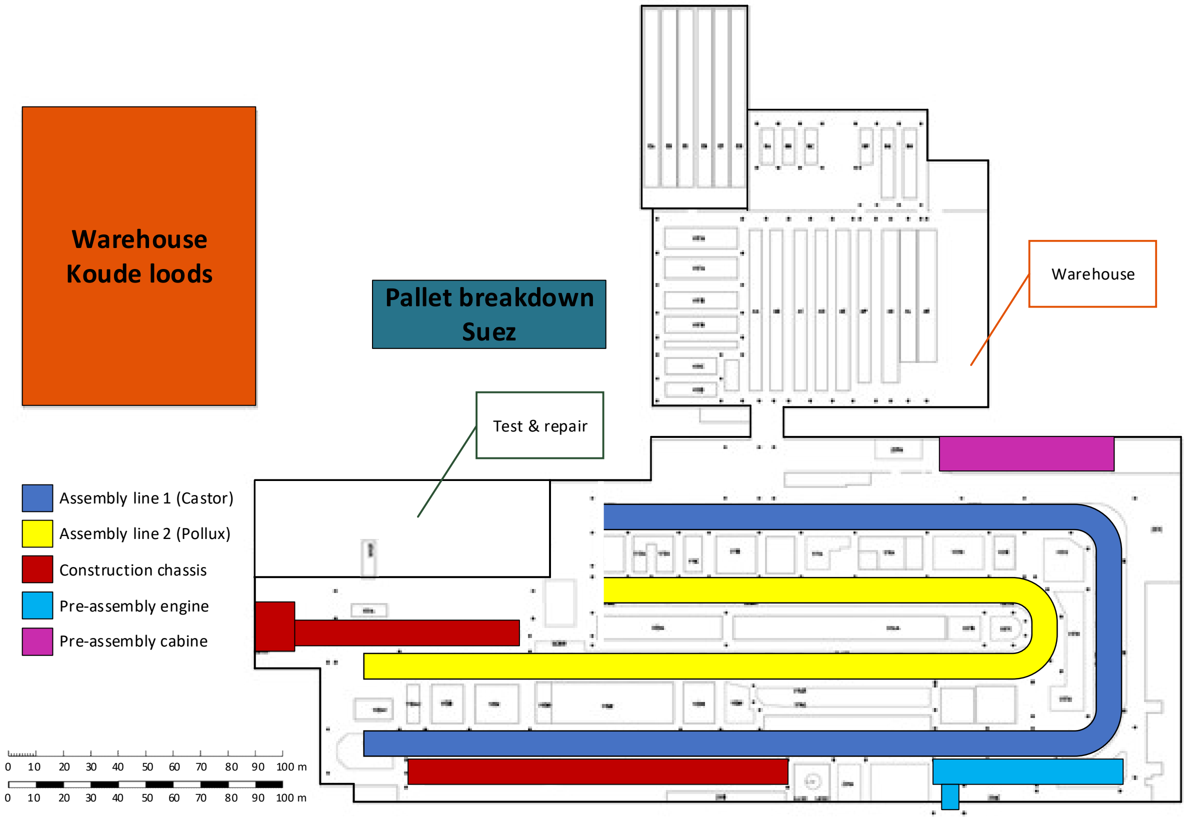


Figure 2.2 Schematic layout SPZ

The trucks are moved through the production hall on a conveyor. Parts required for assembling a truck are available at the assembly line. Most parts are supplied on pallets or boxes along the assembly line. To shorten the lead time of assembling a truck, pre-assemblies are used for certain parts. The engines and cabins are a good example of this, their pre-assemblies are shown in Figure 2.2.

On both assembly lines, the production process starts with the construction of the chassis, then the pipes and cables are assembled on the chassis. After this, the axles are placed under the chassis, then the motor is installed. After installing the engine, the cabin is placed on the truck, and tires are assembled at the axles. The last station is test and repair where trucks are tested and parts are added that could not be added at the assembly line. Special requests from customers are also assembled here.

2.2.1. Takt time

SPZ works in two shifts where it is possible to assemble 200 trucks per day with a truck rolling off the assembly line every 5 minutes. Production is based on customer order, hereby a takt time is used to meet customer demand. The formula to calculate the takt time is:

$$Takt\ time = \frac{Available\ time}{Customer\ demand}$$

where:

$Takt\ time$ = process time per workstation available, e.g., minutes of work per workstation
$Available\ time$ = net time available for work, e.g., minutes of work per day
$Customer\ demand$ = time demand, e.g., units required per day

The takt time determines the speed at which the truck is moved through the production hall from workstation to workstation on an assembly line. This means that every takt time a truck is finished and comes off the assembly line. Mechanics work per workstation to assemble the parts on the truck, the workload in the takt time per workstation depends on the type of truck.

The parts of a truck must be delivered JIT, at the right time at the right place. Delivering too soon to the assembly line leads to too little space at the assembly line while delivering too late could lead to a line stop. Section 2.4 elaborates more about the supply methods.

2.3. Production planning process

This section elaborates more on the production planning process to provide a comprehensive picture of how trucks are scheduled.

SPZ produces only trucks that already have been sold, the production planning process is also designed for this. The process starts with the sale of a truck and ends with the delivery of the truck. Scania agrees with a delivery period with the customer, which determines the period in which a truck should be produced. Scania's goal is to deliver each truck within 8 weeks after a customer has placed an order.

The production planning at SPZ receives the production orders from the headquarters in Sweden, 4 weeks before the start of the production of the truck. The total of these orders is then divided over the two production lines so that they meet as many *mixing rules* as possible. *Line choices* are also taken into account. The planner also takes into account the expected downtime of the assembly lines.

The line choices take into account the pros and cons of the two assembly lines. The Castor line is the high production line where more trucks are assembled on a day, in contrast to the Pollux line where fewer common trucks are produced. For example, there is a line choice to produce the Scania XT Gryphus truck, the truck of the Dutch Ministry of Defense, on the Pollux line since the truck cannot be assembled within the takt time of the Castor at a workstation.

Mixing rules are rules that are requested by the production department or other departments to allow the process to run with a balanced workload or even flow. Each mixing rule has a priority on how important it is to align with the production planning. An example of an important priority mixing rule is that only 1 in 3 trucks can be a truck with a long chassis. If this mixing rule is broken, this can be at the expense of safety or lead to stopping time since the workload is no longer balanced.

The production planner plans the production orders using a planning program that minimizes the number of violations of mixing rules, then the program shows where it cannot meet all mixing rules. The production planner makes manual changes in the production schedule to meet as many important mixing rules as possible. After this, the production schedule is approved by the production department. Where it is not possible to comply with all mixing rules, warnings are issued so that the production department and the logistics department can prepare for the violation of the mixing rules.

Day-to-day changes are made to the production schedule as production can be ahead or behind schedule. For example, it can happen that the assembly line has produced fewer trucks for a day due to the downtime of the line or non-delivery of an important part of a supplier. It can also happen that more trucks are produced than planned. This happens when the downtime is lower than expected. During the night, the production schedule is synchronized with the current production status for the next day without changing the order of the planned trucks.

During the night the daily expected peak consumption is calculated for the USP process for bringing parts to the assembly line. It is considered peak consumption when it is expected that with the normal supply of pallets, there is not enough stock at the assembly line such that there is a chance of a line stop. The calculation for peak consumption is done by comparing the expected number of parts needed, based on the speed of the production line, with the maximum lead time from emptying a pallet to the delivery of a new pallet. Based on the peak consumption, corrective measures are taken to ensure that the line does not come to a standstill.

2.4. Internal logistics

This section describes the internal logistics at SPZ. We distinguish four different supply methods, batch supply, kitting, sequencing, and unit supply.

Good organization and coordination of the logistics process are required to deliver the right parts at the right time at the right location to the assembly lines, according to the JIT principle. For a new part number, the supply method is chosen that suits the part best. In this section, the different supply methods are discussed in more detail.

2.4.1. Batch supply

The batch supply contains parts that fit on fixtures, are not chassis bound and are used regularly. The batches are picked in a warehouse close to the production hall and are brought to the assembly line. The batches are replaced at fixed times by tugger trains, whereby the parts are supplied in a batch to a fixed order-up-to-level. The empty pallets of batch supply are returned with the same tugger trains as they were supplied with.

2.4.2. Kitting

Kitting is the supply of parts on special fixtures or pallets at the assembly line. All parts are transported by a tugger train on a fixture or pallet, are chassis bound, and must be delivered to the assembly line in the production sequence. The parts for kitting are picked in a warehouse nearby the production hall. Within kitting, there is a flow that brings the parts to the assembly line at fixed takt times. There is also a non-takt flow, this flow brings low frequency, chassis-bound parts to the assembly line based on the expected consumption rate for production.

The return flow of the fixtures is takt driven, the fixtures are only returned when the fixture is empty. The return flow of the pallets is part of the USP process, the empty pallets are brought to pallet breakdown on pallet trailers.

2.4.3. Sequencing

In the sequencing flow, chassis-bound parts are delivered to the assembly line in the production sequence. The components have a low consumption rate or are too large to supply with other supply methods. The parts are already sorted in the production sequence by the supplier, which is different from the kitting flow. Within sequencing, a distinction is made between two types of flows. One flow brings large parts to the place of consumption, such as tires, engines, and cabins. The other flow brings, in particular colored, parts to the assembly line with reach trucks. These are parts such as colored grills or colored fuel tanks. The return flow of parts that are delivered on pallets is done by the sequencing flow is done by the return flow of the USP process.

2.4.4. Unit supply

Unit supply is the flow for delivering parts to the assembly line that have a high frequency. A distinction is made between the supply of parts on pallets and the supply of parts in boxes to the assembly line. The pallets and boxes are replenished based on a two-bin system. Parts are delivered from an external warehouse based on fixed schedules, where tugger trains are used for the supply of boxes. The supply of parts on pallets is part of this research and is discussed further in Section 2.5.

2.5. Unit Supply Pallet process

Section 2.4 explained the various internal logistics methods used to bring parts to the assembly line. This section discusses the USP process and its characteristics in more detail.

The USP process is the process that delivers parts with high consumption, on pallets to the assembly line. The process is characterized by using a two-bin system to replenish the pallets, based on fixed routes and fixed cycle times. The process includes a cycle in which pallets are collected from the external warehouse KL, delivered to various locations at the assembly line, after which empty pallets are taken to pallet breakdown. Figure 2.3 shows the simplification of a cycle.

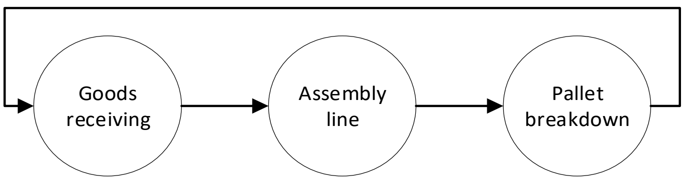


Figure 2.3 Simplified representation of the USP process

Within the USP process, two different flows are distinguished to deliver the pallets to the assembly line. Both flows are responsible for the delivery of pallets for different parts to the production hall. The first flow brings pallets with three pallet trailers to multiple decentralized locations in the production hall, and from there with reach trucks to the consumption location. The second flow takes pallets directly to the consumption location with three tugger trains. Figure 2.4 shows the pallet trailers (a), the tugger trains (b), and the reach trucks (c).

Figure 2.4a Pallet trailer

Figure 2.4b Tugger train
Source: STILL

Figure 2.4c Reach truck
Source: Motrac Linde

The production hall is divided into nine different delivery zones to facilitate the supply of pallets to the assembly line. Each pallet trailer or tugger train supplies three delivery zones based on fixed schedules and fixed delivery routes.

2.5.1. Goods receiving KL

Before the USP process can supply the pallets from the KL to the assembly line, the KL must be supplied first. The supply of the KL is not part of the scope of this research, but to provide a comprehensive picture it is shortly discussed. Figure 2.5 shows the process flow of goods receiving at the KL.

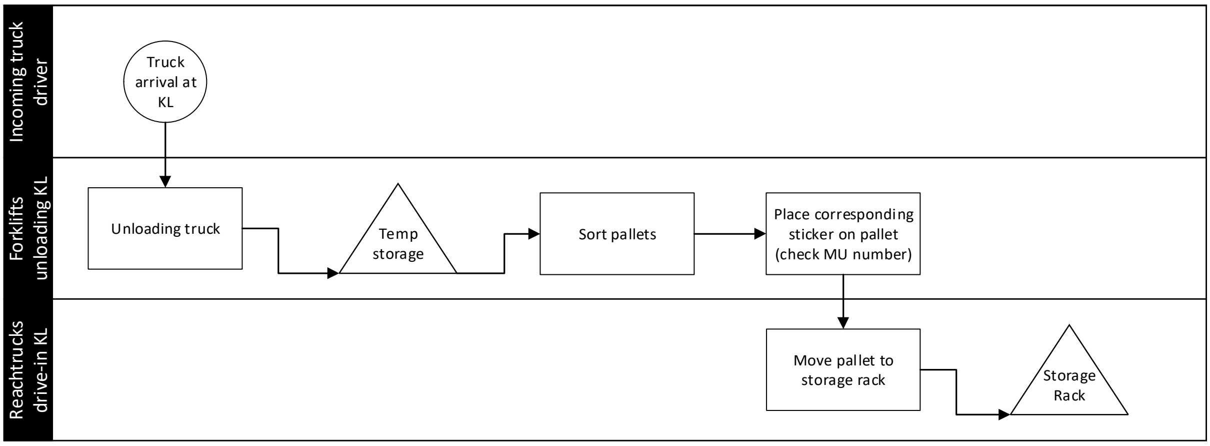


Figure 2.5 Process flow goods receiving at KL

The process starts with the arrival of a truck with pallets at the KL, where the truck is emptied by forklifts. Then the pallets are sorted, stickered, and moved to the storage rack. The tugger trains and pallet trailers are supplied from the storage racks.

2.5.2. Pallet trailer process

The pallet trailer process delivers pallet trailers with new pallets from the KL to the pallet trailer location in a delivery zone in the production hall. A delivery zone contains multiple pallet trailer locations where pallet trailers are placed. The pallet trailer process consists of three recurring cycles in which empty pallets are recorded, prepared, and supplied for different delivery zones. Figure 2.6 shows this schematically. Currently, a cycle consists of 25 minutes. To supply a delivery zone in a cycle, a maximum of two times can be driven from the KL to pallet trailer locations in a delivery zone and back. Each time a pallet trailer driver drives from the KL to the production hall, he takes a set of two pallet trailers.

Pallet trailer process	Cycle 1	Cycle 2	Cycle 3
Pallet recording by recorder	A	B	C
Pallet preparation at KL	C/A	A/B	B/C
Supplying by pallet trailer	C	A	B

Figure 2.6 Schematic representation of the three recurrent pallet trailer cycles, each letter represents a zone

As an example, we discuss the relationship between delivering pallets to delivery zone A and the cycles. In cycle 1, new pallets for delivery zone A are requested. When all pallets from delivery zone A have been requested, they are prepared at the KL. The preparation of pallets starts in cycle 1, as it takes less than 25 minutes to request all pallets in a delivery zone. Subsequently, in cycle 2, the pallets that have been prepared in cycle 1 are supplied. The requested pallets for delivery zone A, which could not be prepared in cycle 1, are prepared in cycle 2. These pallets are supplied when the pallet trailer driver drives for the second time to delivery zone A in cycle 2. In cycle 3 nothing happens for delivery zone A, after which cycle 1 repeats. Resupplying delivery zones B and C are done in the same way, the tasks are only performed in other cycles as shown in Figure 2.6. Based on the number of replenishments and the volume per delivery zone, busy delivery zones and less busy delivery zones are distinguished. A busy delivery zone is often alternated with a less busy delivery zone to avoid peaks at the supply at the KL. Figure 2.7 shows the process flow of the pallet trailer process for the supply of one delivery zone in more detail.

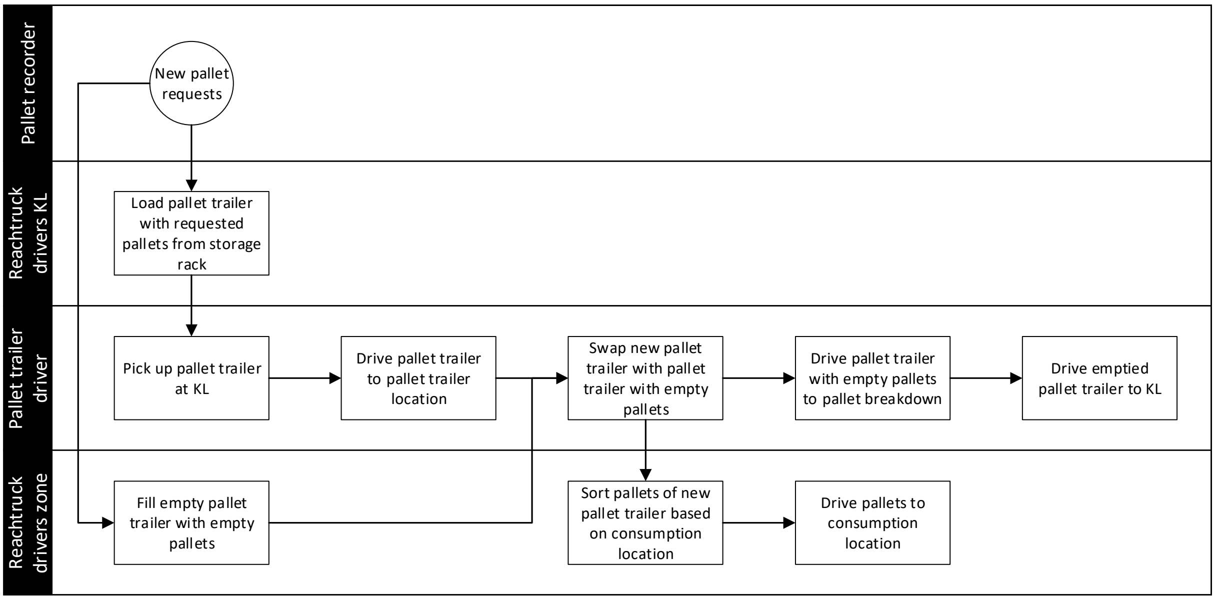


Figure 2.7 Process flow pallet trailer process

The pallet trailer process starts with the request for new pallets by a pallet recorder. This is someone who continuously drives through the production hall to record empty pallets of all pallet trailer delivery zones based on fixed routes and a fixed schedule. In one cycle, a pallet recorder can record new pallets for three different delivery zones. These pallet requests are then followed up in the KL, where reach trucks load the requested pallets on the pallet trailers. Simultaneously, empty pallets of requested pallets are loaded with reach trucks at an empty pallet trailer. Empty pallets from the kitting and sequencing flow are also loaded at an empty pallet trailer by reach truck drivers.

The pallet trailer driver picks up the pallet trailer with requested pallets from the KL for the delivery zone which is scheduled at that moment. The pallet trailer is brought to the pallet trailer location at the scheduled delivery zone. The pallet trailer with requested pallets is replaced for the pallet trailer with empty pallets at the scheduled delivery zone, after which the pallet trailer with empty pallets is taken to pallet breakdown. Here the empty pallets are unloaded from the pallet trailer, after which the pallet trailer driver returns the empty set of pallet trailers to the KL.

As soon as a pallet trailer is placed at the pallet trailer location at the delivery zone, reach truck drivers unload this pallet trailer, sort the pallets and then bring the pallets to their consumption location. Reach trucks do not have a fixed schedule or delivery route and drive according to their insight.

Vision Scania
Within Scania, there is criticism at the pallet trailer process from management. Scania's vision is to get reach trucks out of the production hall due to safety reasons and high traffic intensity, the current pallet trailer process with reach trucks does not fit within this vision. Another drawback to the use of pallet trailers is the space that the trailer uses at decentralized locations in the production hall. With pallet trailers and reach trucks it is also difficult to scale down when fewer trucks are being produced as each pallet trailer and reach truck is assigned to a fixed location in the production hall.

An advantage of the pallet trailer process is the high pallet trailer capacity. Also, reach trucks can supply all pallets, no matter how it is stored or the type of pallet used at Scania, in contrast to the other flow.

2.5.3. Tugger train process

The tugger train process delivers pallet trolleys with new pallets from the KL to the consumption location at the assembly line. The tugger train process consists of three recurring cycles of 25 minutes in which empty pallets are recorded, prepared, and supplied for different delivery zones. These cycles are shown schematically in Figure 2.8.

Tugger train process	Cycle 1	Cycle 2	Cycle 3
Pallet recording by tugger train	A	B	C
Pallet preparation at KL	C	A	B
Supplying by tugger train	B	C	A

Figure 2.8 Schematic representation of the three recurrent tugger train cycles, each letter represents a zone

As an example, we discuss the supply of delivery zone A in cycles. In cycle 1, new pallets for delivery zone A are requested. When all pallets from delivery zone A have been requested, they are prepared at the KL in cycle 2. After preparation, these pallets are supplied in cycle 3. Cycle 1 repeats after cycle 3. Resupplying delivery zones B and C are done in the same way, the tasks are only performed in other cycles as shown in Figure 2.8. The recording and supplying of pallets are done by the tugger train driver, while the preparation of pallets is done at the KL. Also here, peaks at the supply at the KL are avoided by alternating busy delivery zones with less busy delivery zones. Figure 2.9 shows the process flow of the tugger train process for the supply of one delivery zone.

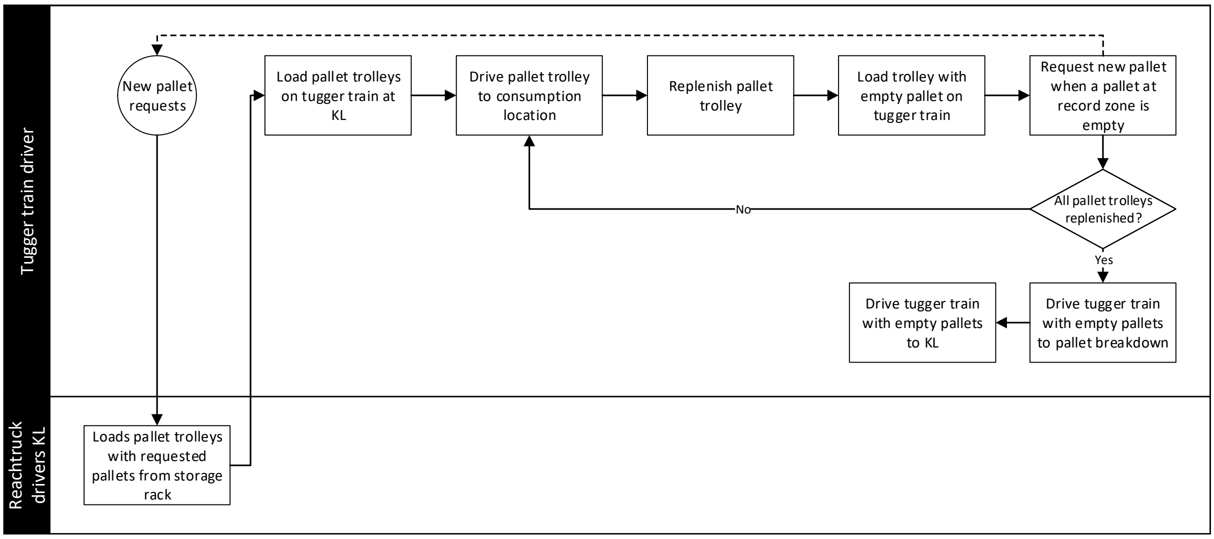


Figure 2.9 Process flow tugger train process

The tugger train process starts with the requests for new pallets at the assembly line. The request for the pallets is made by the tugger train driver simultaneously with the supply of pallets. The requested pallets are placed on pallet trolleys in the KL for collection by the tugger train driver. The pallet trolleys are loaded one by one onto the tugger trains, after which the entire tugger train with pallet trolleys is brought to the consumption locations. At a consumption location, one pallet trolley with the empty pallet is replaced by one pallet trolley with a full pallet. The pallet trolley with the empty pallet is loaded onto the tugger train. Each pallet trolley with a full pallet on the tugger train is replaced by a pallet trolley with an empty pallet at the consumption location. During the supply of pallets, requests are also made for empty pallets for the delivery zone to be recorded. The tugger train with empty pallets is then to pallet breakdown, where the empty pallets are unloaded from the pallet trolleys. After pallet breakdown, the tugger train returns to the KL where new pallets are ready to be brought to the consumption location again.

Vision Scania

The management of Scania sees tugger trains as a good alternative to get the pallet trailers and reach trucks out of the production hall. The management does not yet know to what extent the tugger train can replace the pallet trailer process in its current form since the cost has not been proven to be lower than the pallet trailer process.

An advantage of the tugger train compared to a pallet trailer is that the tugger train driver can replace all the pallets himself without using another machine such as a reach truck. This makes reach trucks unnecessary. Another advantage is that a tugger train does not need a fixed location, so it can easily be scaled up or down when necessary.

A disadvantage of the tugger train is that there is little capacity available for pallets on a tugger train. Furthermore, only a limited number of pallet types can be loaded on a tugger train. Section

2.7.1 elaborates more about this. It can also be hard for a tugger train driver to replenish a heavy pallet on a pallet trolley. Another disadvantage of the tugger train is that it cannot supply places where pallets are still in stock racks in the production hall.

2.6. Decision problems

This section describes the decision problems that are made at SPZ *to design the USP process on different hierarchical levels.*

For the USP process, choices have to be made at different hierarchical levels to efficiently supply parts to the assembly line. These choices are different for the pallet trailer process and the tugger train process. According to Schmid and Limère (2019), decision problems from part feeding problems can be divided into strategic, tactical, and operational decision problems. Decision problems that SPZ must take for the USP process are broken down below.

2.6.1. Strategic level decisions

Strategic decisions usually require a lot of money and effort and are therefore long-termed (Schmid & Limère, 2019). The following strategic choices are made at SPZ for the USP process:

- Location of warehouse: This contains the strategic decision of using decentralized locations in the production hall or delivering from a central warehouse. At SPZ, both methods are used within the USP process.
- Cooperation with suppliers and logistic providers: This is described as the outsourcing decision. Outsourcing the correct number of logistics operations, while taking into account the consequences (Schmid & Limère, 2019). The pallet breakdown process is outsourced within the USP process.
- Replenishment system: This contains the decision about how parts are requested, this can be demand-oriented but also via a kanban system. SPZ uses a kanban system that requires manual checking to see if a pallet is empty.

These decisions are all out of scope and are already determined by SPZ.

2.6.2. Tactical level decisions

Tactical decisions are mid-termed and could also be described as assembly system planning (Schmid & Limère, 2019). The following tactical choices are made at SPZ:

- Decision means of transportation: The choice for which means of transportation are used to bring the parts to the assembly line. Within the USP process, tugger trains and pallet trailers are used as explained in Section 2.5.
- The return process: This contains the decision for an integrated or separated return of empties flow. SPZ uses an integrated return of empties flow for the USP flow as it uses the same means of transportation for the return process.
- Location-allocation pallet trailers: Multiple decisions for the number of decentralized pallet trailer locations to use, where to place them, and which line segments to assign to the pallet trailers. This decision is briefly reconsidered as the takt time increases.

- The routing problem: The decision for the number of reach trucks and tugger trains to use, which line locations to serve, and the determination of the predetermined routes.
- Scheduling problem: For SPZ this is the problem of creating fixed cyclic delivery schedules while minimizing inventory at the assembly line.

The decision for the means of transport and the decision for an integrated or separate return process is fixed. The location-allocation of pallet trailers, the routing problem, and the scheduling problem are part of the scope.

2.6.3. Operational level decisions

Operational decisions are more short-dated and can be changed easily, the aim of planning here is to increase efficiency while satisfying demand (Schmid & Limère, 2019). The following operational choice is made at SPZ:

- Loading problem: Decision for the number of bins to be loaded per tour on a vehicle, such that the capacity of a vehicle is not violated while satisfying demand.

The loading problem is outside the scope of the research as it has already been investigated in a previous master's thesis (Grit, 2018).

2.7. Key figures

This section elaborates more on the key figures and the data behind the process to sketch the current situation. The pallet replenishments, utilization of vehicles, information about line locations, and personnel are discussed. The data used in this section originates from 08-17-2020 to 09-18-2020 and is retrieved from Scania's database.

2.7.1. Pallet replenishments

This section provides information about pallet replenishments to get insight into the current workload of the process. Pallet replenishments are plotted against the number of chassis produced, working hours, delivery zones, and type of pallets.

Replenishments per chassis

Figure 2.7 shows the number of pallets replenished in a day plotted against the number of chassis produced per day. Due to confidentiality, we use the indexed number of chassis produced where 100% is equal to the average number of chassis produced in this period.

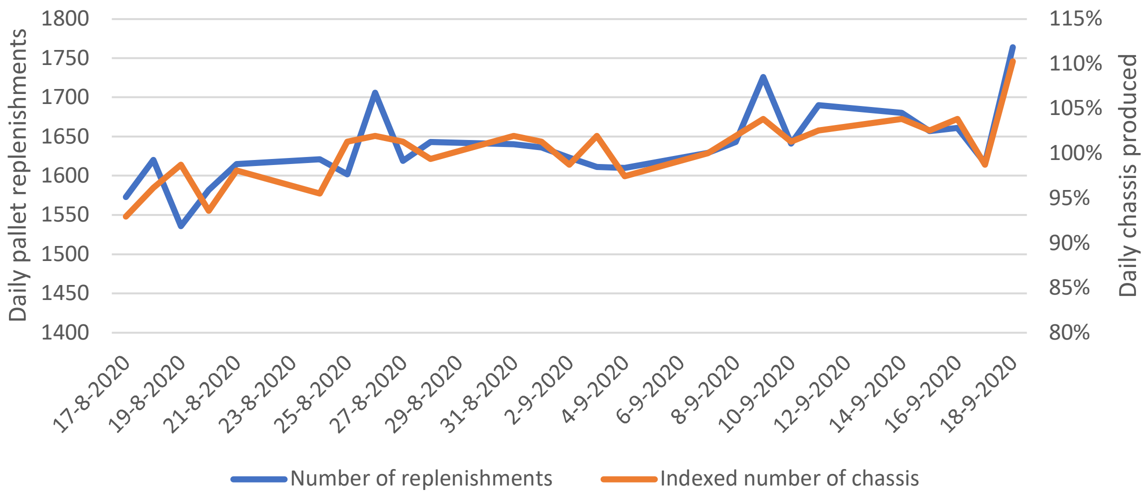


Figure 2.10 Daily number of pallet replenishments vs the indexed number of chassis produced

The figure shows that the number of replenishments per day follows the line of the number of trucks produced per day. This clearly shows the influence of the number of trucks produced on the number of replenishments per day. The deviation between the number of replenishments per day and the number of trucks produced per day can be explained by the stock at the assembly line and the varying product mix.

Replenishments per hour

To deliver the parts at the assembly line to produce the required number of trucks per day, the logistics process works in two shifts. The first shift works from 06.00 to 14.00 and the second shift from 14.45 to 23.15. When overtime is required, the second shift works until 00:00 at the latest. The 45-minute break between the two shifts has been inserted because of the Covid-19 pandemic. Figure 2.11 shows the working hours plotted against the number of daily replenishments and the corresponding volume of the pallets.

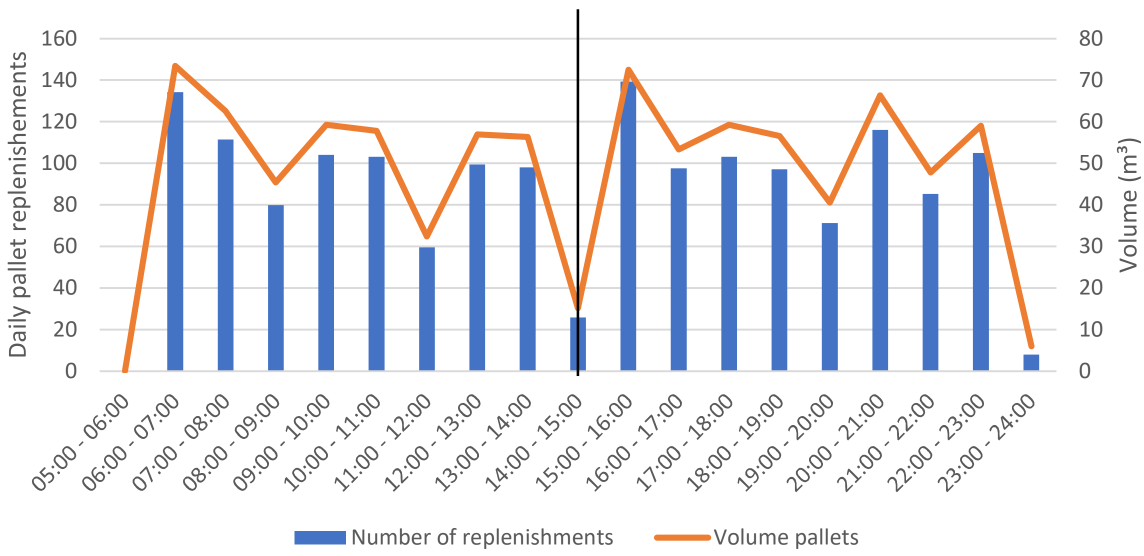


Figure 2.11 Working hours vs replenishments and volume (m^3)

We see that there is a lot of variation in the number of pallet requests per hour. This can be explained by the breaks during the shifts. After the breaks, an increase in the number of pallet replenishments can be seen. The total volume of the pallets does follow the path of the number of pallets replenished in a day.

Replenishments per zone

Figure 2.12 shows the daily number of replenishments per delivery zone with the corresponding volume. Recall from Section 2.5.2 and Section 2.5.3 that delivery zones are supplied by pallet trailers and tugger trains, where every vehicle supplies three delivery zones (A, B, and C).

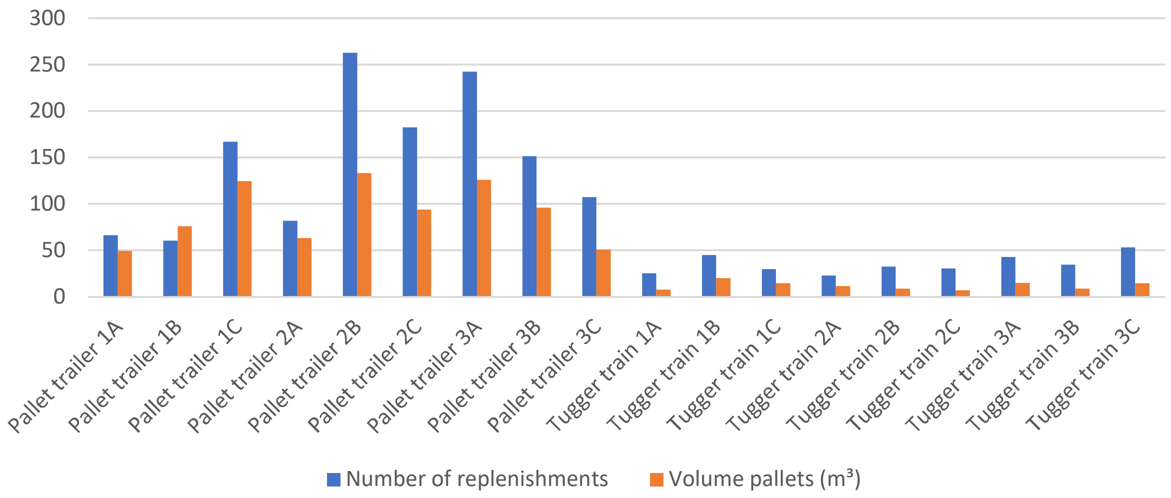


Figure 2.12 Daily pallet replenishments per zone

Figure 2.12 shows that that the daily number of replenishments per delivery zone differs. The volume does not depend on the number of replenishments. This is caused by the different types of pallets used at SPZ. Based on the number of replenishments and their volume, busy delivery zones and less busy delivery zones are distinguished. A busy delivery zone is often alternated with a less busy delivery zone for a pallet trailer or tugger train. The figure shows that more replenishments and volume is transported with a pallet trailer than with a tugger train.

Replenishments per type pallet

At SPZ several types of pallets are used within the USP process. Figure 2.13 shows a Pareto chart of the type of pallets used. The type of pallet is an important parameter since not every vehicle can supply every type of pallet.

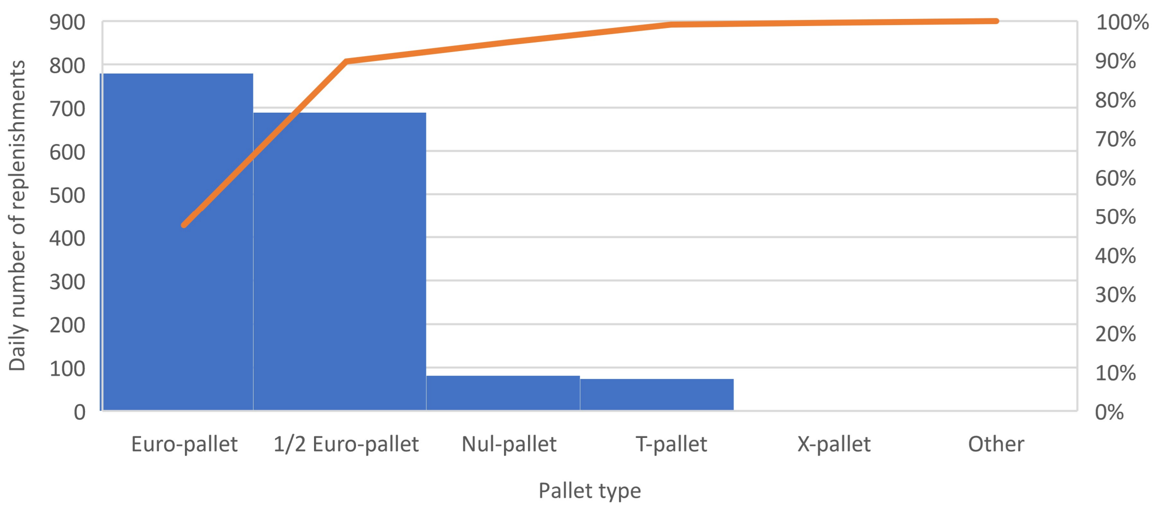


Figure 2.13 Pareto chart pallet types

The figure shows that 90% of the replenishments are packed in Euro-pallets or ½ Euro-pallets. Euro-pallets and ½ Euro-pallets can be transported with a tugger train as well as with a pallet trailer, the other types of pallets can only be transported with a pallet trailer. These pallets are longer or wider and therefore do not fit on a pallet trolley. Each pallet type could be divided into different heights. For example, there is a Euro-pallet with one edge and a Euro-pallet with two edges, the height difference is 20 centimeters. This makes the volume of a pallet a valuable parameter.

2.7.2. Utilization rates

This section provides information about the utilization rates of the means of transportation and delivery zones. The utilization rate is an important Key Performance Indicator (KPI) for measuring the productivity of the USP process.

Utilization vehicles

The utilization indicates how full a vehicle is compared to its maximum capacity. For the pallet trailer process, the utilization of the pallet trailers is calculated by dividing the volume of the pallets on a pallet trailer by the maximum volume of a pallet trailer. For the tugger train process, the utilization is calculated by dividing the number of occupied places on a tugger train by the maximum number of available places. Figure 2.14 shows the daily utilization rate per vehicle. A distinction is made between the three pallet trailers (1, 2, and 3) and the three tugger trains (1, 2, 3).

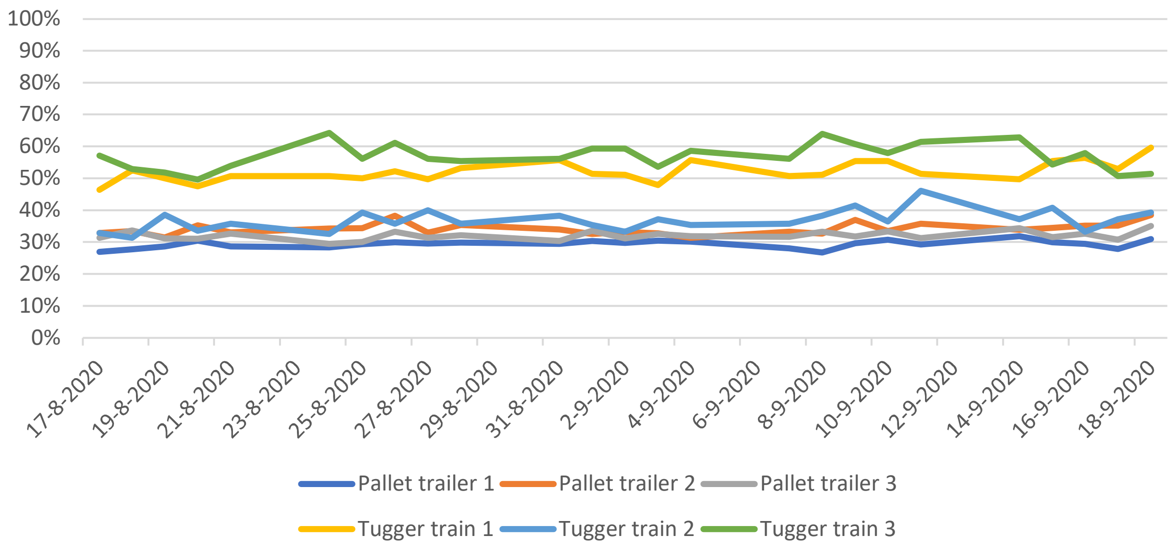


Figure 2.14 Daily utilization rate per vehicle

The figure shows that the utilization rates of the tugger trains are higher than those of the pallet trailers. The utilization fluctuates from day to day depending on the number of replenishments to be done on a day, which depends on the product mix and the stock level at the assembly line. Pallet trailer 1 has the lowest average utilization with a utilization rate of approximately 29%. Tugger train 3 has the highest average utilization with an average utilization of 56%.

It should be noted that the return flows from sequencing and kitting return with the pallet trailer flow, which is not included in the figure. Further in this section, more is explained about the influence of the return flows from sequencing and kitting on the pallet trailer process.

Utilization delivery zones

Figure 2.15 and Figure 2.16 present the utilization rate per delivery zone. A distinction is made between pallet trailer zones and tugger train zones. The vehicle supplying the delivery zone is denoted by a number (1, 2, or 3), while every delivery zone is represented by a letter (A, B, or C) as mentioned in Section 2.5.2 and Section 2.5.3.

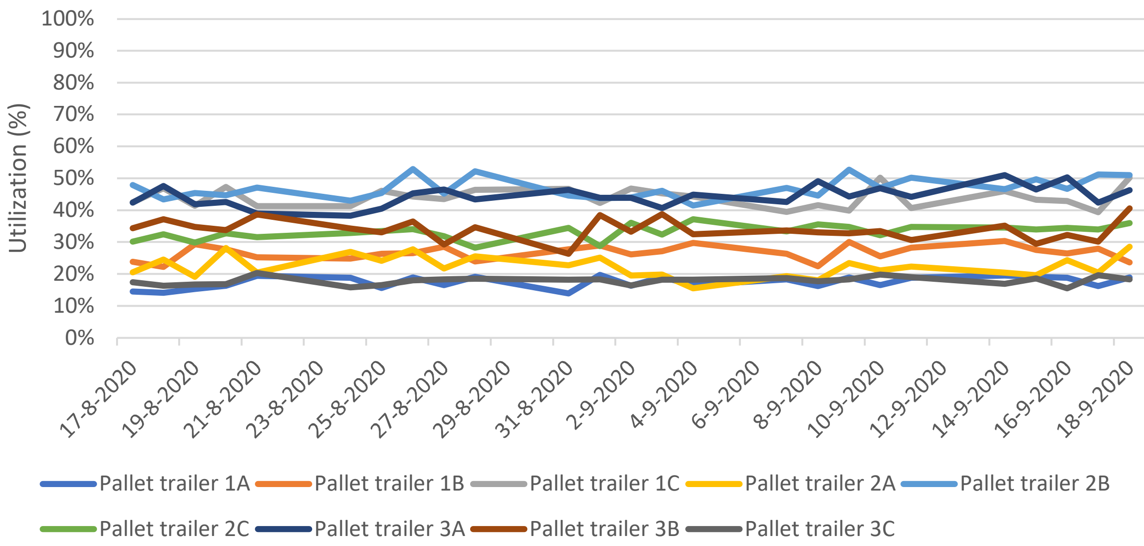


Figure 2.15 Utilization rate pallet trailers per delivery zone

Figure 2.15 shows that the utilization rate of pallet trailers differs per delivery zone. Pallet trailer zone 1A has the lowest average utilization rate of approximately 17%. This is partly caused by the fact that a part of the return flow of sequencing and kitting returns with this delivery zone. Furthermore, pallet trailer zone 2B has the highest average utilization rate of 47%.

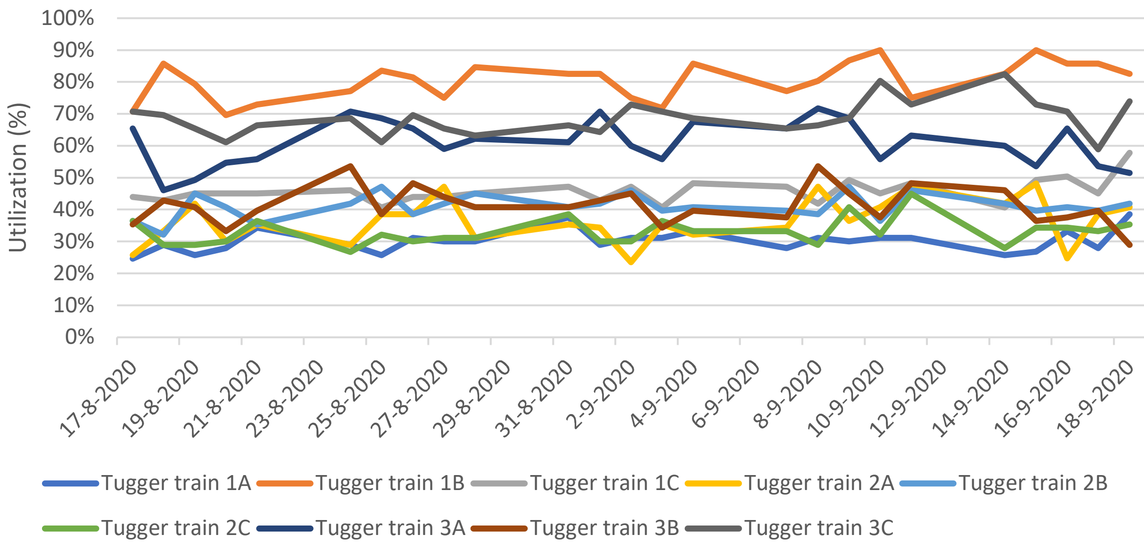


Figure 2.16 Utilization rate tugger trains per zone

Figure 2.16 shows that the utilization rate of the tugger train zones varies even more than that of pallet trailer zones. There is also more variation across the days, this can be explained by the fact that a pallet trailer can replenish more pallets daily than a tugger train. Due to the high number of pallets that are being replenished, the average remains more stable. Also, tugger trains bring pallets to the assembly line from part numbers that are less frequently used than part numbers from pallet trailers. This provides additional variability. Tugger train zone 1B has the highest utilization rate with 81% and tugger train zone 2A with 36% has the lowest utilization rate.

Return flow sequencing and kitting
Section 2.4 introduced the different supply methods used at SPZ and stated that pallets are used for the supply methods sequencing and kitting. These pallets are supplied with forklifts to the assembly line and are returned together with pallets of the pallet trailer process. As a result, the utilization rate of the returning pallet trailers is higher than that of the supplying pallet trailers. The return of empties flow is subsidiary to the supply of pallets since a pallet that does not fit in a pallet trailer does not immediately lead to a line stop. Also, an empty pallet is not bound to a fixed delivery zone when returned with the pallet trailer process and is often taken to the nearest free pallet trailer location.

The effect of the return flow of sequencing and kitting is especially noticeable for pallet trailer zones 1A, 2B, and 3A. However, this does not lead to problems in the process as these delivery zones are supported where necessary by a team leader or an extra pallet trailer driver.

2.7.3. Line locations

This section provides information about the characteristics of line locations at the assembly lines. Not every line location can be supplied by every flow. The space required also differs per part number.

Storage types
The pallets are supplied from the KL to different line locations at the assembly line. Many line locations are located in stock racks. These line locations cannot be supplied by tugger trains without the aid of a reach truck. Table 2.1 shows the percentage of stock racks for pallet trailers and tugger trains. Due to confidentiality, we use the percentage of the total number of line locations.

Storage type	Pallet trailer	Tugger train
In stock rack	55.4%	0.3%
On the ground	25.1%	19.2%

Table 2.1 Percentage of line locations per vehicle type and storage type

The table shows that approximately 55% of the pallets are stored in a stock rack at the assembly line. 25% of the line locations are stored on the ground and are supplied by a pallet trailer. The line locations stored on the ground can be supplied by a tugger train without changes in the storage type at the assembly line. The line locations located in a stock rack, supplied by tugger trains are exceptions. The parts in these pallets are manually placed in the storage racks at the assembly line.

Data also shows that in each pallet trailer zone, stock racks can be found. Most stock racks can be found in pallet trailer zone 2C and pallet trailer zone 2B. Most line locations without storage racks supplied by a pallet trailer can be found in pallet trailer zone 3A.

Pallets at the assembly line

Each part number has pallets at the assembly line. Figure 2.17 shows the number of pallets at the assembly line, plotted against the number of daily replenishments (scatter plot). The figure also presents the number of part numbers with the corresponding number of pallets at the assembly line (bar graph). Due to confidentiality, we use the indexed number of part numbers expressed as the percentage of the total number of part numbers.

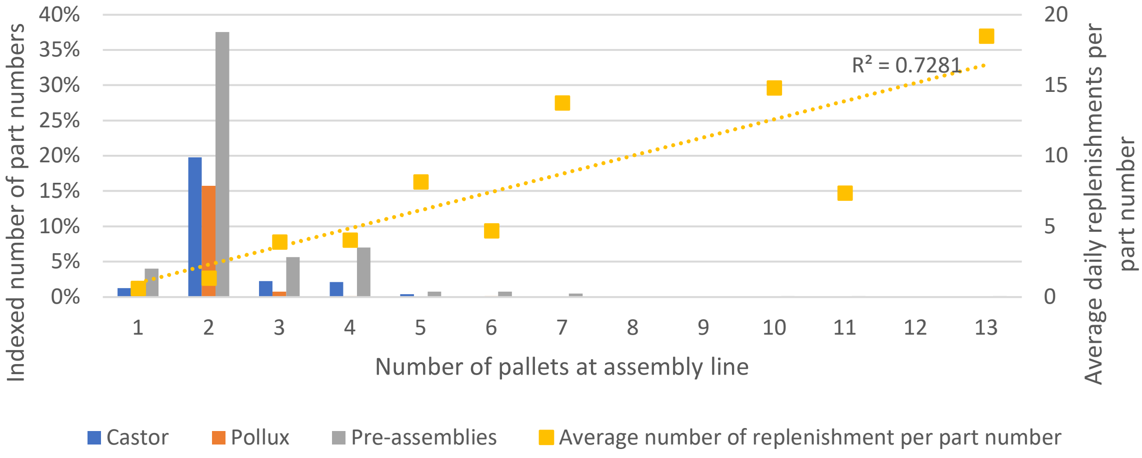


Figure 2.17 Number of pallets at assembly line vs the number of replenishments

We made a distinction between the two assembly lines (Castor and Pollux) and the pre-assemblies. These three groups use many matching part numbers, needed at different locations. In the figure, we see that most part numbers have 2, 3, or 4 pallets at the assembly line. When the number of pallets at the assembly line increases, the average number of replenishments per day, per part number, also increases.

Ideally, each part number has two pallets at the assembly line where the two-bin system can function properly. With a two-bin system, there are two pallets at the assembly line. When a pallet is empty the other is used and a new pallet is requested. Sometimes this is not possible because the consumption of the part number is too high in combination with the lead time, therefore more pallets have to be placed at the assembly line. In special cases it is also possible to have one pallet at the assembly line, this is only possible when the consumption is very low. For these part numbers, pallets are requested when there is a minimum number of parts in the remaining pallet.

For the Castor assembly line, an average of 2.25 pallets per part number can be found at the assembly line. The average number of pallets per part number for the Pollux assembly line is 2.03 and for the pre-assemblies 2.44. The big difference between the number of pallets per part number between these three groups can be explained by the number of parts needed per group. Most parts are needed for the pre-assemblies, followed by the Castor line and the Pollux line. The corresponding space required for the Castor is 318 m^2, for the Pollux 187 m^2, and for the pre-assemblies 921 m^2. Furthermore, the part numbers supplied by the pallet trailers have an average of 2.4 pallets per part number at the assembly line while the part numbers of tugger trains have an average of 2.09. The space required for the part numbers of the pallet trailer process is 1168 m^2 and for the part numbers of the tugger train process is 258 m^2, making it useful to reduce the lead time of the pallet trailer process to decrease the surface needed at the assembly line. Overall, the average number of pallets per part number is 2.32, which needs a total of 1426 m^2 space.

2.7.4. Personnel

The production and logistic teams work in two shifts at SPZ, both shifts have the same amount of FTE available for the USP process. Figure 2.18 schematically shows how a team is built up.

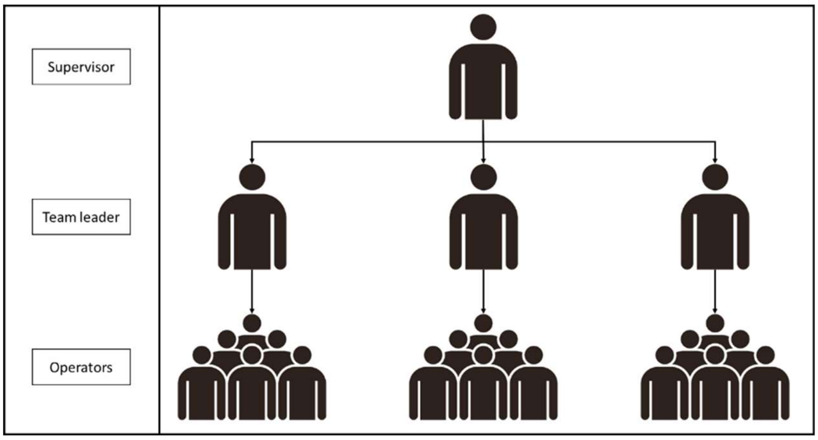


Figure 2.18 Schematic representation of a team

Operators are managed by a team leader, the team leader is managed by a supervisor. For the USP process, there is one supervisor per shift, one team leader for the pallet trailers and pallet trains, one team leader for the reach trucks in the production hall, and one team leader for loading pallets in the KL. Table 2.2 and Table 2.3 show the number of operators per process. The operators who prepare the pallets in the KL are left out.

Tugger train shift	**FTE**
Drive-out KL	1.2
Tugger train drivers	3
Total	**4.2**

Table 2.2 Operators tugger train process per shift

Pallet trailer shift	**FTE**
Drive-out KL	4.8
Pallet trailer drivers	3
Pallet trailer driver other empty pallet flow	(1)
Pallet recorder	1
Reach truck drivers zones	7
Reach truck drivers other empty pallet flow	(3)
Total	**15.8 (18.8)**

Table 2.3 Operators pallet trailer process per shift

In the tables, we see that the tugger train process consists of approximately four operators per shift and the pallet trailer process of approximately 16 operators per shift. The pallet trailer driver and the reach truck driver who only transport empty pallets from other flows are part of the pallet trailer process but are not within the scope of the project. Table 2.4 shows the number of replenishments per day against the number of FTE available in two shifts. We see that the pallet trailer process does slightly more replenishments per operator FTE than the tugger train process and is therefore more cost-efficient.

Train type	Daily replenishments	FTE	Replenishments per FTE
Tugger train	316	8.4	37.7
Pallet trailer	1321	31.6	41.8

Table 2.4 Daily replenishments vs FTE

2.8. Conclusion

This section briefly summarizes Chapter 2 and draws conclusions based on the analysis of the current situation.

The logistics process is closely related to the production process. The takt time determines the production speed at the assembly lines, to which all processes are engineered. The variation that occurs in the production process also directly leads to variation in other processes. The product mix is a good example of this and creates a lot of variation in the logistics process.

Parts are supplied to the assembly line in various ways based on the supply method that suits the characteristics of the part number best. The USP process is the process that brings frequently used parts on pallets to the assembly line. The production hall is divided into delivery zones to facilitate the supply of parts. Two means of transportation are used within the USP process, the pallet trailer, and the tugger train. The pallet trailer takes pallets from the warehouse to decentralized places in the production hall, where reach trucks take the pallets to their consumption location. Reach truck drivers drive on their insights and do not have a fixed routing. The tugger train takes the pallets directly to the place of consumption. Both means of transportation use fixed takt times and fixed routes. In its current form, the pallet trailer process is more cost-efficient and more flexible. Cost-efficient in the form that the costs per pallet are lower and more flexible in the form that it is insensitive to the type of pallet used and the use of stock racks. Also, the benefits of using pallet trailers will increase when the takt increases and more trucks are produced daily.

Pallets are requested manually for both flows. The pallets in a delivery zone are requested in cycles according to a fixed schedule. The pallet is not directly requested when the pallet becomes empty, but according to the fixed schedule at fixed times. Potential for improving the flows lies in the use of a replenishment signal when a pallet is empty, the use of risk pooling by merging delivery zones, and the use of flexible delivery zones and cycles.

SPZ uses the two-bin principle for the USP process, but many part numbers have more than two pallets at the assembly line. The average number of pallets per part number for the pallet trailer process is 2.4 and for the tugger train process 2.09, which need respectively 1168 m^2 and 258 m^2 of space. By reducing the lead time of the pallet trailer process, the surface needed at the assembly line can be drastically reduced.

Furthermore, a lot of potential for improvement can be found in the utilization rates of the vehicles. With the pallet trailer achieving an average utilization rate of 32% and the tugger train an average utilization rate of 49%. The utilization rate also differs per delivery zone, which makes one delivery zone more efficient than another. Another key figure is that 80% of all line locations are supplied by pallet trailers, while the rest is supplied by tugger trains. Also, approximately 56% of the line locations are stock racks, while the other line locations are on the ground.

Due to the high potential of improvement of the pallet trailer process, we focus on the location-allocation problem of pallet trailers and the scheduling of pallet trailers. Chapter 3 classifies the problem based on literature and elaborates on the literature to increase productivity and reduce the lead time of logistics processes, based on the insights of Chapters 1 and 2.

3. Literature review

This chapter classifies the problem and investigates in what way literature can contribute to this research. Section 3.1 describes the different types of assembly lines and the planning problems associated with a mixed-model assembly line. Section 3.2 further discusses the planning problem "Material flow control" and positions the USP process based on literature. After that, Section 3.3 elaborates on similar problems in literature. Section 3.4 describes several solution approaches. Finally, Section 3.5 proposes different solutions in the literature to improve the USP process based on literature.

3.1. Assembly line types

This section elaborates on the assembly line types described in the literature and the corresponding planning problems to provide a comprehensive picture.

Assembly lines are designed to produce products in a cost-efficient, flow-oriented manner. Tasks are performed in a standardized, serial way. Operators work on a workstation with specialized tasks performed repeatedly specific for that workstation (Ozbakir, Baykasoglu, Gorkemli, & Gorkemli, 2011). With this way of producing, standardized products can be made with high quality in mass production while minimizing costs.

Mass customization has been widely used since the 1980s, to make customized products at near mass production costs (Pine, 1993). The result of the shift from mass production to mass customization is that the number of variations on products that are offered to consumers has increased significantly in recent decades (Hu et al., 2011).

To cope with the product variety due to the shift from mass production to mass customization, more flexible and efficient assembly lines must be designed to produce different products (Ozbakir et al., 2011). In the literature, three types of assembly lines are distinguished, the single-model line, the multi-model line, and the mixed-model line (Becker & Scholl, 2006). Figure 3.1 shows the assembly line types schematically.

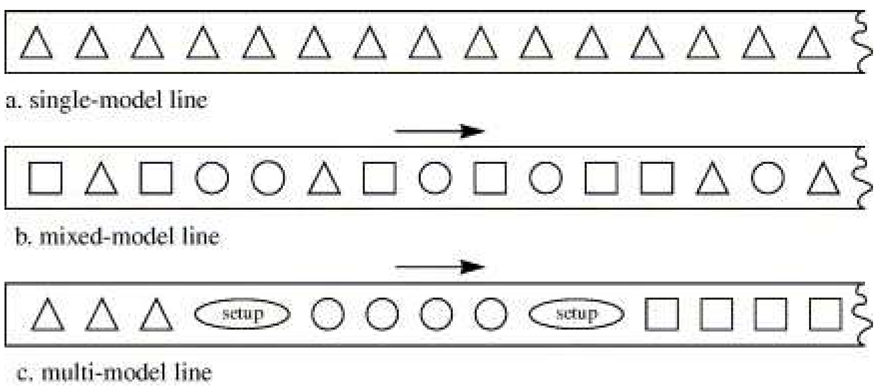


Figure 3.1 Schematic representation of assembly line types (Becker & Scholl, 2006)

When only one product can be assembled on an assembly line, all workpieces are identical and a single-model line is used (a). When multiple products can be assembled on an assembly line, without setup time between the different products, this is called a mixed-model line (b). Different products can be produced interchangeably on a mixed-model line. A multi-model line (c) can assemble multiple products on an assembly line, but it uses a setup time between the different products. Therefore, production is often done in batches.

SPZ uses a mixed-model assembly line to produce a wide range of customized trucks on the two assembly lines, enabling Scania to respond to customer demand. Therefore, the remainder of this chapter focuses on a mixed-model assembly line.

3.1.1. Assembly line planning problems

The challenge for the automotive industry is to produce the various models on a mixed-model assembly line, whereby production can produce in almost arbitrary order under rigid cycle time conditions. In the literature, five main planning problems are associated with mixed-model assembly lines in the automotive industry (Dörmer, Günther, & Gujjula, 2015; Golz, Gujjula, Günther, Rinderer, & Ziegler, 2012):

- Line balancing: Determining the configuration of the assembly line, such as the takt time, assigning tasks to the workstation, and making equipment available at the line.
- Master production scheduling: Assigning production orders of individual trucks to the short-term planning of several days.
- Production sequencing: Determining the sequence of production for each production interval.
- Re-sequencing: The rearrangement of the production sequence due to disruptions at the assembly line.
- Material flow control: Ensure that parts are delivered on time at the right place to the assembly line, this includes the process from the suppliers to the line.

This research is focused on the material flow control problem for a mixed-model assembly line since part-feeding is a sub-process of material flow control. Therefore, material flow control is discussed further in the remainder of the chapter.

3.2. Material flow control

This section elaborates more on the planning problem "Material flow control" and discusses different sequencing strategies and the assembly line feeding problem based on literature.

Part feeding is a sub-process of material flow control and is the supply of parts at the assembly line. The objective within part feeding is to ensure the efficiency of the logistics processes, to avoid line stops due to shortages of parts or overflow of part inventories at the assembly line (Golz et al., 2012).

Figure 3.2 shows the core process steps of a part feeding process (Boysen, Emde, Hoeck, & Kauderer, 2015). The process consists of two subprocesses: external logistics and in-house logistics.

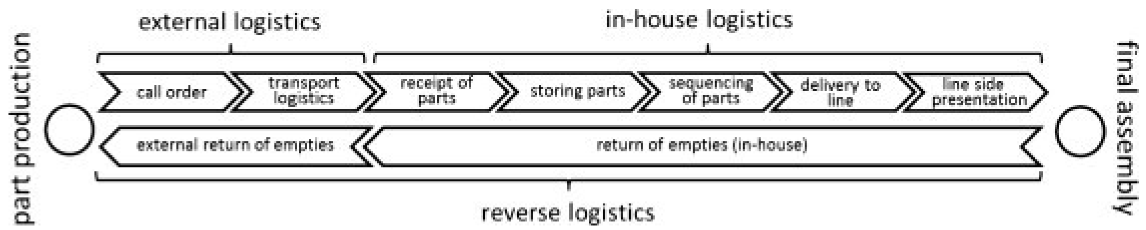


Figure 3.2 Schematic representation part feeding process (Boysen et al., 2015)

This research focuses on in-house logistics. In-house logistics contain all steps from receiving parts to delivering the parts in bins to the line. More specifically, this research focuses on the *sequencing of parts*, the *delivery to line,* and also partly the *return of empties*. Sequencing of parts is the sorting of parts according to production order, delivery to line involves transportation from the sequencing point to the assembly line. Return of empties includes the reverse logistics activities for the return of empty bins.

3.2.1. Sequencing strategies

The sequencing point is the point at which parts are sorted based on the production sequence (Boysen et al., 2015). From a logistics perspective, Boysen et al. (2015) state that there are three potential locations of the sequencing point: prior, during, or after the logistics process. This is shown schematically in Figure 3.3.

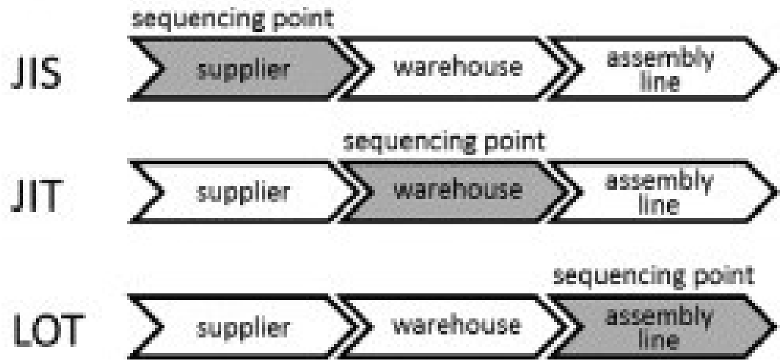


Figure 3.3 Different sequencing points for parts (Boysen et al., 2015)

With Just-In-Sequence (JIS), the sequencing point is located at the supplier, parts are brought to the assembly line without intermediate stock. This is beneficial for large-sized, valuable parts that show a high variety. When the sequencing point is located in the logistics process, for example at a warehouse, parts are delivered Just-In-Time (JIT). This is beneficial for medium-sized, medium-valued parts with medium variety. When the sequencing point is located at the assembly line, lot-wise part delivery is used. This is beneficial for small, low-valued parts with a relatively low variety.

This research focuses on the lot-wise supply of parts since the researched process has similarities with this sequencing method. Pallets are not sorted in production sequence and parts are stored lot-wise directly at the assembly line.

3.2.2. Assembly line feeding problem

The Assembly Line Feeding Problem is a tactical problem of assigning parts to different line feeding policies (Schmid & Limère, 2019). A line feeding policy characterizes how a part number is supplied to the assembly line. The literature distinguishes two line feeding policy groups, line stocking, and kitting (Baller, Hage, Fontaine, & Spinler, 2020). Both policy groups represent multiple line feeding policies.

With line stocking, parts are supplied at the assembly line in a carrier, the carrier content is the same as they are delivered from the supplier (Baller et al., 2020). The line stocking policy group contains four line feeding policies:

- Line side repacking: Parts are supplied at the assembly line without carriers such as racks and trailers, e.g. parts that are hung on a hook.
- Large Load Carrier (two-bin): Supply of bulky carriers in a two-bin system at the assembly line, e.g. pallets with parts.
- Large Load Carrier (one-bin): Supply of bulky carriers in a one-bin system, repacking is necessary to keep one-bin at the assembly line, e.g. pallets with parts.
- Small Load Carrier (FR): Supply of small carriers in a two-bin system, e.g. boxes with parts.

Kitting is applied when several parts are grouped and supplied in one package at the assembly line according to the production sequence (Baller et al., 2020). There kitting policy group contains five line feeding policies:

- JIS: Parts are grouped and brought directly to the assembly line, sequencing is done by the supplier.
- Sequencing: Parts are grouped and brought to the assembly line, sequencing is done by repacking from the supplier.
- Small stationary kit: Multiple parts are grouped, sequenced, and supplied in small boxes to the assembly line at a fixed workstation.
- Large stationary kit: Multiple parts are grouped, sequenced, and supplied in big carriers to the assembly line at a fixed workstation.
- Travelling kit: Parts are grouped, sequenced, and supplied to the assembly line, the kit travels with the end product, and parts are used at different workstations.

This research focuses on the Large Load Carrier two-bin and one-bin, which are part of the line stocking policy group.

3.3. Improving the distribution of pallets

This section positions the problem faced at SPZ *further and elaborates on similar problems in literature.*

In the automotive industry, a supermarket is a decentralized in-house logistics area for the temporary storage of parts before they are brought to the assembly line. Tugger trains are often used which supply the various consumption locations from the supermarket according to a periodical schedule (Battini, Boysen, & Emde, 2013). This concept creates a JIT supply of parts and flexible small-lot deliveries. The decision problems to be solved when implementing the supermarket concept are the following (Emde & Boysen, 2012):

- *Location planning:* Decision to take for the number of supermarkets to be installed on the shop-floor and their exact locations.
- *Routing problem:* Decision for the number of tugger trains to use and to form routes.
- *Scheduling problem:* Determining the point in time for each stopover on any tour along a route.
- *Loading problem:* Decision for the number and types of part bins to be loaded per tour

In literature, the concept of using supermarkets is a relatively new field of research (Zhou & Tan, 2020). This research focuses on the location planning and scheduling problem for pallet trailers. Routes of pallet trailers for transportation to decentralized locations will be taken into account. Routes of reach trucks will not be optimized since reach trucks drive based on their insights. For the tugger train process, the research focuses on the routing and scheduling problem. This chapter discusses this further.

3.3.1. Location planning pallet trailers

At SPZ, the locations of pallet trailers at decentralized locations in the production hall must be determined. This problem has some similarities with the location planning problem for the supermarket concept (Emde & Boysen, 2012). This section classifies this decision problem and looks for solution methods to solve this problem.

General facility location problems

Facility location problems (FLP) include the problems of where to physically locate a facility or multiple facilities, the objective is to minimize costs and meet a set of constraints considering customer demand (Hale & Moberg, 2003). Within FLP, a distinction can be made between continuous and discrete facility location problems. If facilities can be placed at any location, it is considered a continuous facility location problem (Ulukan & Demircioğlu, 2015). Discrete facility location problems are concerned with choosing the best location for facilities from a given set of potential places to locate the facility (Ulukan & Demircioğlu, 2015).

Daskin (2008) classifies discrete facility location problems into three broad areas, this is shown schematically in Figure 3.4. Covering-based models assume that demand is only covered when there can be served within a critical covering time or distance. Median-based models aim to minimize the demand-weighted average distance between a demand node and a facility. Furthermore, there is a category for other models.

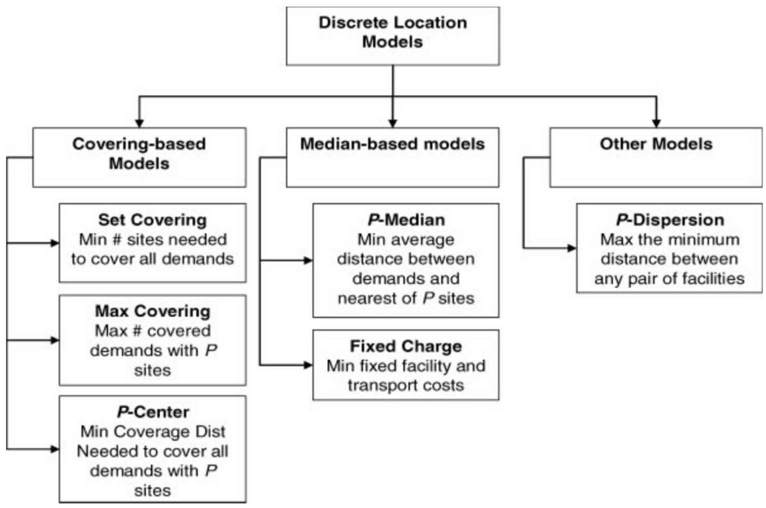


Figure 3.4 Classification of discrete facility location problems (Daskin, 2008)

These are all basic models where the underlying network is given, such as the demand nodes and paths. Also the locations of the demands to be served by the facilities and the locations of existing facilities, if any, are given. The general problem is to determine the location of new facilities by optimizing an objective. This could be distance or another measure that is more or less functionally related to distance, such as demand satisfaction or travel cost (Current, Daskin, & Schilling, 2002).

The p-median model is a classic model in this area, which optimizes the locations of p facilities to minimize the demand-weighted total distance between demand nodes and the locations to which they are allocated (Current et al., 2002). A variant of the p-median model is the capacitated p-median problem (CPMP). The CPMP optimizes the location of p facilities to serve a set of n demand nodes while observing the capacity limit of the facilities (Yaghini, Karimi, & Rahbar, 2013). Minimizing the total cost of servicing is the objective of this problem.

Location-routing models

Current et al. (2002) state that the basic models shown in Figure 3.4 assume that the demand is served directly from the facility. For many scenarios this is valid, however, many facilities use multiple-stop tours where multiple demand locations can be served in one trip (e.g. postal delivery). These problems are also referred to as location-routing problems (Current et al., 2002).

It is well established that modeling the distribution cost of a simple round trip from the facility to a customer is significantly misinterpreted when in reality multiple-stop tours are used (Current et al., 2002). This can result in the selection of sub-optimal facilities.

Stochastic models

A distinction can be made between deterministic and stochastic models. In the basic models shown in Figure 3.4, it is assumed that parameters (e.g., demand, facility cost, or travel time) of the problem are known with certainty (Current et al., 2002), this is called a deterministic model.

When the uncertainty of parameters is included in the model, it is called a stochastic model. Current et al. (2002) states that there are four basic approaches to stochastic facility location problems.

The first approach approximates the uncertainty through a deterministic surrogate. The second approaches uncertainty through chance-constrained models. The third approach explicitly takes into account queueing interactions that take place in a distributed queuing system with facilities at multiple locations in a network. The fourth approach uses scenario planning.

Network models
Within the FLP the underlying network is important for optimizing the facility location. The basic models shown in Figure 3.4 assume that the underlying network is given, while in practice it also occurs that the network is not given (Current et al., 2002). Costs are allocated for adding edges to the network. The total cost is optimized including the costs of adding edges and the cost for placing a facility. This is called a Facility Location-Network Design Problem.

Supermarket location problem
The supermarket location problem (SLP) is the real-world assembly line part feeding problem where supermarkets are used as decentralized intermediate storage areas to supply location at the assembly line (Nourmohammadi, Eskandari, Fathi, & Aghdasi, 2018). The SLP optimizes the number and location of supermarkets from a set of potential places and allocates the stations that should be fed with parts from each supermarket considering some assumptions such that the transportation, inventory, and installation costs of supermarkets are minimized (Nourmohammadi et al., 2018).

The supermarket location problem shows a lot of similarities with CPMP, but there are two differences. First, demand nodes served by a facility are consecutive in SLP. Second, unlike the CPMP, the number of facilities should be optimized and is not given. Therefore the number of supermarkets should be optimized and is not a fixed input parameter (Zhou & Tan, 2020).

3.4. Solution approaches

This section describes several solution approaches to solve FLP. We elaborate on the general solution methods and suitable solution approaches for the problem at SPZ.

Garey and Johnson (1979) state that even the most basic location models, discussed in Section 3.3.1 are classified as Non-deterministic Polynomial-time hardness (NP-hardness). The class NP contains the set of decision problems for which can be verified in polynomial time if a concise certificate is correct or not. A subset of NP is the class P which contains the set of decision problems that can be solved in polynomial time. The class NP-hard contains the most difficult optimization problems in NP. It is suspected that there do not exist algorithms that can solve the NP-hard problems in polynomial time. Solving an NP-hard problem optimally uses for larger instances quite often a large amount of computer memory and an unacceptable amount of time to solve the problem (Current et al., 2002).

The p-median optimization problem, which includes the CPMP, is proven to be NP-hard (Kariv & Hakimi, 1979). Noche and Alnahhal (2015) prove that the decision problem of the SLP is NP-complete, which means that the corresponding optimization problem is NP-hard. Therefore, both problems cannot be solved in polynomial time. Given the difficulty of the problems, exact algorithms are most probably not sufficient to solve this problem in a reasonable time.

3.4.1. General solution methods

Reese (2006) summarizes the literature on solution methods for the p-median problem, both capacitated and uncapacitated variations. Figure 3.5 shows an overview of the different solution methods used in combination with the reference to the source of the paper.

Approximation algorithms	[4] [20–23] [28] [70] [71] [76] [77] [82] [91] [127] [132]
Enumeration	[62] [88]
Graph theoretic	[15] [26] [51] [53] [73] [96] [124]
Heuristics	
Vertex substitution	[5] [36–38] [45] [60] [67] [101] [102] [103] [109] [110] [116] [126] [130] [131]
Other heuristics	[3] [10] [17] [30] [46] [69] [72] [75] [78] [87] [100] [117] [123] [129]
IP formulations and reductions	[6] [9] [11] [29] [44] [105] [114]
LP relaxation	[2] [7] [8] [12–14] [18] [19] [27] [30] [35] [42] [44] [47] [50] [52] [54] [58] [64] [74] [93] [97] [98]
Metaheuristics	
Variable neighborhood search	[32] [33] [49] [55] [65] [66]
Heuristic concentration	[111–113] [115]
Genetic algorithms	[1] [16] [24] [31] [40] [43] [48] [68] [81] [83] [86] [95]
GRASP metaheuristic	[104]
Scatter search	[56]
Tabu search	[59] [107] [113] [118] [128]
Simulated annealing	[25] [80] [106]
Neural network	[40] [89] [90]
Surrogate relaxation	[84] [85] [119–122]

Figure 3.5 Papers by type of solution method for the CPMP (Reese, 2006)

The figure shows that heuristics, LP relaxation, and metaheuristics are most commonly used to solve the p-median problems. The characteristics of these solution methods are shown below:

- Heuristics: A heuristic uses numerous tactics to quickly come to a solution. The performance of a heuristic depends on the tactics used and the optimization objective but often yields a local optimum. Vertex substitution replaces vertexes by approximating the optimal set and only remembers the solution when it is better.
- LP relaxation: With LP relaxation, the integrality constraint of each variable of the corresponding (mixed) integer linear programming (ILP) model is removed. An ILP problem is a program in which some or all variables are restricted to be integers. The corresponding (mixed) ILP model can be solved exactly but is quite often computationally expensive. In contrast, the LP relaxation can be solved in polynomial time. The solution of the LP relaxation can be used to obtain information about the solution of the original integer problem. A disadvantage is that most probably the solution found by the LP relaxation is not feasible due to the relaxation of constraints.
- Metaheuristics: Metaheuristics search for a global optimum. A metaheuristic needs a feasible solution to optimize further. The intention behind metaheuristics is to step out of local optima and search for global optima. This can be done by temporarily accepting worse solutions.

Current et al. (2002) also states that heuristics, LP relaxation techniques, and improvement heuristics, to which metaheuristics belong, are commonly used to solve the CPMP to (near)-optimal solutions. Due to the complexity of the CPMP and the SLP, it is not possible to find an optimal solution for a real-world problem within a reasonable time. LP relaxation often leads to a non-feasible solution and heuristics often yield a local optimum. Therefore, a metaheuristic suits better to the problem.

3.4.2. Suitable solution approaches

This section elaborates on the four most common metaheuristics used to solve the p-median problem (Mladenović, Brimberg, Hansen, & Moreno-Pérez, 2007; Reese, 2006). They include Genetic Algorithm, Variable Neighborhood Search, Tabu Search, and Simulated Annealing.

Genetic algorithm

A genetic algorithm (Holland, 1992) is a stochastic search technique that evolves a population of candidate solutions by applying operators based on natural selection and genetics to the current population. However, a genetic algorithm is mainly used to solve uncapacitated FLP (Basu, Sharma, & Ghosh, 2015). Basu et al. (2015) expect that this is because ensuring the feasibility of each candidate solution is not as straightforward for the capacitated variation as is the case for the uncapacitated variation.

Variable neighborhood search

Variable neighborhood search (Mladenović & Hansen, 1997) is a search technique that alternates a phase to find a local minimum using local search, with a phase to escape local minima. Discrete and continuous problems can be solved using variable neighborhood search.

Tabu search

Tabu search (Glover & Laguna, 1998) is a local search method that can escape from local optima by declaring previously visited solutions as taboo. In each iteration, the best neighbor solution replaces the current solution. The best neighbor solution can be either worse or better than the current solution. Tabu search is computationally efficient because the solution space being searched is only a small subset of all feasible solutions (Glover & Laguna, 1998).

Simulated annealing

Simulated annealing (Kirkpatrick, Gelatt, & Vecchi, 1983) is a probabilistic technique for approximating a global optimum. Simulated annealing (SA) is often used when the search space is discrete. The heuristic uses diversification at the beginning and intensifies more as the heuristic progresses. SA accepts not only better solutions but also worse neighbor solutions with a certain probability. This gives SA the ability to escape from the local minima (Qin, Ni, & Shi, 2012).

Performance metaheuristics

Considering the performance of the four metaheuristics, Mladenović et al. (2007) conclude that the neighborhood structure has the most important role for any metaheuristic for the p-median problem and it is not easy to conclude which metaheuristic dominates others. However, Arostegui Jr, Kadipasaoglu, and Khumawala (2006) compared genetic algorithm, tabu search, and SA under capacitated conditions for FLP and states that genetic algorithm performs poorly compared to tabu search and SA. Tabu search performs best under computational time limitations, while SA performs best under solution limitations (Arostegui Jr et al., 2006).

3.5. Conclusion

This section summarizes the chapter and draws conclusions based on the findings in the literature.

SPZ uses a mixed-model assembly line, which causes a lot of variability in the processes and requires a flexible part feeding process to deliver parts to the assembly line. The USP process uses a two-bin system to deliver pallets to the assembly line while keeping inventory at the assembly line as low as possible. The process has characteristics of both JIT and LOT delivery.

We define the pallet trailer location-allocation problem at SPZ as a Discrete Supermarket Location Problem with Stochastic Demands. Optimizing the number and location of pallet trailers given a set of potential places while taking into account the routing of reach trucks and stochastic demand, by allocating demand nodes to pallet trailers and minimizing the total cost of transportation and the installation costs of supermarkets. The problem shares characteristics with the CPMP and the SLP.

Since the problem is classified as NP-hard, it is not possible to find an optimal solution for a real-world problem within a reasonable time and therefore heuristics should be used. Since LP relaxation often leads to a non-feasible solution, a (meta)heuristic suits better to the problem. A heuristic can be used to construct a feasible solution and after which a metaheuristic could be used to improve the constructive solution.

Furthermore, there are three practical elements where the USP process deviates from the theory. First, at SPZ, the demand is delivered in cycles, which is not discussed in the literature. Second, pallet trailers (supermarkets) have no stock and contain already requested pallets. Finally, models in the literature make use of deterministic demand, where the demand is known in advance without stochasticity, this is not the case at SPZ.

4. Simulation-optimization model

This chapter describes the multi-objective simulation-optimization model that we use to optimize and analyze different scenarios. Section 4.1 explains why we focus specifically on the pallet trailer process within the USP process. Section 4.2 elaborates on the conceptual model with the model scope and model requirements. Section 4.3 describes the model using a toy problem, elaborates on the network of SPZ and input and output parameters. Section 4.4 elaborates on the modeling choices with simplifications and assumptions. Section 4.5 describes the algorithms used to find a solution. Section 4.6 elaborates on the verification and validation of the model. Finally, Section 4.7 concludes the chapter.

4.1. Introduction

In the current situation, pallets are requested by a pallet recorder in cycles according to a fixed schedule. The pallets are not immediately requested when they are empty. There is a delay because of the fixed, cyclic schedule. The potential for improving the productivity of the process lies in risk pooling the number of pallet requests per delivery zone by varying the size of delivery zones. Also, productivity can be increased by automatically requesting pallets when the pallet becomes empty.

Although SPZ uses the two-bin principle for the USP process, there are often more than two pallets at the assembly line. For the pallet trailer process, this is an average of 2.4 pallets per part number which needs 1168 m^2 of space. By shortening the lead time, the number of pallets at the assembly line can be reduced, and thus the surface needed in the factory.

Within the USP process, the pallet trailer process is the largest flow and supplies 80% of all pallets to the assembly line. The utilization rate for the pallet trailer process, without the external return flow of other processes, is 38%, which has great potential for improvement. By improving the location-allocation of pallet trailers, the utilization rate can be improved and thus the process becomes more productive. Given the large amount of potential in the pallet trailer process, this is the focus of this research. Recall from Section 3.5 that we defined the pallet trailer location-allocation problem at SPZ as a Discrete Supermarket Location Problem with Stochastic Demands.

4.2. Conceptual model

In this section, we describe the model scope, the model requirements, and the way the model contributes to the literature.

4.2.1. Model scope

The research aims to redesign the current method of the USP process, such that the productivity increases and the number of pallets per part number at the assembly line reduces, at the lowest possible cost. We focus specifically on the pallet trailer process, the largest flow within the USP process for delivering pallets to the assembly line. Since the process has many practical limitations, the most important ones that influence the goal must be included in the model. Also, the computation time must be reasonable. Therefore we have to determine the scope of the model.

The goal of our model is to allocate consumption locations and pallet trailer locations to delivery zones while taking into account the stochastic demand. Section 2.5.2 describes the pallet trailer process and how the demand per cycle is requested and delivered. The pallet demand of consumption locations differs per cycle. Therefore, the model must evaluate the stochastic demand per cycle. In contrast to the SLP (Nourmohammadi et al., 2018), we choose to determine demand at part number level instead of clustering demand per workstation. This leads to a more accurate solution and a higher level of detail that increases computation time.

The demand generated per cycle is requested by the pallet recorder. Recall from Section 2.5.2 that the imbalance of delivery zones leads to peaks at the KL, where pallets are picked for pallet trailers. To level the peaks in demand at the KL, the schedule is made such that a busy delivery zone is alternated with a less busy delivery zone. This makes the pallet recorder drive crisscross through the factory to request new pallets. In practice, the route of the pallet recorder determines the minimum cycle time that can be achieved. We investigated to include the route of a pallet recorder in the model, to determine a minimum cycle time based on the route the pallet recorder travels. We managed to find (near)-optimal shortest paths for the pallet recorder through the factory. In practice, the route of the pallet recorder depends on the order in which delivery zones are supplied since busy and less busy delivery zones are alternated with each other. Therefore we have left the route of the pallet recorder out of scope. This research provides insight into how the layout of delivery zones can be changed and what the influence is of changing different input parameters on the output parameters described in Section 4.3.5.

Recall from Section 1.5.2 that the external return flows of empty pallets, which are currently collected by the pallet trailer process, are not optimized and are used as an output control parameter.

4.2.2. Model requirements

In this section, we evaluate the requirements that the model must meet. The Discrete Supermarket Location Problem with Stochastic Demands from SPZ shows characteristics with the SLP and CPMP.

Recall from Section 4.1 that the model should be able to evaluate cyclic demand as the pallets are delivered in cycles to the pallet trailer locations. This requirement is essential for SPZ, as there is currently no alternative for recording pallets by a pallet recorder.

In Section 1.3.1, we conclude that the product mix at SPZ causes a lot of variation in the process. This is caused by the mixed-model assembly line. Since the variable pallet requests per cycle have a major impact on the process, it is important to evaluate the impact of stochastic demand on the process. Another constraint for consumption locations is that each consumption location must be assigned to a delivery zone.

Considering the problem at SPZ, a delivery zone can contain multiple pallet trailer locations. This is in contrast to the SLP (Zhou & Tan, 2020) and the CPMP (Yaghini et al., 2013), where only one supermarket or facility is used to supply from. An additional requirement is therefore that a delivery zone can contain multiple pallet trailer locations to supply from.

Nourmohammadi et al. (2018) suggest for the SLP to optimize the number and location of supermarkets from a set of potential places and allocating stations to be fed with parts from each supermarket. For SPZ, this means that not only pallet trailer locations in a delivery zone and the consumption locations are optimized, but also the number of delivery zones. However, since SPZ works with a fixed cyclic schedule, it is not practical to optimize the number of delivery zones. A better approach is to optimize the pallet trailer locations on a given number of delivery zones. After which the number of delivery zones is varied using scenario analysis.

Literature suggests minimizing the travel time, which suits the problem of SPZ. We choose to minimize the travel time per pallet. However, minimizing the travel time per pallet alone can lead to different sizes of delivery zones in terms of volume and replenishments. Due to the fixed cyclic schedule, this could cause peaks when filling the pallet trailers at the KL. As a result, schedules have to be created by alternating busy and less busy delivery zones to spread the peaks at the KL. We add a secondary objective to the model by balancing delivery zones. This will eliminate peaks at the KL. As a result, schedules can be arranged more flexibly and the pallet recorder does not have to drive crisscross through the factory to request pallets.

For the SLP, consumption locations must be consecutive at the supermarket (Zhou & Tan, 2020). Considering the problem at SPZ, this is not a hard constraint. Therefore, we relaxed the constraint where consumption locations are consecutive. However, since the model minimizes travel time, the solution will center the consumption locations around the pallet trailer locations.

In the model, distances from the pallet trailer to the consumption locations must represent reality. Therefore, distances and travel times must be calculated with an accurate method. Furthermore, pallet trailers are volume capacitated. If a pallet exceeds the capacity in a cycle, a rush order is placed for the pallet. To evaluate if the capacity of pallet trailers is exceeded, we must incorporate the pallet size with the corresponding volume of each pallet.

To summarize, our model should contain the following elements:

- Each consumption location must be allocated to one of the delivery zones.
- A delivery zone can contain multiple pallet trailer locations to supply from.
- Consumption location demand is stochastic.
- Consumption locations have different pallet sizes.
- Requested pallets are delivered to the pallet trailer locations in cycles.
- Pallet trailers are capacitated, a rush order is placed if a pallet exceeds the capacity in a cycle.
- Pallet trailer locations can be selected from a set of potential pallet trailer locations.
- Realistic distance and travel time calculations must be used.

- The objective of the model is to minimize travel time and, as secondary objective, balance delivery zones.

4.2.3. Contribution to literature

In the literature, various models can be found for finding optimal locations of facilities and the optimal allocation of demand nodes to these facilities. In contrast to the research that has been done in the literature for minimizing travel times of facility location problems, to lesser extent research has been done into balancing the allocation of customers. What makes our research unique is that we minimize travel time as well as balancing the demand-weighted clusters in combination with stochastic demand. In addition, we use simulation techniques to estimate the objective value of a solution by evaluating the impact of stochastic demand while using a high level of detail.

4.3. Model description

A multi-objective simulation-based optimization model is developed to solve the Discrete Supermarket Location Problem with Stochastic Demands at SPZ. This section describes the model with a toy problem, elaborates on the network of SPZ, and describes the input and output parameters of the model.

4.3.1. Toy problem

This section elaborates on the difficulties of modeling the problem characteristics and presents the general solution approach with a toy problem.

Problem characteristics

First, we have to determine how many delivery zones we want to divide the factory into. A delivery zone refers to the area containing one or multiple pallet trailer locations from which consumption locations are supplied. Given the number of delivery zones, we must determine how many pallet trailer locations are needed in a delivery zone. The number of pallet trailer locations in a delivery zone corresponds to the number of supplies per cycle in a delivery zone. Furthermore, the number of cycles in a day affects the cycle time. When the number of daily cycles increases, the cycle time decreases. The number of delivery zones together with the number of pallet trailer locations and the cycle time together determine the capacity of the process. One influences the other. Due to the busyness and lack of space in the factory, pallet trailers cannot be located at every location within the factory. The potential locations of pallet trailers have been mapped together with the line engineers of SPZ. Section 5.1 elaborates more on this.

To solve the Discrete Supermarket Location Problem with Stochastic Demands at SPZ, we allocate consumption locations and pallet trailers to delivery zones while taking into account the stochastic demand. We primarily minimize the travel time per pallet and, as secondary objective, we try to balance the delivery zones based on their volume per cycle.

Our problem considers the assignment of 620 consumption locations and at most 27 pallet trailer locations to at most nine delivery zones, where the set of potential places for pallet trailer locations contains at most 60 locations. This results in a large solution space and thus large computation times. As stated in Section 3.5, we use a metaheuristic to solve the problem as suggested by the literature. We choose for SA since it is widely used in FLP (Mladenović et al., 2007; Reese, 2006) and has a good performance under capacitated restrictions (Arostegui Jr et al., 2006). Section 4.5.2 elaborates more on SA.

General solution approach

We explain the general solution approach based on a toy problem. Figure 4.1 shows an initial solution to the toy problem. The intersections are indicated with hexagons, the pallet trailer locations with squares, and the consumption locations are indicated with circles. The color indicates a delivery zone.

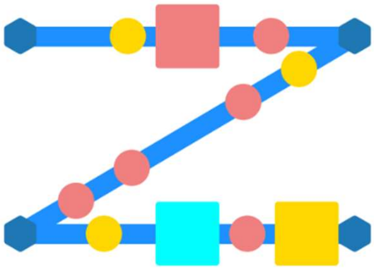


Figure 4.1 Initial solution toy problem

KPI	Value	Metric
Travel time per pallet	29.5	seconds
Balancing ratio	1.7	times
Service level	100	percent

Table 4.1 Output values objective function initial solution

The toy problem consists of eight consumption locations and three potential pallet trailer locations, which must be divided into two delivery zones with one pallet trailer location per delivery zone. Figure 4.1 shows that three consumption locations are added to the gold-colored pallet trailer location and five consumption locations to the light coral-colored pallet trailer location. The cyan-colored pallet trailer location does not belong to a delivery zone and is a potential pallet trailer location. A potential location refers to a location in the factory where space can be created for pallet trailers, but where currently no pallet trailers are placed. In the toy problem, the demand per consumption location is equal. In the problem for SPZ, the demand differs per consumption location. In the case of SPZ's problem, it is also possible to supply from multiple pallet trailers locations in a delivery zone to the consumption locations.

Table 4.1 shows the output values of the objective function for the initial solution. We minimize the travel time per pallet. As secondary objective, we balance the volume per delivery zone. In the literature, the difference between the maximum and minimum of a parameter is often minimized to balance a parameter. Instead of the difference between the maximum and minimum, we minimize the ratio between the maximum and minimum volume of delivery zones to be able to compare scenarios with different volumes per delivery zone with each other. The balancing ratio specifies the extent to which delivery zones are divided equally based on volume. A balancing ratio of 1.7 corresponds to the largest delivery zone being 1.7 times larger, in terms of volume, than the smallest delivery zone. Equation 4.1 shows the formula of the balancing ratio.

$$Balancing\ ratio = \frac{\max\limits_{1 \leq j \leq k} n_j}{\min\limits_{1 \leq j' \leq k} n_{j'}} \tag{4.1}$$

$\boldsymbol{k}$ = number of delivery zones
$\boldsymbol{n}$ = delivery zone volume

The service level is the ratio of pallet deliveries without rush orders to the total number of pallet deliveries. We define a rush order as a pallet that no longer fits in a pallet trailer in a cycle because it is full. We use a penalty function for the service level in the objective function, based on the violation of the service level to the specified service level. This allows us to temporarily accept solutions with a service level lower than the specified service level. For the simplicity of the toy problem, we use a low demand such that there are no rush orders, resulting in a service level of 100%.

The initial solution serves as input for SA, with which we search for better solutions in the neighborhood with swap and move operators. With these operators, we can examine the entire solution space, which makes it possible to find an optimal global solution. The swap operator swaps two pallet trailer locations or consumption locations from different delivery zones. The move operator moves a consumption location from a delivery zone to another. We do not use moves for pallet trailer locations since the number of pallet trailer locations needed is predetermined. With a move, a feasibility check is performed to see if the move is possible and the number of delivery zones is not exceeded. Appendix D elaborates more on the neighborhood structure.

By using the neighborhood operators described above, we search for a better solution. If the objective value of the neighbor solution is lower than the objective value of the current solution, we accept the solution. Otherwise, we accept it with a certain probability. Section 4.5.2 elaborates more on SA.

Figure 4.2 shows the final solution of the toy problem after SA is performed. The figure shows that the delivery zones are clustered and that the potential pallet trailer location is assigned to a delivery zone, replacing the initial pallet trailer location. Figure 4.2 shows the output values of the objective function for the final solution. The table shows that the travel time per pallet is optimized from 29.5 to 13.6 seconds. The balancing ratio is also optimized from 1.7 to 1.0, which means that the zones are perfectly balanced. The service level remains 100%, making the solution feasible.

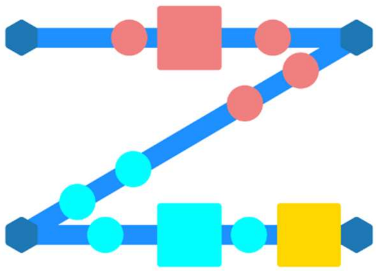


Figure 4.2 Final solution toy problem

KPI	Value	Metric
Travel time per pallet	13.6	seconds
Balancing ratio	1.0	times
Service level	100	percent

Table 4.2 Output values objective function final solution

We use a simulation technique by generating demand per cycle to estimate the objective function value. This allows us to evaluate the robustness of the solution found based on the objective function parameters and other output parameters. Section 4.5.3 elaborates more on the objective function parameters and the way we use simulation techniques.

4.3.2. Network of SPZ

In this section, we describe the network of SPZ on which the pallet trailers and reach trucks drive their routes. The network of SPZ is modeled as a graph. A graph G consists of a vertex set $V(G)$ and an edge set $E(G)$ (West, 2001). The graph G of SPZ is modelled as an undirected weighted graph, which means that each edge is bidirectional and each edge has a numerical weight as explained further in this section.

The vertex set consists of the different intersections in the factory and the edge set consists of the roadways between each vertex. All vertices have unique Cartesian coordinates. These coordinates correspond to the actual distance in millimeters according to the map. Traffic rules apply within the site of SPZ. A traffic rule that is important for road safety is the permitted speed on the site. Outside the factory, a maximum speed is allowed of 15 km/h and within the factory, a maximum speed of 8 km/h is allowed. In consultation with experts within SPZ, an estimate has been made of traffic areas where traffic conditions, crossing parts, or other matters prevent the maximum permitted speed from being driven. The estimated speed in the network has been adjusted to this. Figure 4.3 shows the network of SPZ plotted on a scaled map of SPZ. The color of an edge represents the expected average speed driven on that edge.

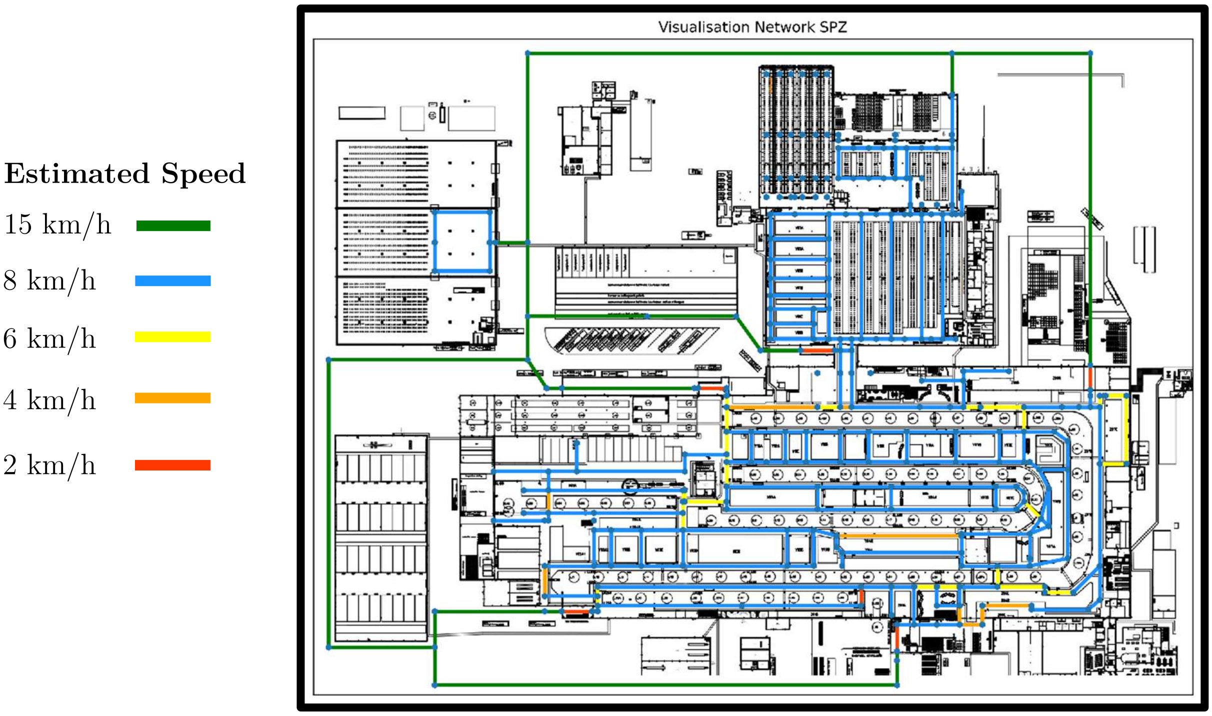


Figure 4.3 Visualization network SPZ with an estimated speed

The modeled graph is edge-weighted (G, w) where G is the graph and $w: E(G) \rightarrow \mathbb{R}$ is a weight function. To accurately estimate both distances and travel time, we define the distance weight function and the travel time weight function. The distance weight function of an edge is modeled as the Euclidean distance between adjacent vertices. Let vertex x have coordinates (x_1, x_2) and adjacent vertex y have coordinates (y_1, y_2), then the distance weight function $d(x, y)$ is given by:

$$d(x,y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2} \qquad 4.2$$

The travel time weight function of an edge is modeled as the distance weight function $d(x, y)$ divided by the estimated travel speed on the edge $v(x, y)$. Then the travel time weight function $TT(x, y)$ is given by:

$$TT(x,y) = \frac{d(x,y)}{v(x,y)} \qquad 4.3$$

Road curves are created by connecting adjacent vertices in the form of the road curve. The graph is the basis of the model and is used to accurately determine routes and travel times from vertex A to vertex B. This is further described in Section 4.3.3.

Now that the network is created, we add the pallet trailer locations and the consumption locations to drive to and from. We model the pallet trailer locations and consumption locations as vertices and add them to the graph. Appendix A.1 contains a flowchart with a description of how the vertices are schematically added to the graph.

4.3.3. Dijkstra's algorithm

Dijkstra's algorithm is designed to determine the shortest paths between the source vertex and every other vertex in the network (Taha, 2013). Dijkstra's algorithm is based on the principle that when vertex R is part of the shortest path from vertex P to vertex Q, knowledge of the latter implies knowledge of the shortest path from vertex P to vertex R.

Appendix A.2 contains a flowchart with a description of how the Dijkstra algorithm is used to calculate the shortest path from a vertex to all other vertices in the graph. We repeat the Dijkstra algorithm for each vertex in the graph to determine the shortest distance and shortest travel time to every other vertex in the graph. These shortest distances and shortest travel times are then used to create a distance matrix and travel time matrix.

4.3.4. Input of the model

This section describes the input parameters of the simulation optimization model.

Network SPZ: The network of SPZ is based on a map with the traffic intersections that come from Lay-CAD, the technical drawing program of SPZ. The edges have been added between the intersections, with each edge given a driving speed and distance. Based on this network, distances and travel times are calculated as described in Section 4.3.3. A drawing showing the plotted network is used to represent solutions.

Information consumption locations: The information of the consumption locations consists of information per part number which is loaded into the model. Each part number contains the consumption frequency, the current delivery zone, a line location with a Cartesian x- and y-coordinate, and the packing type with the corresponding volume and surface of the pallet.

Information pallet trailers: The information of the pallet trailers consists of information about existing pallet trailer locations and alternative pallet trailer locations. Each pallet trailer location has been given a Cartesian x- and y- coordinate and a location classification as will be described in Section 5.1.2. Pallet trailers that are currently in use have been given a delivery zone corresponding to the consumption locations they supply.

Volume external return flows: The total volume of the external packaging of sequencing and kitting is modeled per delivery zone and serves as input for determining the utilization rate and the service level of the return flow, including external packaging.

Other task times: Times for standardized tasks in the process are based on motion time studies performed by SPZ and verified by the corresponding supervisor and team leaders. This applies to tasks such as unloading, loading, sorting, and replacing a pallet, loosening the straps of a pallet trailer, and connecting and disconnecting a new pallet trailer.

4.3.5. Output of the model

This section describes the output parameters of the simulation optimization model. The number of FTE, utilization rate, and surface pallets at the line are calculated using post-processing.

Travel time per pallet: The travel time per pallet indicates how much travel time on average is required per pallet for the delivery and return of empties without the external return flow. This includes the travel time from the pallet trailer to the pallets and back. The lower this number, the shorter the travel time for the reach truck drivers to the pallets. This performance indicator therefore also influences the number of reach truck drivers required.

Distance consumption location to pallet trailer: The average demand-weighted distance from a consumption location directly to the pallet trailer. The lower this number, the closer the consumption locations are to the pallet trailers.

FTE: The number of FTE is an important performance indicator as it indicates the number of FTE required per shift to deliver the pallets from the KL to the pallet trailer locations and the consumption locations. We made a distinction between reach truck FTEs required and pallet trailer driver FTE required.

Service level: The service level indicates the fraction of the number of pallets that can be transported directly with a pallet trailer. We made a distinction between the service level of the supplies and the service level including the return flow of sequencing and kitting. For the service level of the supplies, a pallet that does not fit on the pallet trailer can lead to a rush order and is, therefore, an important parameter.

Utilization rate: The utilization rate indicates the average fill level of the pallet trailers. The utilization rate is an important performance indicator for determining the productivity of the pallet trailer process.

Balancing ratio: The balancing ratio is a performance indicator that indicates to what extent delivery zones are divided equally based on volume. The balancing ratio is calculated by the ratio between the maximum and minimum volume of delivery zones.

Surface pallets at line: The surface that is required to be able to put all pallets at the assembly line. The surface is based on the number of pallets required at the assembly line per part number. By converting the number of pallets to the total surface needed, we can determine to what extent space can be saved in the factory. The lower this number is, the fewer pallets are needed at the assembly line so that more part numbers can be used with the USP process in the coming years.

4.4. Modeling choices

In this section simplifications and assumptions are discussed.

4.4.1. Simplifications

This section elaborates on the simplifications used in the model.

Reach truck routing

The model assumes that reach truck drivers can take a maximum of one pallet during their route from the pallet trailer location to the consumption locations, while in the real world a reach truck driver can take several pallets at the same time. We choose to make this assumption rather than implementing a routing algorithm, for taking multiple pallets in a route, as reach truck drivers also have other tasks such as collecting external packaging or preparing parts from external processes. Since reach truck drivers do these tasks at the same time as supplying pallets, adding a routing algorithm for reach trucks does not lead to a better representation of reality.

Travel time correction

The reach truck routing assumption affects the travel time needed to supply the pallets. In reality, the travel time is shorter than in the model as multiple pallets are transported at the same time with reach trucks. To ensure that the travel time does not take up a larger part of the tasks of a reach truck driver then in reality, a correction factor is added for the travel time. According to the motion studies of SPZ the travel time is in the current situation around 38% of the total time, reach truck drivers need to deliver pallets to their consumption locations. In the model, a travel time correction factor is added such that the travel time is 38% of the total time to deliver pallets for reach truck drivers in the current situation.

Reach truck FTE pooling

In the current situation, each delivery zone has a fixed reach truck driver, who is responsible for the supply of pallets and empty pallets within the USP flow, collecting external packaging, and preparing parts from external processes. Some delivery zones are supported by an additional reach truck driver. Since there is no accurate data on collecting external packaging and preparing parts, and this is outside the scope of the project, we do not use hard bounds for the supply of pallets in delivery zones and pool the number of reach truck drivers such that a reach truck driver can deliver pallets in multiple delivery zones. As a result, the number of reach truck FTEs represents the number of FTEs required to handle the pooled workload of the supply and return of pallets within the USP flow.

External return flows

For the pallets of the external return flows that return with the pallet trailer process, it is not exactly known on which line location the pallets are located. However, it is known how much volume the pallets of the external flows take up in a delivery zone. We assume that the pallets of the external return flows are evenly distributed over the delivery zone.

Part demand

We assume that the demand of a part number follows the Poisson distribution and is independent. After statistical tests, we found out that some part numbers follow the Poisson distribution while others do not. We choose to use the Poisson distribution for sake of simplicity and its ability to generate non-negative integer values only.

4.4.2. Assumptions

This section sums the assumptions used in the model.

- There is no acceleration time for reach truck drivers.
- Per pallet trailer, we assume that 5 m^3 of the 6 m^3 is effectively available for filling with pallets. This is 10 m^3 effectively available for a set of pallet trailers.
- When there are x pallet trailer locations in a delivery zone, there is capacity for x sets of pallet trailers per cycle.
- A rush order is placed for a pallet if the pallet exceeds the capacity in a cycle.
- When a pallet cannot be transported on the pallet trailer, a rush order is placed for this pallet. The pallet will not be postponed.

- Pallets can always be stacked on pallet trailers until a pallet no longer fits on the pallet trailer. In reality, around 5% may not be stacked.
- The demand for consumption locations is based on the number of pallet requests from February 22, 2021, to April 16, 2021. Based on this data, new part demand is generated based on the Poisson distribution.
- The handling time of the return process is equal to the handling time of the deliveries, excluding the external packaging.

4.5. Algorithm explanation

In this section, we present the algorithms used to solve and experiment with the problem at SPZ. We introduce a constructive algorithm to find an initial solution and a metaheuristic to optimize the initial solution. Also, we elaborate on the objective function.

4.5.1. Constructive algorithm

To solve the Discrete Supermarket Location Problem with Stochastic Demands, an initial solution must first be found. An initial solution consists of the pallet trailer locations per delivery zone and the consumption locations allocated to the delivery zones. For the initial solution, we aim to minimize the distance from the consumption locations to the pallet trailer locations. We do not consider balancing delivery zones and achieving the required service level.

In literature, a well-known algorithm for finding an initial solution for a more computationally expensive metaheuristic is the k-means algorithm (Bottou & Bengio, 1995). This algorithm is especially suitable for FLP, because of the ability to cluster data points. The k-means algorithm aims to divide n data points into k clusters while minimizing the distance, where each data point belongs to the cluster with the nearest mean based on the Euclidean distance.

However, the k-means algorithm does not suit the problem at SPZ since the center of a cluster cannot be anywhere in the factory but is bound to discrete locations, the potential pallet trailer locations. In addition, the Euclidean distance does not represent the distances for the problem at SPZ. Therefore, we propose to find an initial solution using a k-medoids algorithm (Kaufman & Rousseeuw, 1990). k-medoids is a partitioning technique that creates k clusters of n data points and designates for every cluster a data point as the center of that cluster (which is called a cluster medoid). k-medoids tries to minimize the distance from each data point to a cluster medoid until the stopping criterion is met. A k-medoids algorithm suits the problem at SPZ better than a k-means algorithm because of its ability to designate a discrete data point as a medoid and the ability to use a distance matrix as input. Also, k-medoids is less sensitive to outliers and reduces noise compared to k-means (Arora & Varshney, 2016).

To apply k-medoids to the problem at SPZ, the n consumption locations must be divided over k delivery zones. Since the problem at SPZ can have multiple pallet trailer locations per delivery zone, we extend k-medoids by designating for every delivery zone m pallet trailer locations as medoids. We use the PAM algorithm to solve the problem (Kaufman & Rousseeuw, 1990). The PAM algorithm searches for k medoids in the data set and assigns each data point n to the closest medoid to create clusters. The aim of the algorithm is to minimize the distance of the data points to the medoids. We modify the PAM algorithm such that only pallet trailer locations can be chosen as medoid. The travel time matrix resulting from the Dijkstra algorithm is used to determine distances with the PAM algorithm. Appendix A.3 presents the flowchart of the PAM algorithm.

4.5.2. Simulated annealing

We use the initial solution generated by the *k*-medoids algorithm as input for our metaheuristic Simulated Annealing (SA). SA searches for a global optimum by using diversification at the beginning of the heuristic and uses intensification at the end of the heuristic. Figure 4.4 shows a flowchart of the SA metaheuristic.

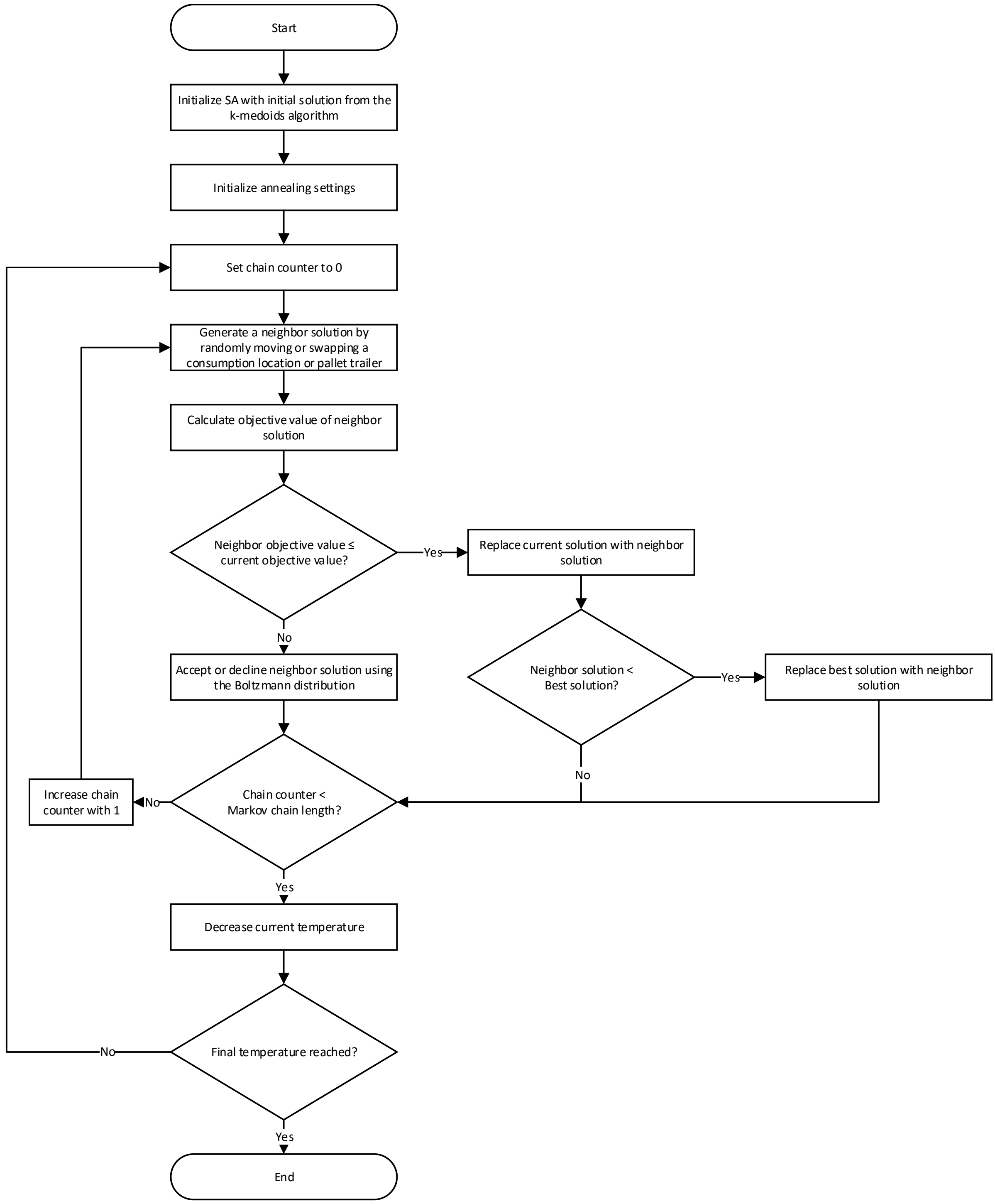


Figure 4.4 Flowchart of the Simulated Annealing metaheuristic

At each step in the heuristic, a neighbor solution is created by using an operator. Recall from Section 4.3.1 that we use the move and swap operator. With these operators, we can examine the entire solution space, which makes it possible to find a (near-) global optimum. Appendix D provides more information about the neighborhood operators.

Any neighbor solution that has a better objective value than the current solution is accepted, making the neighbor solution the current solution. When the objective value of the neighbor solution is also better than the best solution, it becomes the best solution. When a neighbor solution is worse than the current solution, it is accepted with a certain probability. SA uses the acceptance probability according to the Boltzmann distribution to accept a neighbor solution that is worse than the current solution. Equation 4.4 shows this formula.

$$P_{AB}(c) = \begin{Bmatrix} 1 & if\ B < A \\ e^{\frac{A-B}{c}} & else \end{Bmatrix} \qquad 4.4$$

In the formula, A is the current objective value, B the neighbor objective value, and c the current temperature. The smaller the difference between the objective values A and B, the greater the chance that the worse neighbor solution will be accepted. As the temperature of c decreases during the process, the chance of accepting a worse neighbor solution also decreases. SA stops when the final temperature is reached. The acceptance ratio is the ratio of neighbor solutions that are accepted with a certain temperature.

To apply both diversification and intensification during the process, a cooling scheme must be created. The starting temperature determines to what extent diversification is applied and the final temperature determines to what extent intensification is applied. SA works best with an initial acceptance ratio of about 1 and ends with an acceptance ratio of about 0. At the start of the metaheuristic, almost all worse solutions are accepted, while at the end only better solutions are accepted. The Markov chain length determines to what extent exploration is performed per temperature. The decrease factor is used to balance all of this, taking into account the solution time.

Considering our problem, we search for a cooling schedule that runs within acceptable computation time and uses enough diversification and intensification to find a (near)-optimal solution. Figure 4.5 shows the acceptance ratio against the temperature considering our problem.

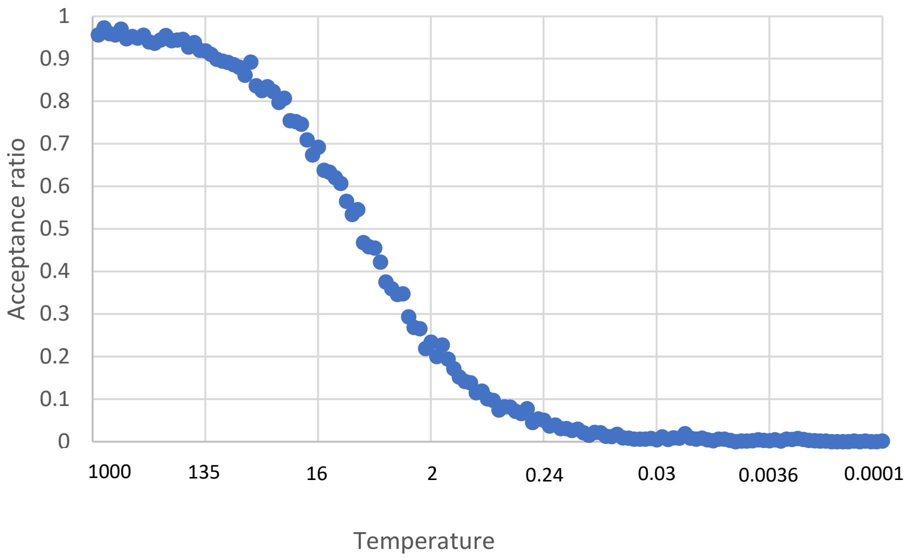


Figure 4.5 Acceptance ratio SA metaheuristic

We determine the start and end temperature based on the acceptance ratio, while we determine the Markov chain length and the decrease factor based on the trade-off between the solution quality and the solution time. Therefore, we find an appropriate cooling scheme for our problem with a starting temperature of 1000, a final temperature of 0.0001, a Markov chain length of 1000, and a decrease factor of 0.9.

4.5.3. Multi-objective function

The multi-objective function consists of two optimization variables and one penalty function, the travel time per pallet, the balancing ratio, and the service level, respectively.

Travel time per pallet: The travel time per pallet indicates how much travel time on average is required per pallet for the delivery of the pallets. The lower this number, the shorter the travel time for the reach truck drivers to the pallets.

Balancing ratio: The balancing ratio indicates to what extent delivery zones are divided equally based on volume. The balancing ratio is calculated by the ratio between the maximum and minimum volume of delivery zones.

Service level: The service level indicates the fraction of the number of pallets that can be transported directly with a pallet trailer. A pallet that does not fit on the pallet trailer can lead to a rush order. Therefore, the service level is an important parameter.

We use the weighted sum method to combine the multi-objective functions into one scalar, composite objective function. Section 5.2.1 elaborates on the weighted sum method and how we scale the different objectives.

In the objective function of SA, we use a simulation technique by generating demand for every cycle in a day. The demand is generated for every consumption location using a Poisson distribution. This allows us to estimate the service level based on the demand of what fits in a pallet trailer and what does not. The simulation technique also estimates the travel time per pallet and the balancing ratio. Section 5.2.2 elaborates on the simulation length and number of replications of the simulation. Furthermore, we use the simulation technique to determine the other output parameters from Section 4.3.5 and can evaluate the influence of stochastic demand.

4.6. Verification and validation

This section describes the validation and verification of the simulation optimization model.

4.6.1. Verification

Verification is the process to verify whether the conceptual model has been properly converted to the model. We verify the model to see if the algorithm and simulation work properly. One of the ways to verify the model is to use debugging. In Python, it is possible to debug the code by placing breakpoints. We check whether a variable takes the value which it should take.

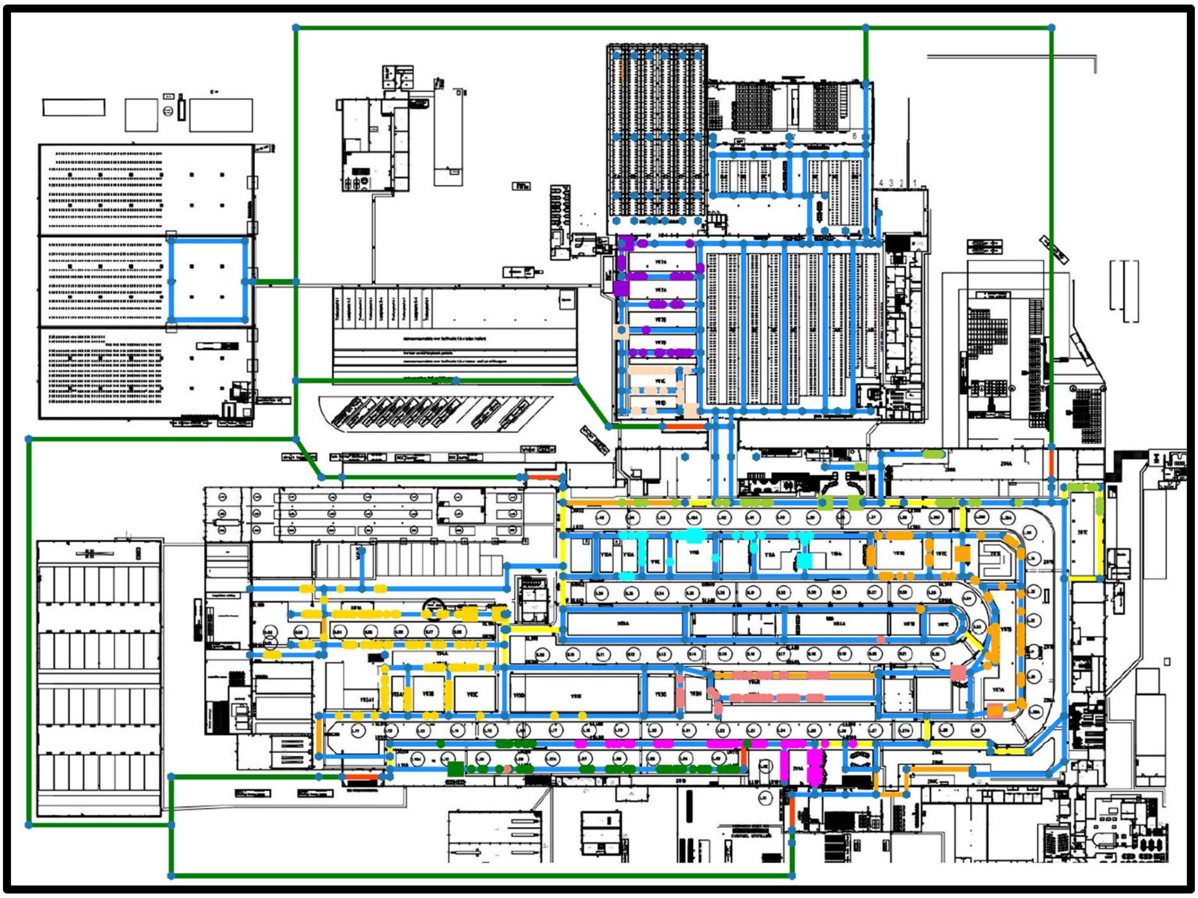
In addition to debugging, we built in some functions that check whether certain functions are working properly. For example, a function is built that checks if overlapping edges are present before forming routes. When overlapping edges are present in the model, route calculation will be inaccurate. Another example is that a message is displayed when certain consumption locations have not been added to the model due to missing x- or y-coordinates.

Another verification technique is to visualize the output. In the model, routes can be verified by visually plotting them on the SPZ network. Each delivery zone is also indicated with a different color, which makes it quickly clear how large a delivery zone is and which pallet trailer belongs to this delivery zone. When there is an error in the model, it is quickly identified.

4.6.2. Validation

We use two ways to validate the model. First, we use the chi-square goodness-of-fit test to validate the number of pallets that the model generates with the number of pallets that are generated on a production day, per delivery zone (Law, 2015). For discrete data, Law (2015) recommends using the equiprobable approach in which intervals are chosen such that the bin size is approximately equal for the real world. The bin size must be a minimum of five observations for the real-world system per interval. When the p-value of the chi-square goodness-of-fit test is greater than 0.05, we can assume that the number of pallets generated per delivery zone is equal to the number of pallets per zone in the real world. The p-values of all pallet trailer zones are greater than 0.05. The results of the chi-square goodness-of-fit test can be found in Appendix C.

Second, we validate our model by checking the visualization of the output and compare the output parameters with reality. Figure 4.6 shows the visualization of the current situation.



1A	1B	1C	2A	2B	2C	3A	3B	3C

Figure 4.6 Visualization of the current situation

We see that there are nine delivery zones, with each delivery zone having a different color. Below the visualization, we reference the delivery zone color to the pallet trailer supply cycle (A, B, C) as mentioned in Section 2.5.2. Pallet trailer locations are presented with squares and the consumption locations with circles. We validated the visualization of the model with representatives within SPZ.

In contrast to the key figures in Section 2.7, we use data from February 22, 2021 to April 16, 2021 in which the production rate increased by 31%. Using the simulation results, we find that, in terms of volume, delivery zone 1A is the smallest delivery zone and delivery zone 2B is the largest. This is consistent with the results from Section 2.7.1. The utilization rate has increased to an average of 51%. The model indicates that in the current situation a service level of 99.2% is achieved on average. Due to the postponement of pallets, explained in Section 1.5.4, team leaders indicate that in practice no urgent orders are brought from the KL to the production hall.

Team leaders indicate that the delivery zones whose service level (including the external return flows) in the model is below 75%, are supported by extra trips (3A, 2A, 2B). Delivery zone 1A has a service level (including the external return flows) of 85% and needs regularly an extra urgent trip. Delivery zone 1C also has a service level of 85%. However, team leaders indicate that in practice no urgent trips are required for this delivery zone. We explain this because the pallet trailers of delivery zone 1B are nearby and that empty pallets that cannot be loaded on the pallet trailers in delivery zone 1C, can also be loaded on the pallet trailers in delivery zone 1B. We consider strict delivery zones bounds for the return flow, where these bounds for the return flow are not as hard in reality as in the model.

The model uses the handling time per pallet to determine the number of reach truck FTE per shift. The handling time per pallet of a reach truck driver consists of the travel time, loading time, unloading time, sorting time, replacing time, and loosening straps. The travel time is variable and the other tasks are fixed per pallet. To determine the number of pallet trailer FTE, we use a trip length of 12.5 minutes to drive from the KL to a delivery zone once, independent of the delivery zone. This time is viable for all delivery zones and is currently used by SPZ.

In the model, the current situation requires an average of 6.4 reach truck FTE per shift to supply the pallets and return the empty pallets at the pallet trailer. This is without other activities such as preparing parts for the assembly line and the external return flows. In reality, it is estimated that this part of the process requires 8 FTE per shift, which corresponds to a workforce utilization rate of 80%. The difference is explained by the fact that the model calculates the average number of FTE required, peaks in demand are not included. Recall from Section 4.2.1 that the goal of the model is to allocate consumption locations and pallet trailers locations to delivery zones while taking into account the stochastic demand. We use post-processing to estimate the number of FTE required. By evaluating different scenarios, the average number of FTE required can be projected on the current situation.

According to the model, the current situation requires 1256 m² of surface for the pallet trailer process. Section 2.7.3 shows that 1168 m² of surface is used in the current situation. The difference can be explained by the fact that the production rate has increased. Furthermore, the input and output of the model have been validated by representatives within SPZ.

4.7. Conclusion

This section summarizes the chapter that describes the simulation-optimization model.

We created a simulation-optimization model to allocate consumption locations and pallet trailers to delivery zones while taking into account stochastic demand. Our objective is to minimize travel time, as well as balancing the volume per delivery zone, maintaining a required service level. In addition, we use simulation techniques to estimate the objective value of a solution by evaluating the impact of stochastic demand while using a high level of detail. Section 4.2 describes the conceptual model with the model scope and requirements in more detail.

Section 4.3 introduces the problem and the problem approach based on a toy problem. We manage to calculate realistic distances and travel times based on the layout of SPZ using Dijkstra's algorithm. This is, in particular, useful for SPZ since the basis of the model with distances and travel times from and to locations can be used to solve other logistics-related problems as well. These can be problems such as the shortest path problem of the pallet recorder and the routing of vehicles throughout the factory, but also other FLP. Furthermore, we define the input and output parameters of the model in Section 4.3. Section 4.4 describes the simplifications and assumptions.

We find an initial solution to the problem by using the k-medoids algorithm that tries to minimize the travel time from each consumption location to the pallet trailer locations on the delivery zones. Our problem is classified as an NP-hard problem and has a large neighborhood due to the high level of detail. Therefore, we use the metaheuristic Simulated Annealing to optimize our problem further. By using the swap and move neighborhood operators, we search for better solutions. Finally, we verify and validate our model in Section 4.6.

5. Experimental results

This chapter presents the different scenarios and their outcomes, which we optimize with the simulation-optimization model. Section 5.1 introduces the scenarios. Section 5.2 elaborates on the experimental design. Section 5.3 presents the solutions for the different scenarios. Section 5.4 describes the results of the sensitivity analysis. Finally, Section 5.5 presents the conclusions of this chapter.

5.1. Introduction of scenarios

In this section, we introduce the different scenarios. We distinguish different scenarios by the input parameters that the model uses and the way of solving the model. The input parameters that are evaluated among the different scenarios are the number of delivery zones, the number of daily cycles, and the number of pallet trailer locations in a delivery zone.

Together with the line engineers, the engineers who maintain the layout at the assembly line, we have mapped out potential locations for placing pallet trailers. Since changing a pallet trailer location may entail changes in the layout, every potential pallet trailer location is classified. Table 5.1 shows the explanation per location classification (LC) according to the evaluation scale of Lean Six Sigma.

Location classification	Description	Number of locations
1	No layout change needed	36
3	Minor layout change needed	15
9	Major layout change needed	9

Table 5.1 Location classification pallet trailers

We use the LC of potential pallet trailer locations to determine the impact on the factory layout, we distinguish different experiments using the LC. The different scenarios are introduced in the following sections.

5.1.1. Scenario 0: Current situation

Scenario 0 is the current situation and serves as a baseline experiment. Results of other scenarios are compared to this scenario. In the current situation, parameters are not optimized but only evaluated using the model. The current situation consists of nine delivery zones with two pallet trailer locations per delivery zone, where 12 cycles are used daily to deliver the pallets.

5.1.2. Scenario 1: Optimizing pallet trailer locations only

In the second scenario, we stay close to the current situation. We optimize only the location of the pallet trailers in a delivery zone. These experiments aim to see what reduction in travel time for reach truck drivers can be achieved by making minimal adjustments to the current situation. We define an experiment for every LC in which we optimize the location of pallet trailers only. These experiments are schematically shown in Table 5.2.

	Pallet trailer location classification		
Scenario	≤1	≤3	≤9
Variable pallet trailer locations	Experiment 1	Experiment 2	Experiment 3

Table 5.2 Experiments with variable pallet trailer locations only

5.1.3. Scenario 2: Optimizing layout delivery zones only

In the third scenario, we only optimize the layout of the delivery zones and the locations of pallet trailers remain the same as in the current situation. This experiment aims to see what reduction in travel time for reach trucks is possible and to what extent delivery zones can be balanced by optimizing the layout of the delivery zones without changing the location of pallet trailers.

Scenario	**Current pallet trailer locations**
Variable layout delivery zones	Experiment 4

Table 5.3 Experiment with variable layout delivery zones only

5.1.4. Scenario 3: Optimizing pallet trailer locations and layout delivery zones

Scenario 3 combines the elements of Scenario 1 and 2. Both, the pallet trailer locations and the layout of the delivery zones are optimized. These experiments aim to see to what extent the current situation can be optimized without changing the input data. We define an experiment for every LC in which we optimize the location of pallet trailers and the layout of delivery zones.

	Pallet trailer location classification		
Scenario	≤1	≤3	≤9
Variable pallet trailer locations & layout delivery zones	Experiment 5	Experiment 6	Experiment 7

Table 5.4 Experiments with variable pallet trailer locations and variable layout delivery zones

5.1.5. Scenario 4: Evaluating variable number of delivery zones

In Scenario 4, we optimize both the pallet trailer locations and the layout of the delivery zones. We also evaluate the impact of fewer delivery zones on the process. By reducing the number of delivery zones, we expect reach truck drivers to have to drive further to a pallet. On the other hand, fewer trips are made from the KL to the pallet trailer locations in the factory because there are fewer delivery zones. By evaluating these options, the trade-off between the number of delivery zones and the number of trips from the KL can be quantified.

Because fewer trips are made from the KL to the factory, the capacity of the process also decreases, which increases the utilization rate. We vary the capacity by increasing and decreasing the number of pallet trailer locations in a delivery zone to prevent the service level from falling below the required level. We evaluate 1, 2, and 3 pallet trailer locations per delivery zone in combination with 9, 8, 7, and 6 delivery zones.

	Number of zones			
Scenario	9	8	7	6
One PT location per delivery zone	Experiment 8	Experiment 9	Experiment 10	Experiment 11
Two PT locations per delivery zone	Experiment 12	Experiment 13	Experiment 14	Experiment 15
Three PT locations per delivery zone	Experiment 16	Experiment 17	Experiment 18	Experiment 19

Table 5.5 Experiments with variable number of zones and variable sets of pallet trailers

Since our research goal is to increase productivity and reduce the number of pallets on the assembly line in the short term, at minimal cost, we choose to include LC 1 and 3 in the set of potential pallet trailer locations. These locations are realistic to be implemented in the short term and the costs are low. Section 5.4.2 elaborates on the impact of the LC used in the model using a sensitivity analysis. The number of cycles remains 12 per day for this scenario.

5.1.6. Scenario 5: Evaluating variable lead times

In the fifth scenario, we evaluate the effect of increasing the number of cycles in a day. This shortens the cycle time, which means that pallets are brought to the line more often. We expect that this will reduce the number of pallets at the assembly line. The pallet trailer locations and the layout of delivery zones are optimized. Because more trips are will be made from the KL to the factory, the capacity will increase if the other parameters remain the same. To avoid extra overcapacity, experiments with one pallet trailer location per delivery zone are also added. In addition to the 12 cycles used in the current situation, we evaluate 18, 24, and 36 cycles per day. This reduces the lead time by 33%, 50%, and 67% respectively.

	Number of cycles			
Scenario	12	18	24	36
One PT location per delivery zone	Experiment 20	Experiment 21	Experiment 22	Experiment 23
Two PT locations per delivery zone	Experiment 24	Experiment 25	Experiment 26	Experiment 27

Table 5.6 Experiments with variable number of cycles and variable sets of pallet trailers

The number of delivery zones remains nine for this scenario. The number of cycles per day and the number of pallet trailer locations per delivery zones depend on the experiment. The set of potential pallet trailer locations contains LC 1 and 3.

5.2. Experimental design

In this section, we discuss the parameters we use for the multi-objective function and determine the simulation length and number of replications.

5.2.1. Multi-objective parameter settings

The multi-objective function consists of the travel time per pallet, the balancing ratio, and the penalty function for the service level violation. We search for an optimal solution for minimizing the travel time per pallet and balancing delivery zones. The service level must meet a certain level to be viable in practice and therefore serves as a penalty function.

We cannot minimize the travel time per pallet and the balancing ratio simultaneously. The solution for optimal balancing is not equal to the solution for minimizing travel time, the objectives are conflicting. Therefore, we search for a Pareto optimal solution. The Pareto optimal solution is the solution where both objectives jointly achieve an optimal objective value, without being dominated by any other feasible solution. This section provides insight into how the settings of the parameters in the objective function are determined.

The travel time per pallet and the balancing ratio in the multi-objective function have different scales, to compare these variables with each other, these parameters must first be normalized. We use the *upper-lower-bound approach* according to Marler and Arora (2005) to normalize the variables in the objective function. They state that the approach is robust and ensures that the transformed functions are dimensionless and have comparable scales. Equation 5.1 shows the formula for the upper-lower-bound approach.

$$F_i^{norm} = \frac{F_i(x) - F_i^0}{F_i^{max} - F_i^0} \tag{5.1}$$

F_i^{norm} = normalized value of parameter i
$F_i(x)$ = input value of parameter i
F_i^0 = lower limit of parameter i
F_i^{max} = Pareto maximum of parameter i

We approximate F_i^0 by optimizing the variable in the objective function individually and use the minimum value of the variable as the lower bound. By optimizing each variable in the objective function, we also find the Pareto maximum F_i^{max}. The Pareto maximum is the highest value of a variable found when optimizing the other variables individually.

Now that the objective function variables have been normalized and contain the same scale, we make the trade-off between reducing the travel time per pallet and balancing delivery zones. We use the weighted sum method to weigh the normalized variables. This results in the following scalarized objective function:

$$U = \sum_{i=1}^{k} w_i F_i^{norm}(x) \tag{5.2}$$

where w_i is the weighting factor and F_i^{norm} is a normalized variable in the multi-objective function. Furthermore, $\sum_{i=1}^{k} w_i = 1$ and $w_i > 0$, which means that the sum of the weights is equal to 1, and every weight is a nonnegative number. Figure 5.1 shows the trade-off between the weights that can be used for the travel time per pallet and the balancing ratio and compares this to the current situation.

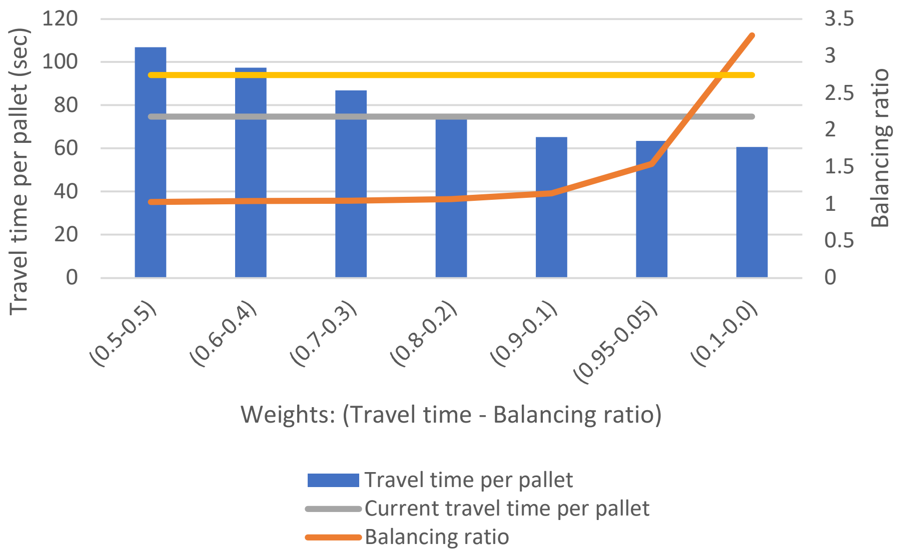


Figure 5.1 Trade-off between the travel time per pallet and the balancing ratio

To optimize both the travel time per pallet and the balancing ratio, we use weight 0.95 for the travel time per pallet and 0.05 for the balancing ratio. This ensures that travel time is kept to a minimum while delivery zones remain balanced.

Furthermore, a service level of 99% is viable since leveling of orders postpones less important pallets if there are too many in a cycle. Therefore, we choose a required service level of 99%. We choose a service level penalty weight that is five times greater than the weights for the optimization parameters. This ensures that when the temperature of SA decreases, a solution is found which meets the required service level. The objective function then becomes:

$$Minimize\ z = 0.95 * F_{TT}^{norm} + 0.05 * F_{BR}^{norm} + 5 * F_{SL} \qquad 5.3$$

F_{TT}^{norm} = normalized value of the travel time per pallet
F_{BR}^{norm} = normalized value of the balancing ratio
F_{SL} = service level violation

5.2.2. Simulation length and number of replications

The model evaluates each cycle and calculates the output parameters per cycle. No warm-up length is required as the output parameters are determined based on the demand generated per cycle. As an example, the number of pallets required for a part number at the line is estimated based on the demand generated on two consecutive cycles. We set the run length per calculation of the objective function to 5 days. We use the common random number method to control the randomness in the model and to be able to evaluate multiple scenarios for the same situation. By using the same random number stream per experiment, we can measure the effect of a scenario with the model.

Each run of a simulation determines a point estimate of the mean of an output variable. To obtain a 95% confidence interval of the mean we need multiple replications. We use the sequential procedure according to Law (2015) to determine the number of replications per simulation run.

Appendix B presents how we calculate the number of replications required. The number of replications required is based on the service level of a scenario. The number of replications required is 4. We expect that the number of 4 replications can be explained by the law of large numbers and the simulation length. The demand of a part number varies from cycle to cycle, but because a delivery zone contains many part numbers, the demand per cycle remains relatively stable and therefore also the service level. The simulation length of 5 days also influences the number of replications. Every simulation day, 12 cycles are evaluated with a simulation length of 5 days, this is 60 cycles per replication.

5.3. Simulation-optimization results

In this section, we present the results for the different scenarios introduced in Section 5.1. The visualizations of the solutions are not included in the thesis. For every experiment, we perform three runs in which the solution with the best objective value presents the solution.

5.3.1. Scenario 0: Current situation

In the current situation, the performance of the process is analyzed using the model. Table 5.7 shows the results for the output parameters defined in Section 4.3.5.

Key Performance Indicator	Current situation
Travel time per pallet	75.3 sec
Distance consumption location to pallet trailer	57.8 m
Reach truck FTE (pallet trailer FTE)	6.4 (3)
Service level (incl. external return flows)	99.2% (75.5%)
Utilization rate	51%
Balancing ratio	2.6
Surface pallets (m^2)	1256

Table 5.7 Results experiments scenario 0

The leveling of orders system ensures that by postponing pallets, the service level of 99.2% does not lead to problems in production. This scenario serves as a benchmark against which to compare with other experiments in different scenarios.

5.3.2. Scenario 1: Optimizing pallet trailer locations only

We see that the travel time-related output parameters decrease when we optimize the location of the pallet trailers. The other output parameters remain the same as the layout of the delivery zones does not change. Table 5.8 shows the results of the experiments with the travel time-related output parameters.

		Pallet trailer location classification		
Key Performance Indicator	**Current situation**	≤1	≤3	≤9
Travel time per pallet	75.3 sec	71.1 sec	67.4 sec	59.6 sec
Distance consumption location to pallet trailer	57.8 m	54.4 m	51.9 m	45.7 m
Reach truck FTE (pallet trailer FTE)	6.4 (3)	6.3 (3)	6.2 (3)	5.9 (3)

Table 5.8 Results experiments scenario 1

The table shows that by choosing pallets from the set LC1, the travel time per pallet reduces 6% compared to the current situation. This is 10% when we choose pallet trailers from the set of LC3 and 20% for pallet trailers in the set of LC9. Changing the pallet trailer locations also leads to a reduction in the required FTE and thus increases productivity. The reduction in required reach truck FTE for LC1, LC3, and LC9 is 3%, 4%, and 8% respectively.

5.3.3. Scenario 2: Optimizing layout delivery zones only

In Scenario 2, we optimize the layout of the delivery zones and keep the location of pallet trailers the same as in the current situation. We see an improvement in travel time-related output parameters as well as in the service level and the balancing ratio of delivery zones. Table 5.9 presents the result of the experiment of Scenario 2.

Key Performance Indicator	Current situation	Optimized layout
Travel time per pallet	75.3 sec	70.2 sec
Distance consumption location to pallet trailer	57.8 m	53.9 m
Reach truck FTE (pallet trailer FTE)	6.4 (3)	6.3 (3)
Service level (incl. external return flows)	99.2% (75.5%)	99.9% (77.3%)
Utilization rate	51%	51%
Balancing ratio	2.6	1.8
Surface pallets (m^2)	1256	1256

Table 5.9 Results experiments scenario 2

The service level increases by 0.7 percent point, the number of reach truck FTE required decreases by 2.5%, which increases productivity. Furthermore, the ratio of the largest to the smallest delivery zone decreases from 2.6 to 1.8, which balances delivery zones.

5.3.4. Scenario 3: Optimizing pallet trailer locations and layout delivery zones

In Scenario 3, we optimize both, the location of pallet trailers and the layout of delivery zones for each location classification. We see that every output parameter in the model improves compared to the current situation. The service level increases, delivery zones are much better balanced since the balancing ratio increases and the travel time-related output parameters decrease. Table 5.10 presents the results of the experiments of Scenario 3.

		Pallet trailer location classification		
Key Performance Indicator	**Current situation**	≤1	≤3	≤9
Travel time per pallet	75.3 sec	70.8 sec	66.5 sec	58.8 sec
Distance consumption location to pallet trailer	57.8 m	51.9 m	49 m	45.2 m
Reach truck FTE (pallet trailer FTE)	6.4 (3)	6.2 (3)	6.1 (3)	5.9 (3)
Service level (incl. external return flows)	99.2% (75.5%)	99.9% (79.6%)	99.9% (78.8%)	99.8% (80.1%)
Utilization rate	51%	51%	51%	51%
Balancing ratio	2.6	1.5	1.4	1.6

Surface pallets (m²)	1256	1253	1256	1256

Table 5.10 Results experiments scenario 3

In Table 5.10, we see that the service level for LC1, LC3, and LC9 increases by 0.6-0.7 percent point. The balancing ratio also improves and remains stable for any LC around 1.4-1.6. For LC1, LC3 and LC9 the travel time decreases by 6%, 12%, and 22% respectively. The reduction in required reach truck FTE is therefore 2%, 5%, and 8% respectively.

5.3.5. Scenario 4: Evaluating variable number of delivery zones

In Scenario 4, we optimize both, the location of pallet trailers and the layout of the delivery zones. We use LC1 and LC3 as input for the potential pallet trailer locations. We see the following effects when we decrease the number of delivery zones during the experiments in this scenario:

- The travel time per pallet, distance to a consumption location, and the number of reach truck FTE increases.
- The number of pallet trailer FTE decreases.
- The utilization rate increases.

This is in line with our expectations. Because there are fewer delivery zones, pallet trailer locations cannot be allocated closer to the consumption locations, leading to an increase in travel time-related output parameters. There is also less capacity available, which ensures that the capacity available should be used optimally. Table 5.11 presents the results of the number of delivery zones versus the number of sets of pallet trailers per delivery zone.

		Number of delivery zones			
Pallet trailer locations	**Key Performance Indicator**	9	8	7	6
One PT location per delivery zone	Travel time per pallet	197.6 sec	202.2 sec	200.4 sec	201.8 sec
	Distance consumption location to pallet trailer	146.8 m	151.1 m	149.5 m	150.5 m
	Reach truck FTE (pallet trailer FTE)	10.4 (1.5)	10.5 (1.3)	10.5 (1.2)	10.5 (1)
	Service level (incl. external return flows)	95% (54.4%)	92% (47.5%)	88.1% (49.2%)	82.8% (43%)
	Utilization rate	102%	114%	131%	152%
	Balancing ratio	1.1	1.2	1.2	1.2
	Surface pallets (m²)	1256	1256	1256	1256
Two PT locations per delivery zone	Travel time per pallet	66.5 sec	70.3 sec	73 sec	81.6 sec
	Distance consumption location to pallet trailer	49 m	52.1 m	54 m	60.9 m
	Reach truck FTE (pallet trailer FTE)	6.1 (3)	6.3 (2.7)	6.3 (2.3)	6.6 (2)
	Service level (incl. external return flows)	99.9% (78.8%)	99.2% (72.8%)	99.1% (76.1%)	99% (71.4%)

	Utilization rate	51%	57%	65%	76%
	Balancing ratio	1.4	1.8	1.5	1.2
	Surface pallets (m²)	1256	1256	1256	1256
Three PT locations per delivery zone	Travel time per pallet	68.1 sec	70.6 sec	71.1 sec	71.9 sec
	Distance consumption location to pallet trailer	52.9 m	52.4 m	52.5 m	53.2 m
	Reach truck FTE (pallet trailer FTE)	6.2 (4.5)	6.3 (4)	6.3 (3.5)	6.3 (3)
	Service level (incl. external return flows)	100% (92.8%)	100% (93.1%)	99.8% (89.9%)	99.7% (82.6%)
	Utilization rate	34%	38%	44%	51%
	Balancing ratio	1.9	2.3	2.2	2
	Surface pallets (m²)	1256	1256	1256	1256

Table 5.11 Results experiments scenario 4

In Table 5.11, we see that when there is one pallet trailer location in a delivery zone, the model cannot achieve a service level of 99% with fewer delivery zones, making these experiments infeasible. In these experiments we see the travel time-related parameters increase, this is caused by the model trying to achieve a service level above 99%.

Furthermore, we see that we can achieve a service level of 99% for all experiments with two pallet trailer locations per delivery zones. The increase in travel time-related output parameters of two pallet trailer locations per delivery zone in combination with six delivery zones is caused by the model trying to achieve a service level of 99%. With this, we see a tradeoff between the number of pallet trailer FTE required and the number of reach truck FTE required, adding more pallet trailer capacity to the process or allowing reach truck drivers to drive further while maintaining the required service level. In the other experiments with two pallet trailer locations, we see that lowering the number of delivery zones increases utilization, decreases the number of pallet trailer FTE required, while the travel time per pallet and the number of reach truck FTE required do not increase compared to the current situation. Also, the balancing ratio is better compared to the current situation.

Table 5.11 shows that when three pallet trailer locations are placed in a delivery zone, the service level remains around 100%. More pallet trailer FTE is required to bring the pallet trailers to the delivery zones. Also, the low utilization rates show that there is also more overcapacity compared to the current situation, which worsens productivity and makes the experiments uninteresting. The travel time-related output parameters are higher compared to the experiments with two pallet trailer locations when the service level can be easily achieved. This can be explained by the fact that an extra pallet trailer has to be placed in a delivery zone. Therefore, pallet trailer locations are chosen that are further from the center of the consumption locations in a delivery zone, which worsens the travel time.

5.3.6. Scenario 5: Evaluating variable lead times

In Scenario 5, we optimize both, the location of pallet trailers and the layout of the delivery zones. The lead time decreases as the number of cycles per day increases. At the same time, the capacity is increased if other parameters remain the same. We see the following effects when we increase the number of cycles per day during the experiments in this scenario:

- The travel time per pallet, distance to a consumption location, the pallet surface needed, and the number of reach truck FTE decreases.
- The number of pallet trailer FTE increases.
- The utilization rate decreases.
- The surface of pallets at the assembly line decreases.

This is in line with our expectations. Because the lead time is shorter, the process capacity increases and there is less demand per cycle, which leads to a decrease in travel time-related output parameters. This also makes it easier to achieve the required service level. Table 5.12 presents the results of the number of cycles per day versus the number of pallet trailer locations per delivery zone.

		Number of cycles			
Sets pallet trailers	**Key Performance Indicator**	12	18	24	36
One pallet trailer per delivery zone	Travel time per pallet	197.6 sec	93.6 sec	61.1 sec	61.7 sec
	Distance consumption location to pallet trailer	146.8 m	69.5 m	45.3 m	45.7 m
	Reach truck FTE (pallet trailer FTE)	10.4 (1.5)	7 (2.3)	5.9 (3)	6 (4.5)
	Service level (incl. external return flows)	95% (54.4%)	99% (71%)	99.3% (77.7%)	99.2% (87.4%)
	Utilization rate	102%	67%	50%	34%
	Balancing ratio	1.1	1.2	1.5	3.1
	Surface pallets (m^2)	1256	1135	1088	1055
Two pallet trailers per delivery zone	Travel time per pallet	66.5 sec	66.7 sec	66.5 sec	61.6 sec
	Distance consumption location to pallet trailer	49 m	49.3 m	49.1 m	45.7 m
	Reach truck FTE (pallet trailer FTE)	6.1 (3)	6.2 (4.5)	6.2 (6)	6.1 (9)
	Service level (incl. external return flows)	99.9% (78.8%)	100% (90.5%)	100% (94.9%)	100% (98.4%)
	Utilization rate	51%	34%	25%	17%
	Balancing ratio	1.4	1.4	1.4	2.8
	Surface pallets (m^2)	1256	1135	1088	1055

Table 5.12 Results experiments scenario 5

With 18, 24, and 36 cycles the lead time is reduced by 33%, 50%, and 67% respectively. By shortening the lead time, the surface of pallets at the assembly line decreases by 10%, 13%, and 16%, respectively. When increasing the number of cycles, the number of pallet trailer FTE increases linearly. This does not apply to the decrease in pallet surface. This can be explained by the fact that at least two pallets must be placed at the assembly line. When parts can also be supplied in smaller packaging, the pallet surface at the assembly line can decrease further but this is not incorporated into the model.

When we compare the scenario with nine delivery zones, one pallet trailer location per delivery zone, and 18 cycles in Table 5.12 with the experiment with seven delivery zones, two pallet trailer locations per delivery zone, and 12 cycles in Table 5.11, we see that the utilization has increased by 2%, and the travel time-related output parameters much more. This can be explained by the law of large numbers (Smith & Kane, 1994). A cycle can be seen as a sample size of the entire population, by shortening the lead time, the sample size per cycle becomes smaller so that the average volume per cycle fluctuates more and more capacity is needed in the process to cope with the variation. We conclude that a delivery zone benefits from a higher volume, since the utilization rate, and thus productivity, can be increased further without affecting other output parameters.

Increasing the number of cycles leads to more pallet trailer FTE and a higher capacity. By placing one pallet trailer location in a delivery zone instead of two, the capacity is reduced. The experiment with 24 cycles and one pallet trailer location per delivery zone is an interesting alternative for SPZ. The pallet surface decreases and travel time is shortened for reach truck drivers compared to the current situation. An additional advantage of using one pallet trailer instead of two is that less space is required in the factory, which benefits the limited space at the assembly line.

5.3.7. Promising combinations

Based on the experiments of Scenario 4 and Scenario 5, we define six more promising experiments in which we combine big delivery zones with an increase in the number of cycles per day. The first three experiments consist of two pallet trailer locations per delivery zone in combination with 18 cycles. We evaluate 4, 5, and 6 delivery zones. Table 5.13 shows the results of these experiments.

		Number of delivery zones		
Number of cycles	**Key Performance Indicator**	4	5	6
18 cycles	Travel time per pallet	85.5 sec	74.9 sec	69.9 sec
	Distance consumption location to pallet trailer	63.7 m	55.9 m	52.2 m
	Reach truck FTE (pallet trailer FTE)	6.7 (2)	6.4 (2.5)	6.2 (3)
	Service level (incl. external return flows)	99.1% (66.6%)	99.6% (74.7%)	99.7% (83.1%)

Utilization rate	75%	60%	50%
Balancing ratio	1	1.4	1.9
Surface pallets (m²)	1135	1135	1135

Table 5.13 Results promising experiments set 1

We see that the model can increase the number of cycles per day and increase the utilization rate while maintaining a service level above 99%. With four delivery zones, the travel time per pallet increases compared to the current situation, which is not desirable. On the other hand, we need 1 pallet trailer FTE less per shift. For the combination with five and six delivery zones does the performance not outweigh the performance of the combination between 24 cycles, nine delivery zones, and one pallet trailer location per delivery zone of Scenario 5 and is therefore not viable.

The fourth, fifth, and sixth experiments consist of one pallet trailer location per delivery zone in combination with 24 cycles. We evaluate 6, 7, and 8 delivery zones. Table 5.14 shows the results of the experiments.

		Number of delivery zones		
Number of cycles	**Key Performance Indicator**	6	7	8
24 cycles	Travel time per pallet	188.1 sec	93.2 sec	71.1 sec
	Distance consumption location to pallet trailer	137.6 m	68.8 m	52.8 m
	Reach truck FTE (pallet trailer FTE)	10 (2)	7 (2.3)	6.2 (2.7)
	Service level (incl. external return flows)	98.9% (65.6%)	99% (72.1%)	99.1% (74.5%)
	Utilization rate	76%	65%	57%
	Balancing ratio	1.1	1.1	1.5
	Surface pallets (m²)	1088	1088	1088

Table 5.14 Results promising experiments set 2

In the table, we see that the model is not able to achieve a service level of 99% with six delivery zones. For seven delivery zones, the travel time per pallet increases, which is not desirable. With eight delivery zones, the travel time per pallet decreases compared to the current situation and the number of pallet trailer FTE decreases by 0.3 per shift. However, the decrease in pallet trailer FTE cannot outweigh the decrease in travel time per pallet with 24 cycles, nine delivery zones, and one pallet trailer location per delivery zone of Scenario 5 and is therefore not viable.

5.4. Sensitivity analysis

We use a sensitivity analysis to map the uncertainties in the proposed model. Law (2015) states that the importance of an input parameter could be investigated by changing the value and solving the model for several values. We perform a sensitivity analysis for the required service level and the production rate. Furthermore, we evaluate the impact of the location classification on the travel time per pallet.

5.4.1. Required service level and production rate

Recall from Section 4.5.3 that the service level indicates the fraction of the number of pallets that can be transported directly with a pallet trailer. We use a required service level of 99% in the model. In this sensitivity analysis, we vary the required service level from 90% to 100% to check the influence of the required service level on the output parameters. Furthermore, the results of Section 5.3 are based on the production rate from February 22, 2021 to April 16, 2021. The production rate could be increased or decreased in the future, therefore it is important to perform a sensitivity analysis for the production rate.

We perform the sensitivity analysis for *Experiment 15* as the process is running at its limits under these input parameters. This makes sure the effects of the required service level and the production rate on the output parameters can be visualized well. Recall from Section 5.1.5 that *Experiment 15* has six delivery zones, 12 cycles per day, and two pallet trailer locations. We take the average of the runs to evaluate the performance of the output parameters. Figure 5.2 shows the results of the sensitivity analysis for the required service level and the production rate. We see that the required service level and the production rate significantly influence the travel time per pallet and balancing ratio, while the service level meets the required service level.

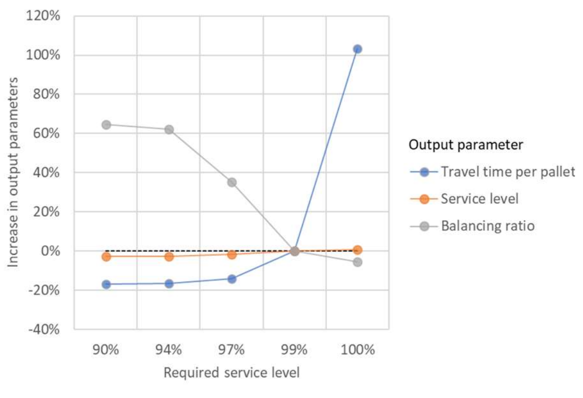


Figure 5.2a Sensitivity analysis of required service level on output parameters

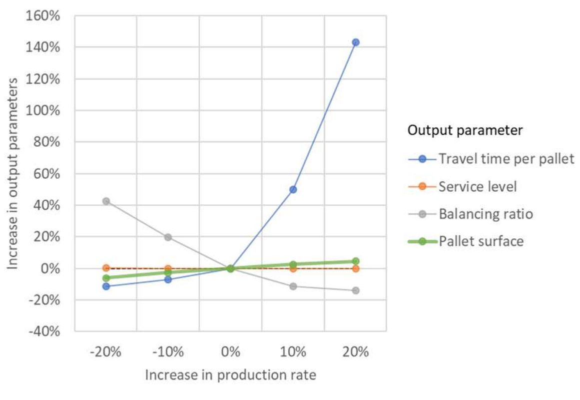


Figure 5.2b Sensitivity analysis of production rate on output parameters

For the required service level (a), we explain the influence on the output parameters because the Pareto optimum between the normalized parameters travel time per pallet and the balancing ratio can be achieved with a required service level of 94% or lower. When the required service level increases, the available capacity must be divided more evenly to achieve the required service level. This forces the model to increase the travel time per pallet and balance delivery zones more evenly.

We explain the significant influence of the production rate (b) on the output parameters because a higher production rate leads to a higher volume per cycle. The increase in volume per cycle makes it more difficult to achieve the required service level with the same capacity. This ensures that delivery zones are better balanced, which is at the expense of the travel time per pallet. Furthermore, we conclude that the production rate does not have a major influence on the surface of pallets needed at the assembly line. We explain this because there must be at least two pallets per part number at the assembly line. When the production rate increases, the two pallets per part number can be sufficient to meet the extra demand.

5.4.2. Location classification

Recall from Section 5.1 that the location classification (LC) indicates the impact of a potential pallet trailer location on the layout, with LC 1 the lowest impact and LC 9 the highest impact. Our research goal is to increase productivity and reduce the number of pallets at the assembly line in the short term, at a minimal cost. Therefore, we decided in consultation with SPZ to not include LC 9 in our experiments to determine the impact of fewer delivery zones and shorter lead time on the process. We performed four runs of four different experiments with the model for every LC to evaluate the impact of the LC on the travel time per pallet. Figure 5.3 shows the outcome of these experiments with a box plot, where LC ≤3 is the base experiment.

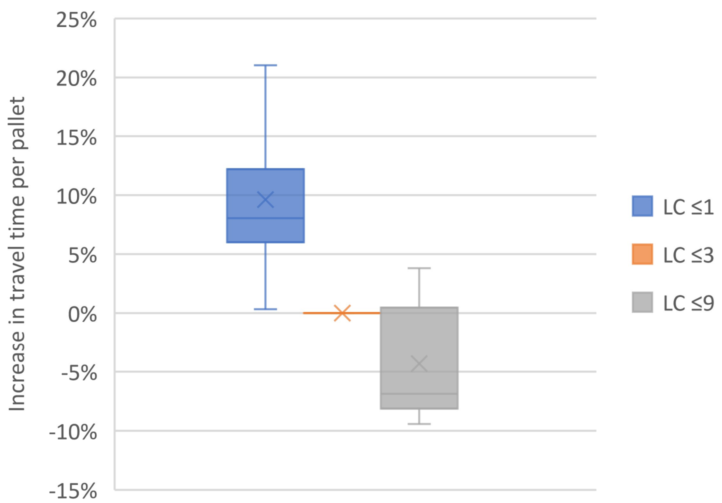


Figure 5.3 Sensitivity analysis of the location classification on the travel time per pallet

The figure shows that with the use of LC ≤1, the average travel time per pallet increases by 10% compared to LC ≤3. When SPZ chooses to add LC 9 to the model, the travel time per pallet reduces on average 4% compared to LC ≤3. Furthermore, it might seem strange that sometimes an experiment with LC ≤9 has worse performance on the travel time per pallet than with LC ≤3. We can explain this because the model aims to find a Pareto optimal solution between the travel time per pallet and the balancing ratio, this results in solutions that sometimes have a better performance on the travel time per pallet and sometimes on the balancing ratio.

5.5. Conclusion

We introduced several scenarios in which we experiment with reducing the number of delivery zones, increasing the number of cycles in a day, and varying the number of pallet trailer locations per delivery zone. Furthermore, we solve different experiments by optimizing the pallet trailer locations, the consumption locations, or both.

Considering the scenarios in which we improve the current situation by optimizing the pallet trailer locations, the consumption locations or both, we can reduce the travel time per pallet by a maximum of 22% compared to the current situation, without deteriorating other output parameters. As a result, up to 8% less reach truck FTE is required, which increases productivity. An additional advantage is that traffic intensity in the factory is reduced since less distance is traveled per pallet. A quick win with a 6% reduction in travel time per pallet can be achieved by relocating pallet trailer locations wherefore no layout change is needed. This requires 2% less reach truck driver FTE. Furthermore, we show that our model can decrease travel time-related output parameters while keeping delivery zones balanced.

Based on the scenarios in which we reduce the number of delivery zones and increase the number of cycles per day, we conclude the following:

- There is a tradeoff between adding more pallet trailer capacity to the process and allowing reach truck drivers to drive further while maintaining the required service level.
- The pallet trailer process benefits from the law of large numbers. With a higher volume per cycle, a higher utilization rate can be achieved while maintaining the required service level.
- Due to overcapacity in the current process and the law of large numbers, productivity can be increased, and/or lead time can be reduced while maintaining the required service level.
- Lowering the number of delivery zones results in a decrease in capacity and only a small increase in travel time output parameters. By lowering the number of delivery zones, the pallet trailer process benefits from the law of large numbers, such that a higher utilization rate can be achieved while maintaining the required service level.
- Lead time reduction leads to less pallet surface needed at the assembly line, but also to an increase in capacity and pallet trailer FTE required. The pallet trailer process does not benefit from the law of large numbers if the lead time is decreased. A lower utilization rate is required to achieve the required service level.
- It is not beneficial to drive to have more than one pallet trailer location in a delivery zone since travel time increases with multiple pallet trailer locations in a delivery zone unless it benefits from the law of large numbers. In addition, a pallet trailer location takes space in the factory where there is already little space.

Furthermore, we propose four alternatives for SPZ based on the experiments performed. Table 5.15 shows the characteristics of the proposals with output parameters.

Experiment:	**Exp. 0**	**Exp. 6**	**Exp. 14**	**Exp. 15**	**Exp. 22**
Number of delivery zones	9	9	7	6	9
Number of cycles	12	12	12	12	24
Number of sets pallet trailers per delivery zone	2	2	2	2	1
Travel time per pallet	75.3 sec	-11.7%	-3.1%	8.4%	-18.9%
Reach truck FTE (pallet trailer FTE)	6.4 (3)	-0.3 (0)	-0.1 (-0.7)	+0.2 (-1)	-0.5 (0)
Service level	99.2%	+0.7 p.p.	-0.1 p.p.	-0.2 p.p.	+0.1 p.p.
Utilization rate	51%	+0 p.p.	+14 p.p.	+25 p.p.	-1 p.p.
Surface pallets (m^2)	1256	0.0%	0.0%	0.0%	-13.4%

Table 5.15 Alternative proposals for SPZ

Experiment 0 represents the current situation. *Experiment 6* optimizes the current situation which balances delivery zones and minimizes the travel time per pallet by 11.7%. *Experiment 14* and *Experiment 15* goal is to increase productivity by reducing the number of delivery zones. In *Experiment 14* travel time decreases and the number of pallet trailer FTE decreases as well, while the utilization increases. In *Experiment 15* there is exactly 1 pallet trailer FTE needed less per shift and therefore needs the least total number of FTEs. However, the travel time increases and the process is running at its limits, while maintaining the required service level. *Experiment 22* reduces the pallet surface at the assembly line by 13.4% by reducing the lead time by 50%. The number of reach truck FTEs required also decreases with 0.5 FTE per shift since the travel time is reduced by 18.9%. In addition, less space for pallet trailers is needed in the factory as only one pallet trailer location per delivery zone is required. Furthermore, for all alternatives applies that delivery zones are better balanced, which leads to fewer peaks at the KL.

Given the results of the model, we conclude that productivity can be increased by applying one of the proposed alternatives. To decrease the pallet surface needed at the assembly line, the lead time must be decreased, which is part of *Experiment 22*. The condition for applying *Experiment 22* in the current situation, is that the pallet recorder must be able to record all empty pallets within a cycle. This should be tested in reality. Even more efficient for the process will be when a pallet recorder is no longer needed but a replenishment signal is used when a pallet is empty.

We advise SPZ to implement *Experiment 22* to decrease the pallet surface needed at the assembly line and improve the productivity of the process. It has the best performance overall and there is still space left to cope with higher demand. As a second solution, we advise SPZ to apply *Experiment 6*. The travel time is reduced and delivery zones are balanced better. *Experiment 14* with seven delivery zones is also viable, but since it is only beneficial for SPZ if an integer number of pallet trailer FTE can be saved per shift, this does not yield much in terms of costs. In *Experiment 15*, 1 pallet trailer FTE can be saved. However, travel time increases and the process runs at its limits.

6. Conclusions and recommendations

This chapter presents the conclusions and recommendations from our research. Section 6.1 presents the conclusions about the current USP process. Section 6.2 gives recommendations about the alternatives and Section 6.2.3 ends the chapter with recommendations on further research. The objective of this research is to redesign the USP method such that productivity increases and the number of pallets per part number at the assembly line reduces, at the lowest possible cost.

6.1. Conclusions

In this section, we present the conclusions from our research carried out at SPZ.

We seek for a solution to increase the productivity of the USP process and reduce the number of pallets per part number at the assembly line. Using a problem cluster we found the root cause that the current USP method with fixed takt times, fixed routes and the process layout suffers from the variation in pallet requests, leading to fluctuations in fill rates of vehicles and long pallet lead times, causing a loss in productivity and a lack of pallet space at the assembly line.

Chapter 2 presents the outcomes of the analysis of the current situation of the USP process. A comparison is made between the pallet trailer process and the tugger train process. Pallet trailers deliver around 80% of the pallets of the USP process and tugger trains around 20%. The pallet trailer process is more flexible in the types of pallets it can handle and the type of line locations it can supply compared to the tugger train process. The tugger train process is more flexible with scaling up and down at a takt time change. Tugger trains and pallet trailers have an average capacity utilization of 49% and 32%, respectively. Even though the average utilization rate of pallet trailers is much lower than that of tugger trains, the process is more cost-efficient. Furthermore, we saw that SPZ uses a two-bin Kanban system, while in reality there are more than 2 pallets at the assembly line. Because the number of part numbers increases in the coming years, there is no longer enough space in the factory, which means that the number of pallets per part number has to be reduced. We focus on the pallet trailer process due to the great potential for improvement in the utilization rate and because the process already supplies 80% of the pallets. More specifically, we focus on the location-allocation problem of the pallet trailer locations in a delivery zone and their consumption locations.

Using a literature study, we position the problem faced at SPZ as a location planning problem. We show that the problem has similarities with the capacitated p-median problem and the supermarket location problem and define the problem as a Discrete Supermarket Location Problem with Stochastic Demands. There are three practical elements where the pallet trailer process deviates from the theory. First, at SPZ, the demand is delivered in cycles, which is not discussed in the literature. Second, pallet trailers (supermarkets) have no stock and contain already requested pallets. Finally, models in the literature make use of deterministic demand, where the demand is known in advance without stochasticity, this is not the case at SPZ. Therefore, we propose a model that copes with these elements.

We propose a simulation-optimization model to allocate consumption locations and pallet trailers to delivery zones while taking into account stochastic demand. Our objective is to minimize travel time as well as balancing the demand-weighted delivery zones in combination with stochastic demand, maintaining a required service level. In addition, we use simulation techniques to estimate the objective value of a solution by evaluating the impact of stochastic demand while using a high level of detail. Furthermore, we manage to calculate realistic distances and travel times based on the layout of SPZ using Dijkstra's algorithm. This is, in particular, useful for SPZ since the basis of the model can be used to solve other logistics-related problems. We find an initial solution to our problem by using a k-medoids algorithm that tries to minimize the travel time from each consumption location to the pallet trailer locations on the delivery zones. Our problem is classified as an NP-hard problem and has a large solution space due to the high level of detail. Therefore, we use the metaheuristic Simulated Annealing to optimize our problem further. By using the swap and move neighborhood operators, we search for better solutions.

We experiment with the model by evaluating different scenarios. We distinguish different scenarios by reducing the number of delivery zones, increasing the number of cycles in a day, and varying the number of pallet trailers per delivery zone. Furthermore, we solve different problems by optimizing the pallet trailer locations, the consumption locations, or both. We mapped out potential pallet trailer locations using a classification that indicates the impact on the layout. When we consider the location classifications wherefore no layout change or minor layout change is needed and optimize the current situation, we can decrease travel times by 13% while balancing delivery zones and maintaining a service level of 99%. This improves the productivity of the process, reduces traffic in the factory, and prevents peaks at the KL.

During the experiments with fewer delivery zones, shorter lead times, and variable number of pallet trailer locations per delivery zone, we conclude the following:

- The pallet trailer process benefits from the law of large numbers. With a higher volume per cycle, a higher utilization rate can be achieved while maintaining the required service level.
- There is a trade-off between adding more pallet trailer capacity to the process and allowing reach truck drivers to drive further while maintaining the required service level.
- Due to overcapacity in the current process and the law of large numbers, productivity can be increased, and/or lead time can be reduced while maintaining the required service level.

Based on the experiments performed, we propose four alternatives for SPZ. Table 6.1 shows the characteristics of the alternatives proposed for SPZ to increase productivity and/ or reduce the lead time.

	Experiment:	Exp. 6	Exp. 14	Exp. 15	Exp. 22
Input	Number of delivery zones	9	7	6	9
	Number of cycles	12	12	12	24
	Number of pallet trailer locations per delivery zone	2	2	2	1
Output	Travel time per pallet	-11.7%	-3.1%	8.4%	-18.9%
	Reach truck FTE (pallet trailer FTE)	-0.3 (0)	-0.1 (-0.7)	+0.2 (-1)	-0.5 (0)
	Service level	+0.7 p.p.	-0.1 p.p.	-0.2 p.p.	+0.1 p.p.
	Utilization rate	+0 p.p.	+14 p.p.	+25 p.p.	-1 p.p.
	Surface pallets (m^2)	0.0%	0.0%	0.0%	-13.4%

Table 6.1 Alternative proposals for SPZ

Experiment 0 represents the current situation. *Experiment 6* optimizes the current situation which balances delivery zones and minimizes the travel time per pallet by 11.7%. *Experiment 14* and *Experiment 15* goal is to increase productivity by reducing the number of delivery zones. *Experiment 22* increases the number of cycles per day by 12, which reduces the lead time by 50%. For *Experiment 15* there is exactly 1 pallet trailer FTE less needed per shift and therefore needs the least total number of FTEs. However, the travel time increases and the process is running at its limits, while maintaining the required service level. *Experiment 22* reduces the travel time per pallet the most and also reduces the surface of the pallets needed by 13.4%. In addition, less space for pallet trailers is needed in the factory as only one pallet trailer location per delivery zone is required. *Experiment 14* shows that it is possible to reduce the number of delivery zones by two while also reducing the travel time per pallet. For all alternatives applies that delivery zones are better balanced, which leads to fewer peaks at the KL.

We advise Scania to not reduce the number of delivery zones as less than 1 pallet trailer FTE can be eliminated per shift without an increase in travel time. Therefore no significant cost can be saved. We advise SPZ to implement *Experiment 22* to decrease the pallet surface needed at the assembly line and improve the productivity of the process. It has the best performance overall and there is still space left to cope with higher demand. As a second solution, we advise SPZ to apply *Experiment 6*. The travel time is reduced and delivery zones are balanced better.

6.2. Recommendations

This section describes the recommendations for the proposed alternatives. In addition, we also make recommendations that are not related to the proposed alternatives and propose recommendations for further research.

6.2.1. Recommendations proposed alternatives

- The condition for implementing experiments in which the lead time decreases is that the pallet recorder must be able to record all empty pallets within a cycle. This should be tested in reality, otherwise, another pallet recorder must be added or a replenishment signal must be used.

- The model minimizes travel distances and balances delivery zones. The model does not take the safety of the solution into account. The solution the model generates could not be desired due to safety or congestion in the factory, even though it is faster in terms of travel time. This should be checked before the solution is implemented.
- The production rate influences the utilization rate. When the production rate decreases for a longer period, the utilization rate can decrease to such an extent that it is viable to implement more cost-efficient solutions. We advise Scania to use our model in the future to check if the delivery zones are optimally divided if the production rate increases or decreases.
- We advise implementing solutions only if the solution is beneficial if the required pallet trailer FTE is rounded up to an integer. The job of pallet trailer drivers is to bring pallets from the KL to the factory. If less than 1 FTE can be saved per shift, the FTE cannot be saved and it is not beneficial for SPZ.
- The visualization of the solution can be used to implement the layout of delivery zones.

6.2.2. Other recommendations

- SPZ uses a query to calculate expected peak demand in the USP process. The peak demand is a list of part numbers that are likely to be delivered too late at the assembly line. When a part number is often on this list, an extra pallet is added at the assembly line. However, there is no list to check if there are too many pallets at the assembly line. During this research, we could indicate several part numbers that had more pallets at the assembly line than needed. Therefore, we recommend SPZ to create a query that checks if the number of pallets per part number at the assembly matches the demand of the part number.
- The pallet trailer process is more efficient than the tugger train process in terms of costs. When, in the model, consumption locations from the tugger train process are added to the pallet trailer process, the total costs decrease. There is less extra reach truck FTE needed than the number of tugger train FTE in the current situation. Therefore, we recommend investigating the possibility to merge the flows.
- Since the start of Covid-19, production works non-stop in a shift without breaks. Logistics, on the other hand, does have breaks at fixed times. This leads to demand peaks in the logistics process. Logistical operators indicate that it is often extremely busy after a break. We advise SPZ to cope with this peak by synchronizing the working hours of logistics with production.
- Currently, there is no accurate information about the volume and line locations of the pallets of external processes that return with the pallet trailer process. We advise keeping track of the demand of line locations of external processes. This allows the pallet trailer process to be synchronized with the external return flows.

6.2.3. Recommendations for further research

- In the current process, the consumption locations are divided into fixed delivery zones and are supplied in fixed cycles. To increase the productivity of the process by better absorbing variation in the process, we recommend investigating the possibility of supplying in flexible delivery zones and flexible cycles.

- In the current situation, new pallet requests are generated by a pallet recorder. We recommend searching for alternatives for this method. The pallet recorder drives through the factory to record empty pallets, the minimum cycle time depends on the time the pallet recorder needs for this. This makes the process not flexible. In addition, the number of FTE in the process can also be reduced when this task is superfluous.
- This research is restricted to the roadways that are currently used at SPZ and optimizes the pallet trailer locations and consumption locations. The model could be extended by optimizing the roadways and evaluate if it is beneficial to add new roadways in the factory. In the literature, this is described as a network problem.

Bibliography

Arora, P., & Varshney, S. (2016). Analysis of k-means and k-medoids algorithm for big data. *Procedia Computer Science, 78*, 507-512.

Arostegui Jr, M. A., Kadipasaoglu, S. N., & Khumawala, B. M. (2006). An empirical comparison of tabu search, simulated annealing, and genetic algorithms for facilities location problems. *International Journal of Production Economics, 103*(2), 742-754.

Baller, R., Hage, S., Fontaine, P., & Spinler, S. (2020). The assembly line feeding problem: An extended formulation with multiple line feeding policies and a case study. *International Journal of Production Economics, 222*, 107489.

Basu, S., Sharma, M., & Ghosh, P. S. (2015). Metaheuristic applications on discrete facility location problems: a survey. *Opsearch, 52*(3), 530-561.

Battini, D., Boysen, N., & Emde, S. (2013). Just-in-Time supermarkets for part supply in the automobile industry. *Journal of Management Control, 24*(2), 209-217.

Becker, C., & Scholl, A. (2006). A survey on problems and methods in generalized assembly line balancing. *European journal of operational research, 168*(3), 694-715.

Bottou, L., & Bengio, Y. (1995). *Convergence properties of the k-means algorithms.* Paper presented at the Advances in neural information processing systems.

Boysen, N., Emde, S., Hoeck, M., & Kauderer, M. (2015). Part logistics in the automotive industry: Decision problems, literature review and research agenda. *European journal of operational research, 242*(1), 107-120.

Current, J., Daskin, M., & Schilling, D. (2002). Discrete network location models. *Facility location: Applications and theory, 1*, 81-118.

Daskin, M. S. (2008). What you should know about location modeling. *Naval Research Logistics (NRL), 55*(4), 283-294.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische mathematik, 1*(1), 269-271.

Dörmer, J., Günther, H.-O., & Gujjula, R. (2015). Master production scheduling and sequencing at mixed-model assembly lines in the automotive industry. *Flexible Services and Manufacturing Journal, 27*(1), 1-29.

Emde, S., & Boysen, N. (2012). Optimally routing and scheduling tow trains for JIT-supply of mixed-model assembly lines. *European journal of operational research, 217*(2), 287-299. doi:https://doi.org/10.1016/j.ejor.2011.09.013

Garey, M. R., & Johnson, D. S. (1979). *Computers and intractability* (Vol. 174): freeman San Francisco.

Glover, F., & Laguna, M. (1998). Tabu search. In *Handbook of combinatorial optimization* (pp. 2093-2229): Springer.

Golz, J., Gujjula, R., Günther, H.-O., Rinderer, S., & Ziegler, M. (2012). Part feeding at high-variant mixed-model assembly lines. *Flexible Services and Manufacturing Journal, 24*(2), 119-141.

Grit, K. (2018). *Forecasting and levelling workload for a part feeding system at the automotive industry.* (Master's Thesis). University of Twente, Enschede. Retrieved January 21, 2021 from http://essay.utwente.nl/74917/

Hagberg, A., Swart, P., & S Chult, D. (2008). *Exploring network structure, dynamics, and function using NetworkX*. Retrieved from

Hale, T. S., & Moberg, C. R. (2003). Location science research: a review. *Annals of operations research, 123*(1-4), 21-35.

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., . . . Smith, N. J. (2020). Array programming with NumPy. *Nature, 585*(7825), 357-362.

Heerkens, H., & van Winden, A. (2012). *Geen probleem, een aanpak voor alle bedrijfskundige vragen en mysteries.* Buren: Business School Nederland.

Holland, J. H. (1992). *Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence*: MIT press.

Hu, S. J., Ko, J., Weyand, L., ElMaraghy, H. A., Lien, T. K., Koren, Y., . . . Shpitalni, M. J. C. a. (2011). Assembly system design and operations for product variety. *60*(2), 715-733.

Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *IEEE Annals of the History of Computing, 9*(03), 90-95.

Kariv, O., & Hakimi, S. L. (1979). An algorithmic approach to network location problems. I: The p-centers. *SIAM Journal on Applied Mathematics, 37*(3), 513-538.

Kaufman, L., & Rousseeuw, P. J. (1990). *Finding groups in data: an introduction to cluster analysis* (Vol. 344): John Wiley & Sons.

Kirkpatrick, S., Gelatt, C. D., & Vecchi, M. P. (1983). Optimization by simulated annealing. *science, 220*(4598), 671-680.

Kortenhorst, N. (2019). *Improving the internal sequencing logistics at Scania Production Zwolle.* (Master's Thesis). University of Twente, Enschede. Retrieved January 21, 2021 from http://essay.utwente.nl/78996/

Law, A. M. (2015). *Simulation modeling and analysis* (Vol. 5): Raghu Srinivasan.

Marler, R. T., & Arora, J. S. (2005). Function-transformation methods for multi-objective optimization. *Engineering Optimization, 37*(6), 551-570.

McKinney, W. (2010). *Data structures for statistical computing in python.* Paper presented at the Proceedings of the 9th Python in Science Conference.

Mladenović, N., Brimberg, J., Hansen, P., & Moreno-Pérez, J. A. (2007). The p-median problem: A survey of metaheuristic approaches. *European journal of operational research, 179*(3), 927-939.

Mladenović, N., & Hansen, P. (1997). Variable neighborhood search. *Computers & operations research, 24*(11), 1097-1100.

Noche, B., & Alnahhal, M. (2015). A genetic algorithm for supermarket location problem. *Assembly Automation, 35*(1), 122-127.

Nourmohammadi, A., Eskandari, H., Fathi, M., & Aghdasi, M. (2018). A mathematical model for supermarket location problem with stochastic station demands. *Procedia CIRP, 72*, 444-449.

Novikov, A. V. (2019). PyClustering: Data mining library. *Journal of Open Source Software, 4*(36), 1230.

Ozbakir, L., Baykasoglu, A., Gorkemli, B., & Gorkemli, L. (2011). Multiple-colony ant algorithm for parallel assembly line balancing problem. *Applied Soft Computing, 11*(3), 3186-3198. doi:https://doi.org/10.1016/j.asoc.2010.12.021

Pine, B. J. (1993). *Mass customization* (Vol. 17). Boston: Harvard business school press.

Qin, J., Ni, L.-l., & Shi, F. (2012). Combined simulated annealing algorithm for the discrete facility location problem. *The Scientific World Journal, 2012*.

Reese, J. (2006). Solution methods for the p-median problem: An annotated bibliography. *NETWORKS: an international Journal, 48*(3), 125-142.

Schmid, N. A., & Limère, V. (2019). A classification of tactical assembly line feeding problems. *International Journal of Production Research, 57*(24), 7586-7609. doi:10.1080/00207543.2019.1581957

Sileyew, K. J. (2019). Research Design and Methodology. In *Text Mining-Analysis, Programming and Application*: IntechOpen.

Smith, M. L., & Kane, S. A. (1994). The law of large numbers and the strength of insurance. In *Insurance, risk management, and public policy* (pp. 1-27): Springer.

Taha, H. A. (2013). *Operations research: an introduction*: Pearson Education India.

Ulukan, Z., & Demircioğlu, E. (2015). A survey of discrete facility location problems. *International Journal of Industrial and Manufacturing Engineering, 9*(7), 2487-2492.

Van Rossum, G. (2020). The Python Library Reference, release 3.8. 2. *Python Software Foundation*, 36.

West, D. B. (2001). *Introduction to graph theory* (Vol. 2): Prentice hall Upper Saddle River.

Yaghini, M., Karimi, M., & Rahbar, M. (2013). A hybrid metaheuristic approach for the capacitated p-median problem. *Applied Soft Computing, 13*(9), 3922-3930.

Zhou, B.-H., & Tan, F. (2020). A self-adaptive estimation of distribution algorithm with differential evolution strategy for supermarket location problem. *Neural Computing and Applications, 32*(10), 5791-5804.

A. Flowcharts of algorithms

This Appendix presents the flowcharts of algorithms used which are not explained in the context.

A.1. Adding a vertex to the graph

Figure A.1 shows a flowchart of how the vertices are systematically added to the graph.

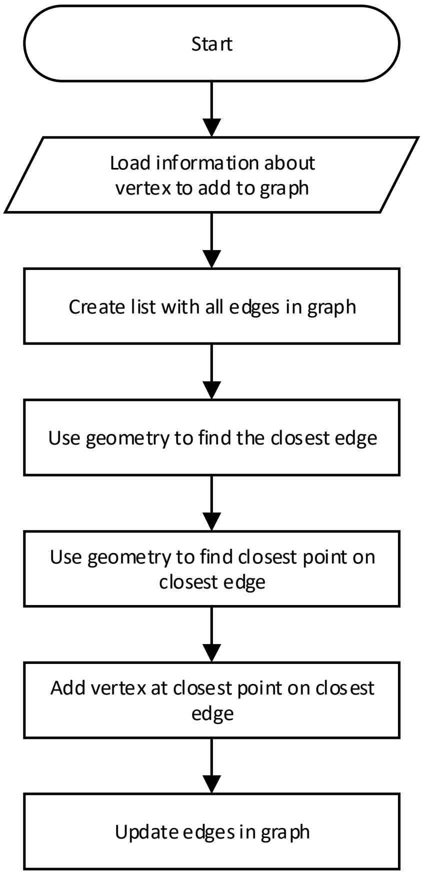


Figure A.1 Flowchart for adding a vertex to the graph

First, we load the information of the vertex that has to be added with the Cartesian coordinates. After this, a list is created with all edges in the existing graph. We use geometry to determine the distance from the vertex to each edge in the graph. For the edge closest to the vertex, the closest coordinates to the edge are calculated. The new vertex is added to these coordinates, after which the original edge is split into two edges and the edge weights are updated.

A.2. Dijkstra algorithm

Figure A.2 shows a flowchart of how the shortest path is calculated for a vertex using the Dijkstra algorithm (Dijkstra, 1959).

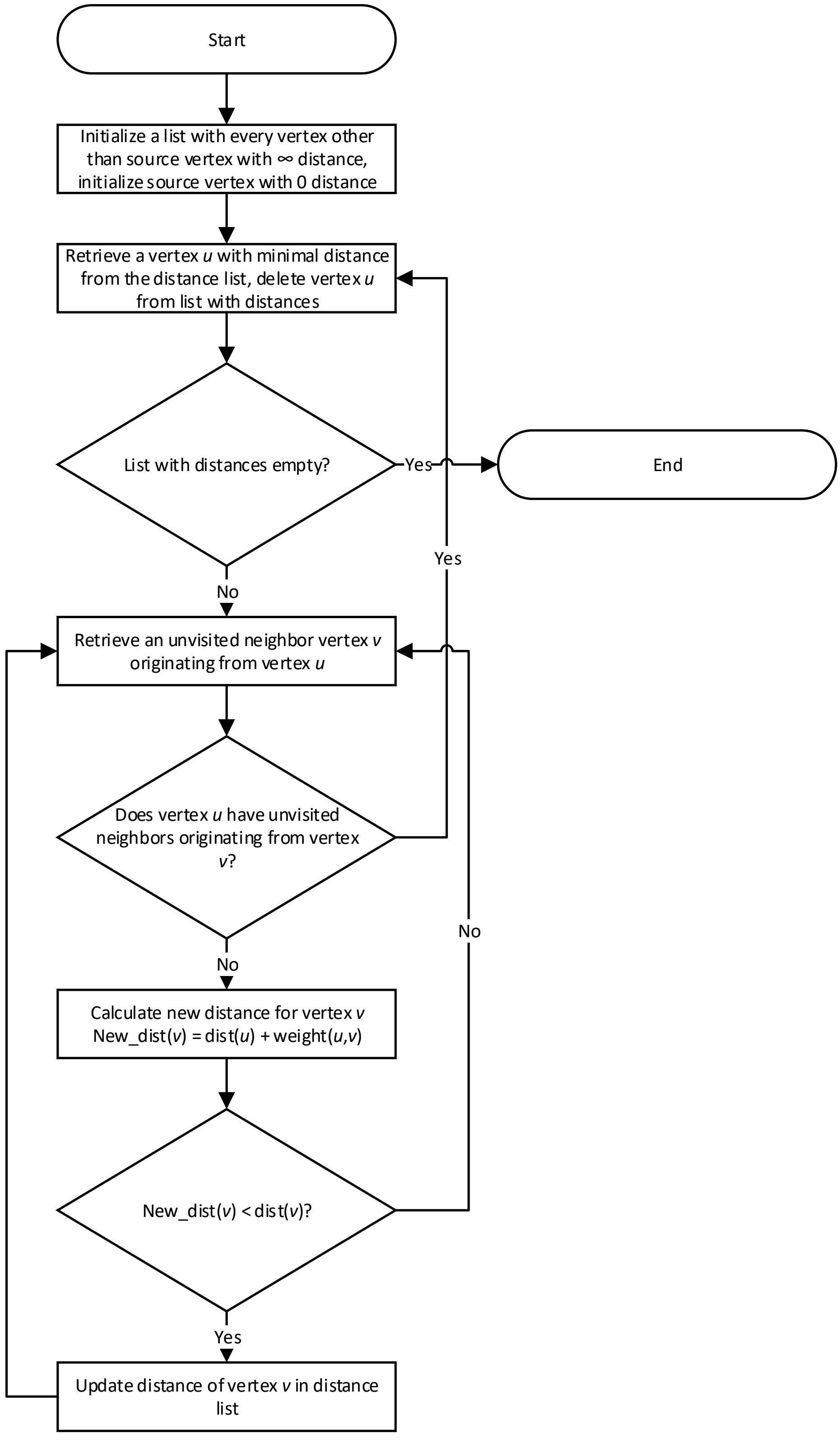


Figure A.2 Flowchart of Dijkstra's algorithm

First, a list with distances is initialized with ∞ distance from the source vertex to all other vertices. The distance to the source vertex is set to 0. Then a vertex u is retrieved with a minimum distance from the source node from the list, which is at first the source vertex. The distance is calculated from vertex u to each neighbor vertex v. The distance here refers to the weight function of an edge, as described in Section 4.3.2. When the new distance from vertex v is less than the distance from vertex v in the list with distances, it will be replaced by the new distance in the list. Then a new vertex is chosen and this loop repeats until minimum distances are found for each vertex in the graph.

A.3. K-medoids algorithm

Figure A.3 shows the flowchart of the PAM algorithm used to solve the k-medoids problem (Kaufman & Rousseeuw, 1990).

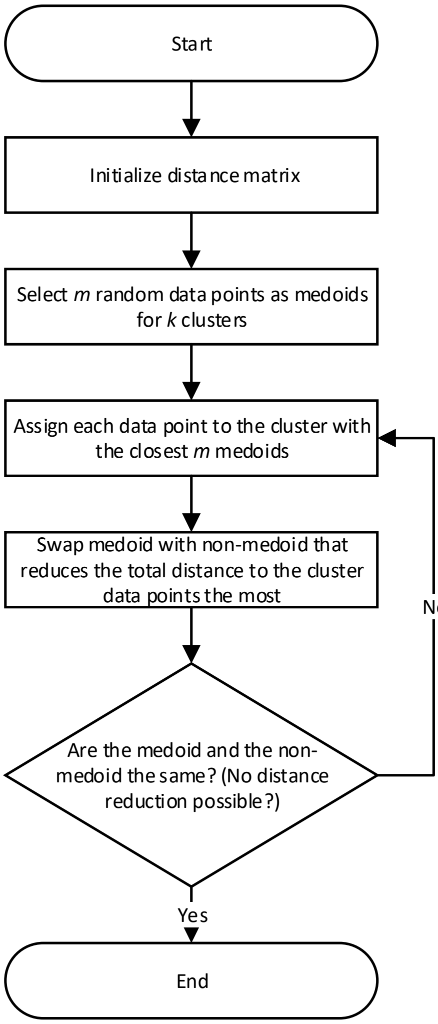


Figure A.3 Flowchart of the PAM algorithm used to solve k-medoids

B. Statistical techniques

When calculating confidence intervals based on multiple replications in the simulation, the confidence interval half-width $\delta(n, \alpha)$ relative to the sample mean $\bar{X}$ indicates the performance of the estimated mean. The confidence interval half-width is calculated with the following formula:

$$\delta(n, \alpha) = t_{n-1,1-\frac{\alpha}{2}} * \sqrt{S^2/n} \tag{B.1}$$

S^2 = the sample variance
n = the number of replications
α = the confidence level
$t_{n-1,1-\frac{\alpha}{2}}$ = t-value from the Student's t-distribution

Law (2015) presents a sequential procedure in which new replications are added one at a time to obtain an estimate of the mean with a specified relative error that takes only as many replications as are needed. We use this sequential procedure to determine how many replications we need to obtain a 95% confidence interval.

$$\frac{\delta(n, \alpha)}{\bar{X}} < \frac{\gamma}{1 + \gamma} \tag{B.2}$$

$\delta(n, \alpha)$ = the confidence interval half-width
$\bar{X}$ = the sample mean
γ = relative error

Law (2015) states that the relative error should be lower than 0.15. We use a relative error of 0.05 and a confidence level of 0.05 to determine the number of replications.

C. Model validation

Section 4.6.2 explains how the number of pallets generated per delivery zone on a production day is validated with reality. Intervals are chosen such that the expected observations of the real world are approximately equal. Table C.1 shows an example of how the test statistic X^2 is calculated for the delivery zone of pallet trailer 3B. This test statistic results in a p-value of 0.340 with the corresponding 5 degrees of freedom. A p-value higher than 0.05 implies that the number of pallets generated per delivery zone is equal to the number of pallets generated per delivery zone in the real world.

Interval	Observed	Real-world observation	Test Proportion	Expected	Contribution to Chi-Square
[0,206)	7	6	0.166667	6	0.167
[206,214)	6	6	0.166667	6	0.000
[214,223)	8	6	0.166667	6	0.667
[223,231)	6	6	0.166667	6	0.000
[231,237)	1	6	0.166667	6	4.167
[237,∞)	8	6	0.166667	6	0.667
					$X^2 =$ 5.667

Table C.1 A chi-square goodness-of-fit test for pallet requests data of zone pallet trailer 3B

Table C.2 shows the p-values of the chi-square goodness-of-fit test for all other delivery zones.

Delivery zone	p-value
Pallet trailer 1A	0.059
Pallet trailer 1B	0.951
Pallet trailer 1C	0.298
Pallet trailer 2A	0.295
Pallet trailer 2B	0.070
Pallet trailer 2C	0.152
Pallet trailer 3A	0.110
Pallet trailer 3B	0.340
Pallet trailer 3C	0.176

Table C.2 p-values of the chi-square goodness-of-fit tests for all pallet trailer delivery zones

D. Neighborhood structure

Our neighborhood structure contains swap and move operators. First, we randomly select a pallet trailer location or consumption location. When it is a pallet trailer location, we use the swap operator to switch the location. When it is a consumption location, there is a 50% probability of a swap and a 50% probability of a move.

D.1. Swap operator

A random position is chosen for all delivery zones and potential pallet trailer locations, this can be either a pallet trailer location or a consumption location. When the random position is a pallet trailer location, the position being swapped is a pallet trailer location that is already in use (Figure D.1) or a potential pallet trailer location (Figure D.2). When the random position is a consumption location, there is a 50% probability of a swap, and the position is swapped with a consumption location (Figure D.3).

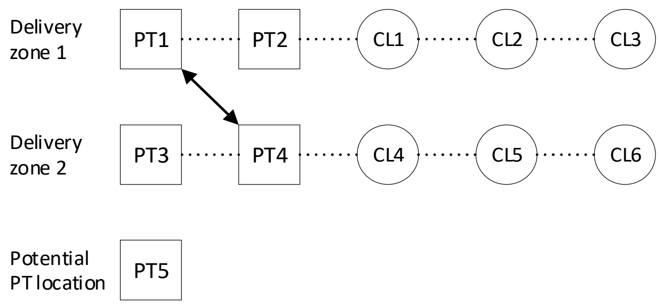


Figure D.1 Swap between used pallet trailer locations

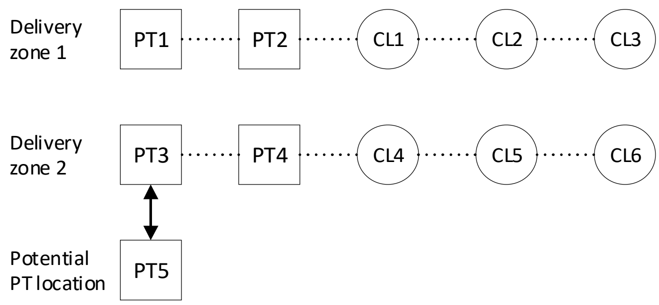


Figure D.2 Pallet trailer location swap with potential pallet trailer location

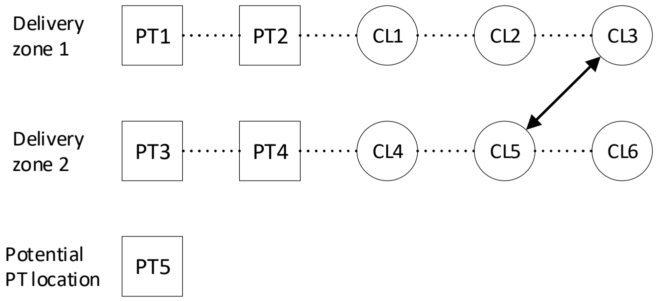


Figure D.3 Swap between consumption locations

D.2. Move operator

A random position is chosen for all delivery zones and potential pallet trailer locations, this can be either a pallet trailer location or a consumption location. When the random position is a consumption location, there is a 50% probability of a move, and the position is moved to another delivery zone (Figure D.4).

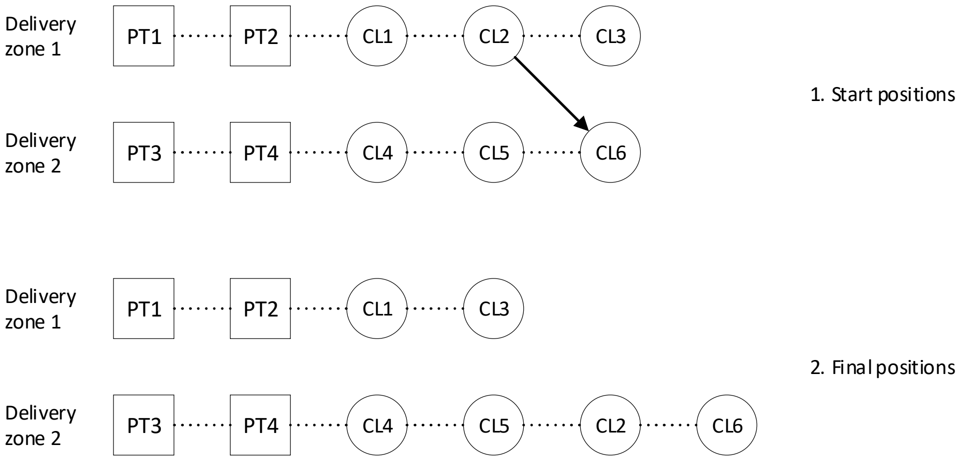


Figure D.4 Move consumption location to another delivery zone

E. Python packages

copy (Van Rossum, 2020)

csv (Van Rossum, 2020)

itertools (Van Rossum, 2020)

math (Van Rossum, 2020)

Matplotlib (Hunter, 2007)

Networkx: (Hagberg, Swart, & S Chult, 2008)

Numpy (Harris et al., 2020)

Pandas: (McKinney, 2010)

pickle (Van Rossum, 2020)

pyclustering (Novikov, 2019)

random (Van Rossum, 2020)

time (Van Rossum, 2020)