UNIVERSITY OF TWENTE

MASTER'S THESIS

Improving the internal sequencing logistics at Scania Production Zwolle

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Preface

With pleasure I present to you my master's thesis, which is the result of my graduation project at Scania Production Zwolle. This master's thesis is the final step in obtaining my master's degree in Industrial Engineering and Management from the University of Twente. I would like to thank several persons who contributed to this result.

I thank my colleagues at Scania for always having a helpful mindset and the good atmosphere. It made my graduation project into a pleasant period in which I learned a lot. In particular, I thank my company supervisor, Frank Beverdam, for his effort in guiding me during my graduation project.

I express my gratitude to my supervisors Marco Schutten and Peter Schuur of the University of Twente for always providing me with constructive feedback and guiding me in the right direction. With their expertise and insights, I was able to get my thesis at a higher level.

Finally, I thank my university colleagues for making my study time into a great study time during the past years. I especially had a great time working together on several projects with Carly, Sébastiaan, and Thom. Thank you all!

All that remains for me is to wish you a pleasant read.

Niek Kortenhorst, August 2019

Management summary

This thesis is about improving a part of the internal sequencing logistics at Scania Production Zwolle.

Scania is a large global manufacturer of trucks, busses, coaches, and engines. Scania Production Zwolle is Scania's largest truck assembly plant where two assembly lines provide the capacity to assemble a wide variety of trucks. The two main internal part supply methods to provide the workforce at the assembly line with the right parts are called factory feeding and line feeding. Line feeding uses intermediate on-site warehouses where parts are stored temporarily, whereas with factory feeding the parts are directly supplied to the assembly lines. This thesis focuses on the improvement of the internal sequencing supply method, which is a branch of the line feeding supply method. In this supply method, parts are picked on pallets in the warehouses from where the pallets must be transported to their destination in the factory. Reach trucks deliver the pallets to their destination in the factory.

Each pallet in the warehouse that is ready for delivery holds a card with the earliest assembly time of parts on that pallet. Reach truck drivers combine these times with observations of locations where a replenishment is possible, to determine which pallet to transport in a delivery tour. This need to drive around, combined with the fact that the times on the pallets are incorrect, results in a lowered productivity of the workforce responsible for the delivery of these pallets. The research question of this thesis is the following:

"How can we improve the productivity of the workforce responsible for the delivery of internal sequencing parts to the assembly lines?"

We divide our research in different phases to answer this research question. In the first phase we analyse the current situation of the internal sequencing supply method. Next, we evaluate the available literature related to our research to use as input for our solution alternatives. We come up with and evaluate the following alternatives for improving the productivity of the workforce responsible for the delivery of the internal sequencing pallets:

- **1 separated:** Providing the workforce with reliable information about pallet depletion and due times of the pallets ready for delivery. The workforce is allocated to different warehouses and is allowed to make their own delivery route.
- **1 merged:** Providing the workforce with reliable information about pallet depletion and due times of the pallets ready for delivery. The departments of the workforce responsible for the delivery of the pallets are merged. The workforce 'pool' serves both warehouses and is allowed to make their own delivery route.
- **2:** Generating delivery tours on request. The departments of the workforce responsible for the delivery of the pallets are merged. The workforce 'pool' serve both warehouses.
- **3:** Replacing the reach trucks with tugger trains for the alternatives *1 separated*, *1 merged*, and *2*.

We evaluate these alternatives by means of a simulation study. There are 7 FTE available under *alternative 1 separated*, just like the current situation. By merging the departments of the workforce responsible for the delivery of the pallets, we can reduce this number to 6 FTE in

total. Table 1 presents the results of the simulation study compared to the current situation, in which 'RTs' stands for reach trucks and 'TTs' for tugger trains. Providing the reach truck drivers with improved pallet depletion information and due times of pallets mainly results in an improvement of the lead time per pallet and the travelled distance per pallet. By merging the departments of the workforce and lowering the workforce to 6 FTE in total (*alternative 1 merged*) the average utilisation of the workforce increases and the lead time per pallet reduces. As there are more pallets transported per FTE while the lead time per pallet and distance per pallet decreased, the productivity of the workforce is improved. *Alternative 2* provides the workforce with a new delivery tour when requested. This reduces the distance per pallet even further compared to *alternative 1 merged*. As the utilisation dropped compared to *alternative 1 merged*, this alternative is able to handle more pallets if required.

	Reduction in				Increase in			
	lead time per pallet		distance per pallet		service level		average utilisation	
Alternative	RTs	TTs *(alt. 3)*	RTs	TTs *(alt. 3)*	RTs	TTs *(alt. 3)*	RTs	TTs *(alt. 3)*
1 separated	25.0%	23.4%	13.9%	-7.2%	0.33 p.p.	0.27 p.p.	0.9 p.p.	12.0 p.p.
1 merged	22.9%	19.1%	1.0%	-7.8%	0.36 p.p.	0.33 p.p.	20.3 p.p.	25.5 p.p.
2	24.8%	19.9%	11.8%	14.7%	0.30 p.p.	0.30 p.p.	13.1 p.p.	11.6 p.p.

TABLE 1: Simulation results of the alternatives compared to the current situation. 'RTs' stands for reach trucks, 'TTs' for tugger trains (alternative 3), and p.p. for percent point.

When using tugger trains (TTs) as means of transport, the travelled distance per pallet only improves under *alternative 2*. This is due to the construction of delivery tours. For the other alternatives, the distance per pallet increases when using tugger trains, mainly due to some one-way paths in the factory and the lower manoeuvrability of the tugger trains compared to reach trucks. The reduction in lead time per pallet is slightly lower when using tugger trains compared to reach trucks, due to the higher average number of pallets in a tour. The utilisation also is slightly lower when using tugger trains compared to using reach trucks.

Given that *(i)* reach trucks are already available for the transport of the pallets, *(ii)* not all pallet locations in the factory are suitable yet to be supplied by a tugger train, *(iii)* the better performance of reach trucks under *alternative 1 merged*, and *(iv)* the small difference in performance between reach trucks and tugger trains under *alternative 2*, we advise Scania to not invest in tugger trains. We advise Scania to start with the implementation of *alternative 1 merged* and later expand this to *alternative 2*, both using reach trucks as transport means. By doing so, Scania has an intermediate period in which the performance of the system can be evaluated and settings of trigger times in the ERP system can be adjusted, if necessary.

Implementing the proposed solution requires an application that is connected to the ERP system and to devices on the reach trucks. The application matches the bill-of-materials of every chassis, the production progress in the factory, and the picked pallets in the warehouses to provide the workforce with the correct information about what pallet to transport. For *alternative 2*, the application should be expanded with the algorithm assigning pallets to the reach trucks if a new delivery tour is requested.

Finally, we present our recommendations to Scania Production Zwolle. Table 2 presents these recommendations in a roadmap. The table is sorted on short term to longer term actions. The department represents the responsible department to execute the recommended action.

Priority	Action	Department
1	Investigate the possibilities to merge other logistic flows originating from the same warehouses that are not 100% flows (i.e. the parts not required for every chassis) with the internal sequencing supply method.	Logistical department
2	Investigate the use of AGVs as transport means for the internal sequencing supply method to reduce number of FTEs for the delivery of pallets.	Development department

TABLE 2: Roadmap of recommendations.

Contents

List of Abbreviations

Abbreviation	Meaning	Introduced on page
BP	**B**atch **P**icking	10
FF	**F**actory **F**eeding	1
FTE	**F**ull-**T**ime **E**quivalent	15
JIT	**J**ust **I**n **T**ime	1
LF	**L**ine **F**eeding	1
POU	**P**oint **O**f **U**se	10
RT	**R**each **T**ruck	42
SPZ	**S**cania **P**roduction **Z**wolle	1
TT	**T**ugger **T**rain	42
USB	**U**nit **S**upply **B**in	10
USP	**U**nit **S**upply **P**allet	10
WPL	**W**ork **PL**ace	9

1 Introduction

This report is the result of my master thesis project at Scania Production Zwolle, to obtain the degree master of science in Industrial Engineering and Management. First, Section 1.1 introduces Scania after which Section 1.2 explains the research motivation. Then, Section 1.3 identifies the core problem by means of a problem cluster that leads to the research objective. Finally, Section 1.4 describes the scope of the thesis and Section 1.5 describes the research questions with the approach we take and the structure of the report.

1.1 Scania

Scania is a large global manufacturer of trucks, busses, coaches, and engines. The company is founded in Sweden in 1891 and produced its first truck in 1902. Nowadays, Scania has around 50,000 employees in about 100 countries. Production units are in Europe and Latin America.

Scania Production Zwolle (SPZ) is the largest European assembly unit of Scania. About 2400 employees make sure that a wide variety of trucks are produced on two assembly lines. One of the core values of Scania is the elimination of waste in everything they do. This means, for the flow of parts, that Scania strives for just-in-time (JIT) delivery, both externally as well as internally.

1.2 Research motivation

The large variety of trucks produced at SPZ results in the need for different parts for different trucks, despite their interchangeability due to the modular production concept. All these parts need to be at the right place at the right time during production. Figure 1.1 presents the two main internal supply methods at SPZ: Factory Feeding (FF) and Line Feeding (LF).

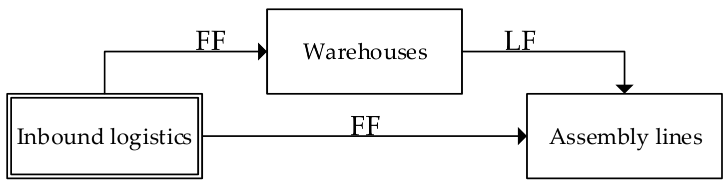

FIGURE 1.1: Internal logistics at Scania Production Zwolle.

After unloading the trailers with parts at inbound logistics, parts are stored in a warehouse or directly supplied to the assembly lines *(FF)*. FF from inbound logistics directly to the assembly lines is mainly used for large parts, such as engines and tires. LF uses three on-site warehouses for intermediate storage of parts before supplying the assembly lines. The main supply methods FF and LF can be subdivided into more specific supply methods. Chapter 2 describes these supply methods.

The flow of parts from one of these warehouses to the production line is not controlled in a way that satisfies Scania. This flow is the internal sequencing supply method. Chapter 2 describes the internal sequencing supply method. As opposed to other logistic processes at Scania, the logistic process from this warehouse to the production line is too much dependent on the experience and attentiveness of employees, which results in too many inefficiencies, waste, in the process. Because of this, the improvement potential is presumed to be high. Scania is looking for a solution to improve the productivity of these employees.

1.3 Core problem

The core problem can be found by means of a problem cluster. In a problem cluster the causal relationships are shown to identify the core problems. They can be identified by going upstream in the problem cluster. The causes that are hard to change or contribute little to the solution are no core problems (Heerkens & van Winden, 2012). Figure 1.2 presents the core problem. The red box indicates the experienced problem, the green boxes indicate potential core problems, and the yellow boxes the problems with little impact or which problems are hard to influence.

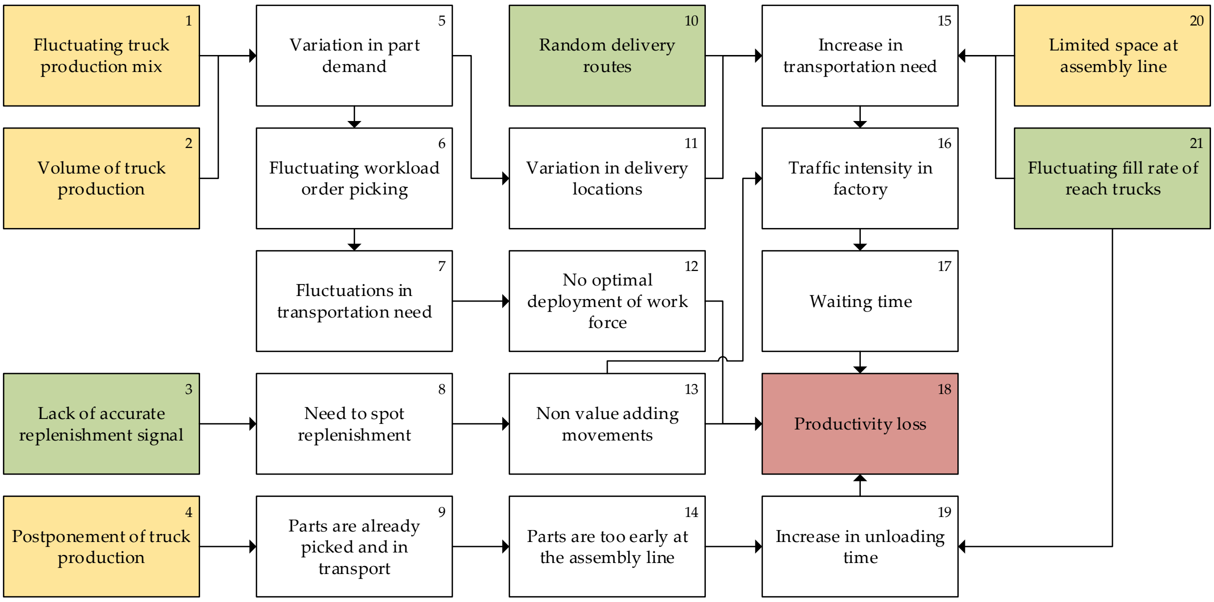

FIGURE 1.2: Problem cluster of part delivery process internal sequencing. Green = potential core problem. Yellow = problems with little impact or hard to influence problems. Red = experienced problem.

Figure 1.2 shows that the productivity loss is the experienced problem in the delivery process of the internal sequencing supply method *(18)*. Since SPZ uses JIT delivery of parts in their production process, a lot of parts need to be transported to the assembly lines. The replenishment frequency is high, as the space at the assembly lines is limited *(20)*. With the internal sequencing supply method, the delivery of parts is on pallets and fixtures by reach truck. These reach trucks can transport a stack of pallets or a single fixture. Reach truck drivers determine themselves how many pallets they stack up. This leads to a fluctuating fill rate of the reach trucks *(21)*. The fluctuating fill rate of reach trucks and the limited space, create an increase in transportation need *(15)*. When more transport is needed, the traffic intensity in the factory will increase *(16)*. The traffic intensity in the factory results in additional waiting time for the reach truck drivers and other moving equipment *(17)*. This waiting time contributes to the loss of productivity of reach truck drivers *(18)*.

Trucks are only produced if they are sold. This causes the truck production mix not to be the same each day *(1)* due to the large variety of possible configurations of a truck. Also, the number of trucks that need to be produced per day can fluctuate *(2)*. These factors influence the demand of parts at the assembly lines *(5)*. Some trucks require parts that are not needed on another truck. Moreover, the difference in required parts translate to different delivery locations of parts *(11)*. This non-recurring kind of demand, together with no predetermined delivery routes *(10)* and the causes explained in the preceding paragraph, creates an increase in transportation need *(15)*.

A consequence of variation in part demand is fluctuation in workload for the order pickers *(6)* since parts that are picked need to be transported to the assembly lines. The peak in workload is therefore also present for the reach truck drivers *(7)*. Due to the fluctuating workload for reach truck drivers, they are not always optimally deployed as the workforce is not very flexible in scaling up or down in manpower.

Order pickers start picking the orders based on the sequence of picking lists generated by the production system. They continue picking parts up to a certain time from which the next shift continues the picking. Full pallets and fixtures are temporarily placed in a buffer. As there is no accurate replenishment signal for parts at the assembly lines *(3)*, reach trucks drive around to spot replenishment needs *(8)*. This non-value adding movement *(13)* leads to increased traffic in the factory *(16)* and contributes to productivity loss of reach truck drivers *(18)*.

It happens that parts are not delivered to Scania on the time agreed upon. If this part is easy to install after the truck comes off one of the assembly lines, the truck will go into production and this part will be installed afterwards. If this part is not easy to install afterwards, the complete truck will not be assembled on the planned time but will be postponed instead. The postponement of the production of a truck can happen short before it is scheduled to be assembled. Parts for this truck are at that moment already picked and in transport *(9)* to one of the assembly lines. This means that the parts that are supposed to be assembled remain waiting at the assembly line until they are needed *(14)* and thereby disrupt the part feeding process. Additional movement of parts is necessary when other parts, that are needed earlier, are delivered at the same place at the assembly line. This, together with the number of pallets a reach truck stacks up *(21)*, result in an increase in unloading time *(19)*.

The three potential core problems identified in Figure 1.2 are:

- The lack of an accurate replenishment signal *(3)*
- The randomness of delivery routes *(10)*
- The fluctuating fill rate of reach trucks *(21)*

By solving the core problem(s) with the highest expected potential, the experienced problems will be solved as good as possible. By solving the lack of an accurate replenishment signal, non-value adding movements can be reduced which contribute to an improved productivity. Also, reducing this movement contribute to a decrease in traffic in the factory. Optimising the current randomness of the delivery routes together with the current fluctuating fill rate of reach trucks leads to a decrease in transportation need and thereby in traffic intensity in the factory. We identify the core problem as follows:

The lack of an accurate replenishment signal and random delivery routes for the internal sequencing supply method leads to inefficient use of equipment, causing a loss in productivity.

The objective of this research is to create a method to increase the productivity of the workforce responsible for the delivery of internal sequencing parts to the assembly lines. We translate this objective into the following research question:

"How can we improve the productivity of the workforce responsible for the delivery of internal sequencing parts to the assembly lines?"

1.4 Research scope

Different supply methods ensure the supply of parts to the assembly lines. Section 2.3 elaborates the different supply methods used at SPZ. This thesis covers a part of the flow from the on-site warehouses (named Hoogbouw and Laagbouw) to the assembly lines, which is the LF flow in Figure 1.1. Different supply methods are part of the LF flow, of which one is internal sequencing.

Internal sequencing comprises the flow of parts mainly originating from the warehouse 'Hoogbouw' (HB), and partly from the 'Laagbouw' (LB), and ends at the assembly lines. Picking of parts that production requires take place at these warehouses. Order pickers place the parts on pallets or on fixtures after which transport to the assembly lines takes place. Section 2.4 elaborates this supply method. This thesis focuses on this supply method, as there is no decent method to control this flow.

1.5 Research questions and approach

This section elaborates the research questions with the approach we take to answer them.

1. *What is the current situation regarding the supply of the internal sequencing flow?*
   Chapter 2 answers this question. The answers to the following sub-questions capture the current situation:

   (a) How is the assembly of a truck organised?
   (b) How is the production planned?
   (c) Which supply methods are used?
   (d) How is the internal sequencing flow organised?
   (e) What is the current performance of the internal sequencing flow from the warehouses to the assembly lines?

   We answer the first four sub-questions by consulting multiple people at SPZ and by gathering information from the intranet of SPZ. We gather data from the ERP system and perform measurements for the last sub-question.

2. *Which concepts and methods are described in literature that can be used to improve the productivity of the internal sequencing flow?*
   Chapter 3 answers this question. This chapter also addresses research problems with similarities to this research.
3. *How can the internal sequencing flow be organised to improve the productivity of the workforce?*
   (a) Which factors of the internal sequencing flow should be improved in order to increase the productivity of the workforce?
   (b) How can literature contribute to increasing the productivity of the workforce?

   Chapter 4 selects the factors to influence of the internal sequencing flow. Next, by combining the literature with the situation at SPZ, we propose alternative solution procedures to control the flow.
4. *What is the performance of the new proposed method of controlling the internal sequencing flow of parts?*
   Chapter 5 elaborates the simulation study to test the performance of the method proposed and presents the results of the simulation study.

The deliverables of this research are the following:

- Internal sequencing consumption location heat map dashboard.
- Solution design to control the internal sequencing supply method.
- This thesis report with current state analysis, solution design, and recommendations.

2 Current situation

This chapter elaborates the current situation to clarify the processes concerned with the internal sequencing flow from the HB and LB warehouse to the assembly lines. First, Section 2.1 explains the production process. Section 2.2 explains the planning process and Section 2.3 describes the supply methods used at SPZ. Section 2.4 elaborates the internal sequencing supply method. Finally, Section 2.5 investigates the current performance of the internal sequencing flow.

2.1 Production process

This section describes how Scania organises its production process at SPZ.

SPZ produces trucks on two different assembly lines. Figure 2.1 shows a map of SPZ. Factory building *1* situates the two assembly lines, factory building *2* is the HB warehouse, and factory building *3* is the LB warehouse. The other buildings are not relevant for this research.

Each assembly line is split up into several consecutive areas. Each area consists of multiple workplaces (WPLs). Figure 2.2 in Section 2.2 provides a schematic example of these areas and workplaces. The design of each workplace is specific for a single part or multiple parts. The production process starts with constructing the frame. Subsequently, the frame is moved to the first workplace of the assembly line. The 'truck' moves through the factory on the assembly line from this moment. Some parts are first pre-assembled before they can be assembled at the assembly line. Pre-assembly workplaces exists for these parts. At SPZ, production is working in two shifts to meet the required number of trucks to produce.

FIGURE 2.1: Map of SPZ. Scale: building 1 is 340 meters wide from left to right.

Takt time
Both assembly lines make use of a takt time. This is the available time for each workplace before the truck moves to the next workplace. This means that one finished truck leaves the factory after each takt time. A group of mechanics perform a predetermined set of tasks at each workplace. Work instructions detail these tasks. As not all trucks are the same, these tasks differ from truck to truck. To make sure all needed tasks at a workplace finish within the takt time, team leaders support where needed. Due to limited space around the assembly line and the JIT philosophy, parts must be present at the right location at the right time. Section 2.3 explains the different supply methods used to get parts at the right time at the right location.

2.2 Planning process

The production plan specifies which parts are needed when and where, causing transportation need. Section 2.2.1 elaborates the establishment of the production plan and Section 2.2.2 elaborates the usage of plan areas as they play a role in the part demand triggering.

2.2.1 Production plan

The planning of the production of a truck starts with the sale of a truck. The agreed delivery period determines in which production period the truck needs to be produced, to deliver on time. The global planning at the headquarters in Sweden allocates the trucks to produce to the production plants. Global planning takes restrictions of suppliers, as well as restrictions of production plants into account. With these restrictions in mind, SPZ receives a set of production orders that need to be produced in the specified production period. In the remainder of this section we elaborate how local planning at SPZ details its production plan for these production periods as this influences the moment when parts are required in the assembly process.

The production planners at SPZ take multiple sequence constraints into account while planning the production. These constraints are also called mixing rules. Mixing rules are needed to take technical limitations of the production line into account. Moreover, mixing rules are used to balance the workload for the mechanics as some trucks require more assembly time than other trucks due to their configuration. For instance, a truck with five axles is more complex than a truck with two axles. Regardless of the configuration of the truck, the mechanics at the assembly line have the same amount of time available, the takt time, for each truck they need to work on before it moves to the next station. A mixing rule can, for instance, make sure that only one out of five trucks is a truck with 4 or more axles. The production plan for SPZ is ready 20 days before the start of a production period. This plan is sent back to the headquarters after which the sequence cannot be changed anymore. However, it might happen that parts arrive late from suppliers at the SPZ plant. Therefore, the production plan is revised before every working day and adapted when necessary. If a truck cannot be produced for any reason whatsoever, it will be postponed without changing the planned sequence of the other trucks.

The revision of the production plan is done at night and is called a 'night-run'. This night-run makes sure the production system is synchronised again with the actual progress of production. Production can be ahead, on, or behind schedule, depending on the problems that occur. The production system assigns a planned consumption time to each part. Section 2.2.2 elaborates how this works. The production system does not update the consumption times during the day. So, if there are a lot of problems during production, the gap between the planned time of consumption and the actual time of consumption of parts increases. If there are few problems during production, it is possible to produce more trucks than planned. This can happen as the production schedule incorporates some slack time to cope with problems during production without running behind schedule immediately. So, when few problems occur, production can be ahead of schedule.

2.2.2 Plan areas

Both assembly lines consist of several plan areas. These plan areas consist of 1 up to 10 workplaces. Roughly, the design of plan areas is such that the truck must undergo a major change in the assembly process, such as the chassis receiving all the needed wiring and cabling, or the chassis receiving the engine. This explains the varying number of workplaces in a plan area. A truck moves from a workplace to its successive workplace after each takt time, as explained in Section 2.1.

We now demonstrate how plan areas and workplaces play a role in assigning consumption times to the parts required at a workplace. For the internal sequencing supply method, the production system triggers the request for parts, based on the planned arrival time of a chassis at the beginning of a plan area. Figure 2.2 schematically shows the structure of plan areas for the assembly line, as well as for pre-assemblies. Plan area *1* consists of 4 workplaces (WPLs) in this figure, starting with WPL *L11*. The dashed line indicates the time trigger for part requests at the pre-assembly (plan area *P1*). The time required at a pre-assembly to complete an assembly depends on the kind of parts to assemble. If plan area *P1* takes, for example, one hour to complete, the planned consumption time for the parts required at this plan area is one hour earlier than the planned arrival of the chassis at plan area *1*. The production system assigns the same consumption time to the parts required at different workplaces for the same chassis as the first workplace in that plan area. Through this, the parts that are not required at the first workstation of a plan area are assigned a wrong consumption time by the production system.

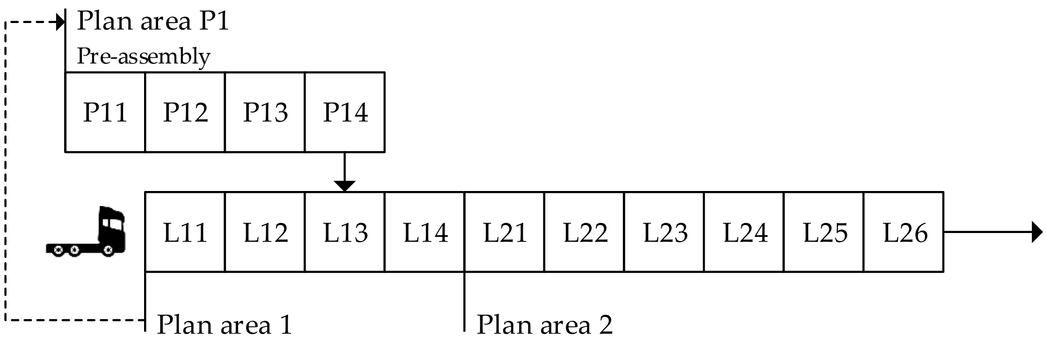

FIGURE 2.2: Structure of the plan areas and workplaces of the production system of the assembly lines at SPZ.

Due to the inaccurateness of the planned consumption times, parts arrive at the wrong moment at the assembly line. When the consumption location of a part is at the first workplace in a plan area, the planned consumption time is correct. Since the planned consumption time is the same for each workplace in a plan area, the planned consumption time for a part at, for instance, workplace 1 is the same as for a part at workplace 6. This means the larger a plan area is, the larger the difference between planned consumption time and real consumption time is. We call this the standard time error T_w^{error} for workplace w. Equation 2.1 shows the formula of this error. This error exists for each workplace at one of the assembly lines that is not the first in a plan area. We define T_w^{line} as the takt time of the corresponding assembly line of workplace w and P_w as the position number of workplace w. For example, WPL *L14* in Figure 2.2 has position number 4. This means that WPL *L14* has a standard time error of $T_w^{error} = (4-1) \cdot T_w^{line} = 3 \cdot T_w^{line}$.

$$T_w^{error} = (P_w - 1) \cdot T_w^{line} \tag{2.1}$$

2.3 Supply methods

In this section we elaborate the different internal supply methods at SPZ. The scope of this thesis is the internal sequencing supply method. Section 2.4 elaborates the internal sequencing supply method in more detail.

Working with the JIT principle requires good organised logistics. Every part needs to be at the right place at the right time to keep production running. SPZ uses different supply methods for the delivery of parts to their point-of-use (POU). The most suitable supply method for a part is determined based on its dimensions, consumption frequency, and space constraints at the line. The different supply methods used at SPZ are:

- **Unit Supply Pallet (USP)** – Placement of pallets with parts at the assembly line, without repacking the parts into another, smaller packing. Intermediate on-site storage of USPs happens before part consumption from the USPs at the assembly lines. A two-bin system regulates the replenishment of USPs and internal tugger trains facilitate the transport of USPs in a takt flow. This means the replenishment transport is scheduled in one of the tugger trains driving at fixed routes every couple of minutes. Figure 2.3 shows a tugger train without pallets.
- **Unit Supply Box (USB)** – Placement of boxes on special fixtures at the assembly line. Tugger trains facilitate the transport of the fixtures. Just like USPs, a two-bin system regulates the replenishment of USBs. USBs are often used for low value parts, such as nuts and bolts. Downsizing is sometimes applied to reduce the content per box, compared to the supplier package.
- **Batch Picking (BP)** – Placement of parts on special fixtures at the assembly line. Tugger trains facilitate the transport of the fixtures. Replenishments take place with a fixed interval of time. During replenishment, the complete fixture is swapped at the assembly line for a filled one, even if the current fixture is not empty yet.
- **Kitting** – Placement of parts on special fixtures or pallets at the assembly line. Tugger trains facilitate the transport of the fixtures. All parts in one kit are dedicated to a certain chassis number. The replenishment of fixtures is pull triggered and organised in a takt flow, meaning replenishment takes place after consumption of the parts. The replenishment of pallets is also pull triggered and not organised in a takt flow. Kitting is often used for lower frequency parts.

- **Consumption location kitting** – This supply method combines kitting with internal sequencing. It can be considered as an intermediate step to merge a non-takt flow with low frequency parts with a takt flow. Delivery of fixtures is organised according to the 1-2-4 principle. This principle indicates that a certain fixture is transported every train run, alternating on a train run, or one in four train runs. Depending on the consumption rate of parts, that are typically high for this flow, the transport of the fixture is one of these frequencies. Parts on the fixture are in sequence of truck production. Low frequency kits come from the HB warehouse and normal frequency kits from the LB warehouse.
- **External sequencing** – Used for high frequency chassis specific parts. Parts are presented to the assembly line in production sequence. Cabins, engines, and axles are examples of external sequencing parts. These parts arrive in the correct sequence from the suppliers and are temporarily stored in a buffer after which they are transported to the assembly line.
- **Internal sequencing** – Picking of parts on truck sequence at the HB warehouse and the LB warehouse. Reach trucks, shown in Figure 2.4, facilitate the transport of parts to the assembly line. This is a non-takt flow and is time driven. Lower frequency parts use this supply method. This thesis focuses on this supply method and Section 2.4 discusses this supply method in more detail.

FIGURE 2.3: Tugger train. *source: STILL*

FIGURE 2.4: Reach truck. *source: Toyota Material Handling*

2.4 Internal sequencing

This section describes the internal sequencing flow and gives insight in the flow characteristics.

Figure 2.5 presents the internal sequencing process. By means of this figure we explain the process steps involved in the internal sequencing supply method. The process starts with the production system generating sequence lists with parts that must be picked, based on the bill-of-material of the trucks to produce. The order pickers pick the parts and places them on a pallet. There are different sizes of pallets used in the internal sequencing supply method. Figure 2.9 presents an overview of the different pallet types. Engineers determine which pallet size is required at a consumption location based on the part sizes. A consumption location is the location where the pallet must be delivered to. The production system determines how many parts to include in a sequence list (the content of a pallet), either based on a maximum number of parts or based on the number of parts in a pre-determined time window, depending on which condition is met first. The amount of parts in a time window is the amount of parts planned for consumption during the length of that time window at the consumption location of the pallet.

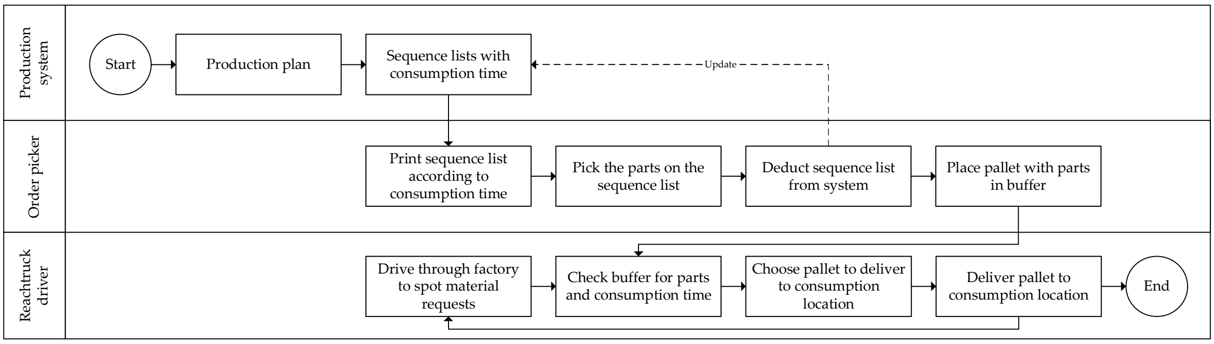

FIGURE 2.5: Process overview of the internal sequencing supply method.

The order picker places a finished pallet in a buffer before the transportation to its consumption location. It is the responsibility of reach truck drivers to make sure these pallets are at their consumption location in time. Because the planned consumption times on the pallets are not reliable, as we saw in Section 2.2, reach truck drivers need to visually check the consumption locations at the assembly line for a replenishment need, to prevent delivering pallets too early with the risk of the consumption location not being empty yet. Reach truck drivers choose themselves which pallets to transport in a run.

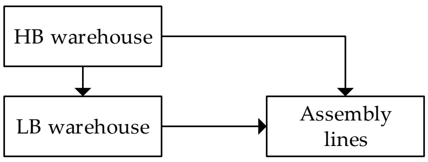

FIGURE 2.6: Pallet flow structure of the internal sequencing supply method.

When zooming in on the delivery part of the internal sequencing process, the process starts with the pickup of pallets at either the HB warehouse or the LB warehouse. Figure 2.6 shows the three different flows, namely, from the HB warehouse to the assembly line, the HB warehouse to the LB warehouse, and from the LB warehouse to the assembly line.

The pallets to deliver must be ready for transport if the reach truck driver wants to transport these pallets. Therefore, the order pickers start picking the orders approximately 6 hours before their planned consumption time. The picking process is a push organised process. This means, for the morning shift, that order picking continues until the planned consumption time on a sequence list reaches 20:00. The same thing happens in the evening shift. They continue order picking until the planned consumption time on a sequence list reaches 12:00. Subsequently, the

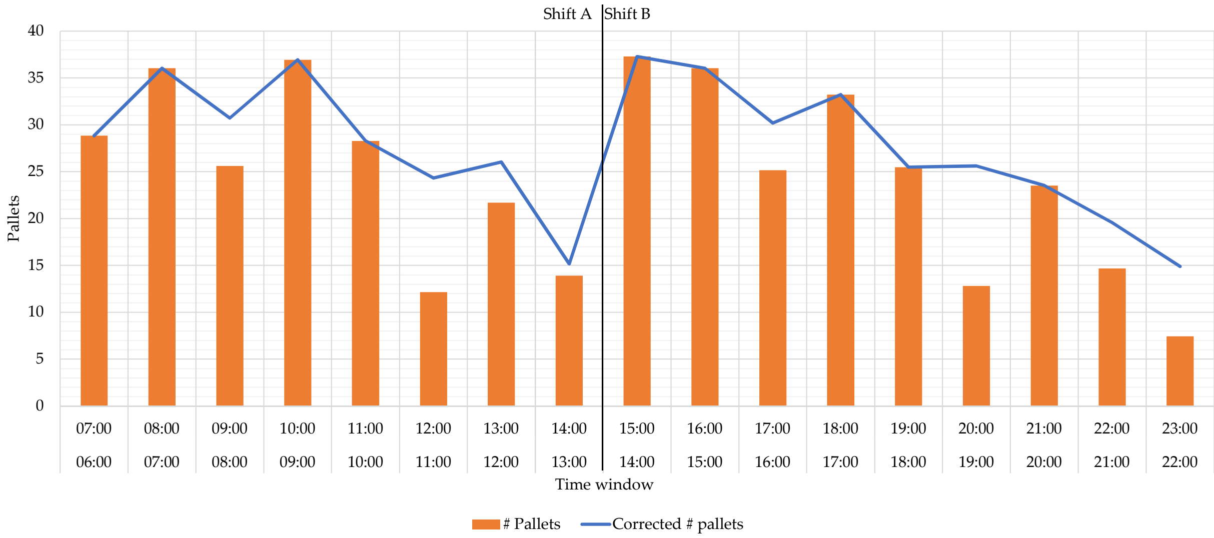

FIGURE 2.7: The average number of pallets picked per time window per production day. *Source: ERP Scania*

morning shift starts picking orders with a planned consumption time upward of 12:00. Figure 2.7 shows the average number of pallets picked per time window per production day. By means of this figure we show the process being push organised in the current situation. The average number of pallets picked per time window is based on the data of a period of two and a half month, starting from mid-August 2018. The figures presented in this chapter are based on this same period. The blue line in Figure 2.7 represents the number of pallets that would have been picked if picking continued during breaks. For example, if during a time window of 60 minutes a break of 10 minutes is held, the output without that break is calculated by multiplying the number of pallets by 6/5. By means of this line the breaks are eliminated as they can cause a biased view of the number of pallets picked in a time window. The bars in Figure 2.7 represent the actual average number of pallets picked per time window. When we combine this figure with observations in the warehouses and conversations with the responsible managers and order pickers, we conclude that pallets are available for transport on time. Moreover, these figures show that the workload of the order pickers is not evenly distributed over their shift; they work ahead of schedule by pushing the picked parts to the buffer. As the reach truck drivers act, among others, upon the pallets in the buffer, the risk of delivering a pallet to the assembly line too early becomes larger. One of the reasons for this to happen, is the consumption time on a pallet, acting as a replenishment signal, not being accurate as we explained in Section 2.2. Besides, the pallets in the buffer are not always sequenced on their planned consumption time. Therefore, reach truck drivers must search and sort the pallets before transport, causing additional material handling time.

Figure 2.8 shows the number of pallets transported for each of the three internal sequencing pallet flows, and the indexed number of chassis (trucks) produced on a day, with 100% being the average number of chassis produced per day in this period. By means of this figure we demonstrate the transportation need for pallets of the internal sequencing flow is not the same for every production day. There are several causes for this to happen, such as the production plan and unplanned line stops. If the production plan contains more chassis requiring parts

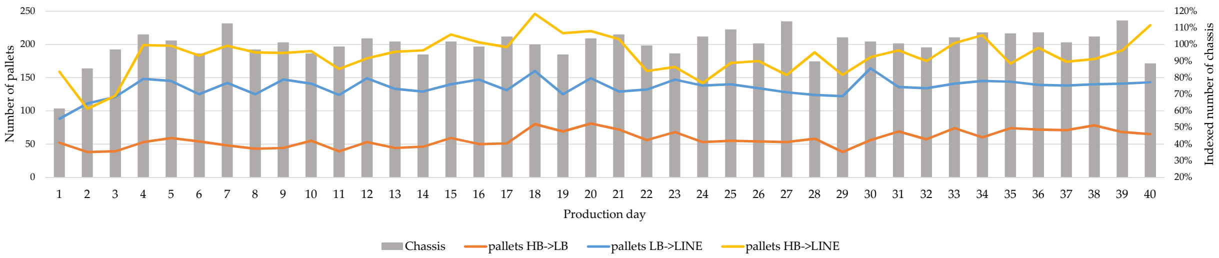

FIGURE 2.8: The number of pallets used versus the number of chassis produced on a production day. *Source: ERP Scania*

for which internal sequencing is the supply method, the number of pallets per chassis will increase. Also, the production plan mainly causes the fluctuating difference between the number of pallets to transport from each warehouse. At a production day, trucks may require more parts for which storage takes place in, for instance, the HB warehouse, whereas another day this could be the LB warehouse. If production cannot meet the production plan, the number of pallets to transport is less than the expected number of pallets to transport on that day. Hopp and Spearman (2008) classify the coefficient of variation as low variability if it is less than 0.75, as moderate variability if it is between 0.75 and 1.33, and as high variability if it is greater than 1.33. For each of the three pallet flows the variation in used number of pallets over the production days is low. The variation for the HB->LB, LB->LINE, and HB->LINE are 0.21, 0.10, and 0.15, respectively.

Pallet type usage

Reach truck drivers facilitate the transport of the internal sequencing pallets. The reach truck drivers are assigned to a warehouse from where they deliver the pallets to consumption locations. Two reach truck drivers deliver pallets from the HB warehouse to the line, one reach truck driver from the HB to the LB, and two from the LB warehouse to the line, per shift. Figure 2.9 shows the distribution of pallet types used. The first three types cover 84% of the pallets used. These types are EUR-pallets with collars and half EUR-pallets with collars.

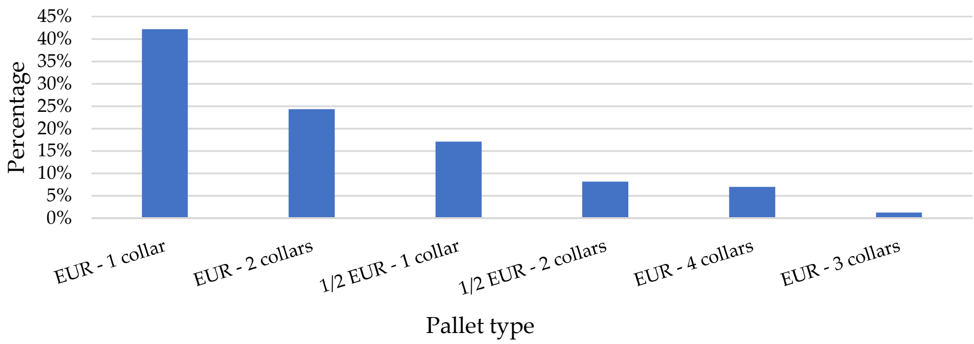

FIGURE 2.9: Distribution of the pallet type usage of the internal sequencing supply method. *Source: ERP Scania*

The capacity of a reach truck depends on which kind of pallets are loaded on the reach truck. A reach truck can transport multiple pallets at the same time by stacking them. At SPZ, the maximum stacking height of internal sequencing pallets during transport by reach truck is nine collars, where the pallet itself counts as one collar. So, for example, a reach truck may transport three EUR-pallets with two collars each. Two half EUR-pallets placed behind each other can be considered as one EUR-pallet. The height constraint is also valid for half EUR-pallets.

2.5 Performance internal sequencing

This section describes the performance of the internal sequencing flow. It addresses the work content of the workforce and the current productivity of the flow.

In the current situation reach truck drivers search the buffer for the pallets to transport to their consumption location, as pallets are not always put away in the buffer based on their planned consumption time. When pallets are not put away on the planned consumption time, additional sorting of pallets is required which costs extra handling time. The planned consumption time is generated by the production system and is updated during a night-run, which takes the actual production progress into account. If there is much delay during a production day, the printed planned consumption times of pallets that are planned for the next day are not accurate anymore and may be in the wrong sequence. Also, if there is a lot of delay during a production day, the actual consumption times are deviating more and more from the planned consumption times as the day progresses. This causes the reach truck drivers to drive through the factory to spot a replenishment need themselves.

Not all reach truck drivers are fully assigned to the transport of internal sequencing pallets. Table 2.1 shows for each driver what part of its work content is spent on the transport of pallets and what part on other activities. The HB->LINE(1), HB->LB, and LB->LINE(2) drivers have other activities in their work content whereas the other two drivers are dedicated to the transport of pallets. The LB->LINE(2) driver had additional activities next to the delivery of pallets that are not specified in its work description. It is not exactly traceable what part of its work content can be allocated to the delivery of pallets, but after consulting reach truck drivers and responsible managers, we determine the amount of time allocated to transporting pallets at 50%. Combining the figures in Table 2.1 result in a total of 3.66 FTE (full-time equivalent) per shift. As production takes place in two shifts, the total amount is 7.32 FTE.

Reach truck driver	HB->LINE(1)	HB->LINE(2)	HB->LB	LB->LINE(1)	LB->LINE(2)
Transporting pallets	76%	100%	40%	100%	50%
Other activities	24%	0%	60%	0%	50%
FTE (total)	1.52	2	0.8	2	1

TABLE 2.1: Work content reach truck drivers and the corresponding number of FTEs.

On average, there are 400 pallets to transport in the internal sequencing flow each day. As we saw in Figure 2.6 (Section 2.4), the pallet flow structure of the internal sequencing supply method consists of three different flows. The flow from the HB warehouse to the assembly line is the largest with an average of 185 pallets per day. There are two reach truck drivers responsible for the pallet transport of this flow. The number of pallets each driver (HB->LINE(1) and HB->LINE(2)) delivers is unknown as they choose themselves what to deliver, so we merge the two reach truck drivers into a single measure for this flow. The second largest flow is the flow from the LB warehouse to the assembly line where also two reach truck drivers (LB->LINE(1) and LB->LINE(2)) are responsible for the transport of pallets. The smallest flow is the flow from the HB warehouse to the LB warehouse. One reach truck driver (HB->LB) is responsible for the delivery of pallets in this flow.

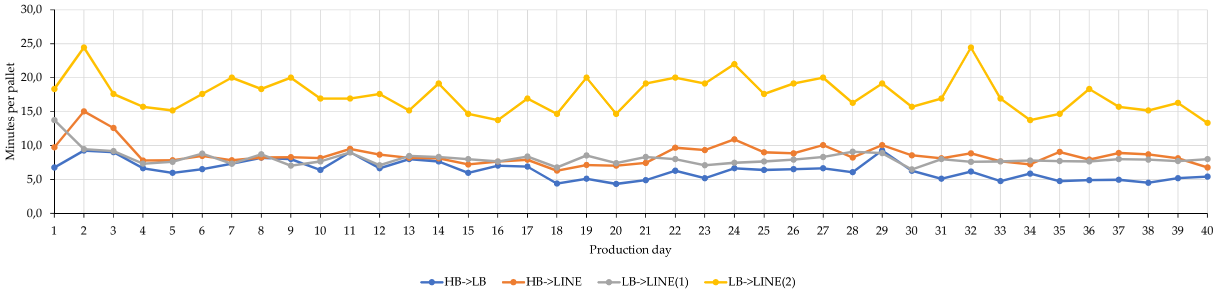

FIGURE 2.10: The average amount of time available for a reach truck driver to deliver one pallet. *Source: MRP Scania*

Figure 2.10 shows the amount of time available for the transport of a single pallet to its consumption location. The figure incorporates the percentage of time a reach truck driver has available to transport pallets and assumes that the pallets are evenly distributed throughout the day. By means of this figure we can compare the different flows. We observe that the LB->LINE(2) flow has the largest amount of time available per pallet, suggesting a large improvement potential there. However, reach trucks can transport more than one pallet at a time and the consumption locations of the pallets are different. No data is available about what is transported when, due to the fact that reach truck drivers determine themselves what to deliver in a delivery run, and due to the lack of data collection of this process. At the end of this section the theoretical productivity is calculated by using the available data and by measurement data.

Figure 2.10 divides the LB->LINE flow into two separate flows because different delivery strategies are used for these flows. The LB->LINE(1) flow is organised as a two-bin system with three dedicated pallets per consumption location in a closed loop. This means that there are two pallets located at the consumption location and one pallet located at the warehouse. A full pallet with picked parts in the warehouse is a signal to the reach truck driver that this location needs a replenishment. However, it is still unknown if the full pallet can be swapped for an empty one at its consumption location. A visual check (if one of the two-bins has emptied at the consumption location) by the reach truck driver is still necessary. The size of this flow is 110 pallets per day, on average. The LB->LINE(2) flow is, like the flow from the HB warehouse to the assembly lines, an open two-bin system. In these flows, there is no closed loop with dedicated pallets for a consumption location. This means that if there is no request for parts for a long time at a consumption location, no pallets will be assigned to this consumption location. This flow is the smallest flow, with an average of 26 pallets per day. The flow from the HB warehouse to the LB warehouse consists of 60 pallets per day, on average.

The flow from the HB warehouse to the LB warehouse is a different kind of flow (store-to-store). As opposed to the other flows, the destination of a pallet is not the consumption location of the parts on the pallet. For this flow, the consumption location is an intermediate step where the delivered pallet, originating from the HB warehouse, is stored in the LB warehouse and used as an order pick location. This pallet empties over time and scanning an empty pallet generates the replenishment signal. As the pallets in this flow have no consumption location as destination, a trigger method is already in place for this flow, and the relatively small flow size (15% of the total internal sequencing flow, on average), we exclude this flow from our research.

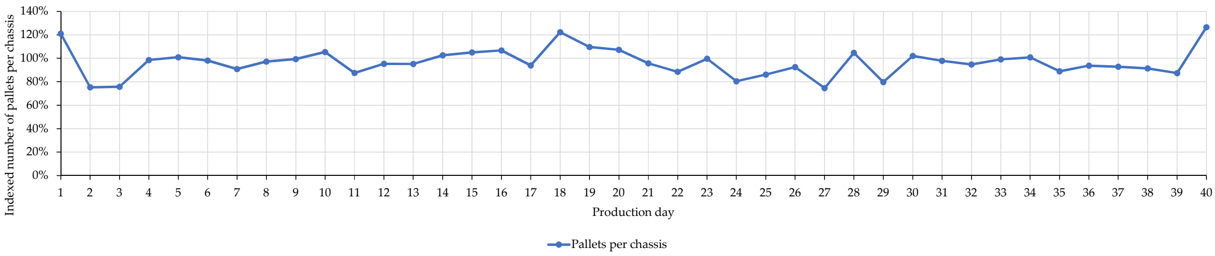

FIGURE 2.11: The indexed number of pallets per chassis per production day. *Source: MRP Scania*

Figure 2.11 shows the indexed number of pallets per chassis on a production day, with 100% being the average number of pallets per chassis per day. By means of this figure we show that the truck production mix causes fluctuation in the demand of parts delivered through the internal sequencing supply method. This variation in the number of pallets per chassis between production days cannot be taken away due to the mixing constraints of the production plan. The coefficient of variation of the number of internal sequencing pallets per chassis is 0.12 and can be classified as low variability (Hopp & Spearman, 2008).

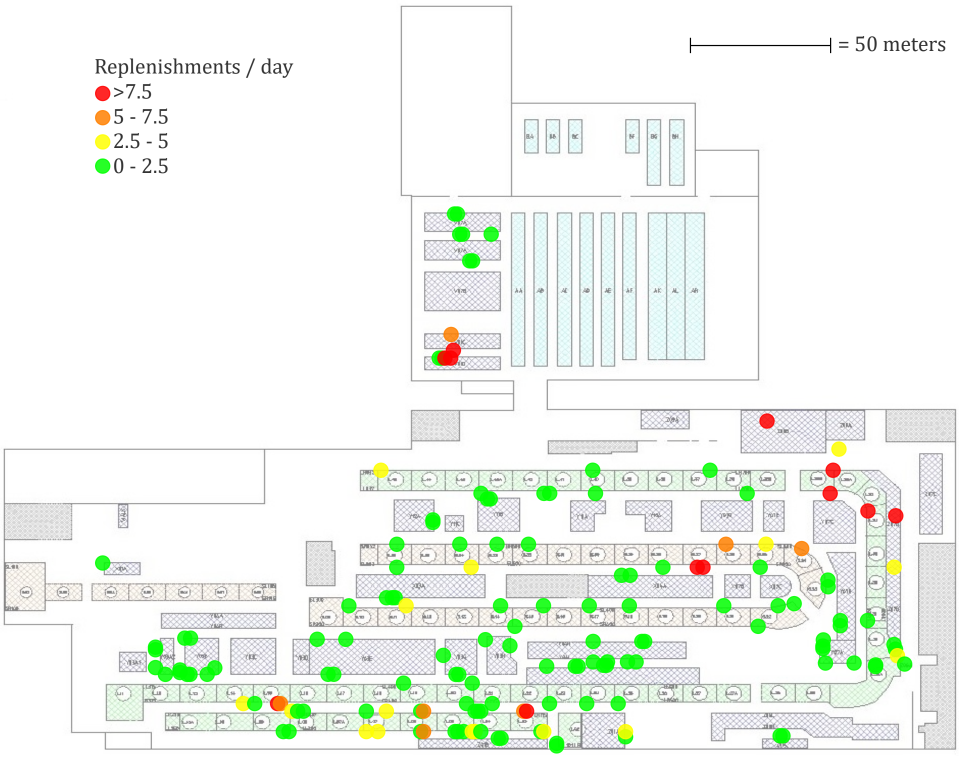

FIGURE 2.12: Heat map of the internal sequencing consumption locations. *Source: MRP Scania*

Another form of variation in the internal sequencing supply method is the variation in consumption location demand. There are 286 locations in the factory where consumption of internal sequencing parts can take place. As the need for parts depend on the production plan, the need per consumption location also varies. Figure 2.12 shows a heat map of the internal sequencing consumption locations to gain insight in the spread of these locations together with their average replenishment frequency. The orientation of the map is the same as in Figure 2.1. Buildings 1, 2, and 3 (see Figure 2.1) are visible in Figure 2.12. The heat map shows data of the same 40 production days as the other figures in this section. A green dot indicates a low replenishment frequency and a red dot a high replenishment frequency. The lowest value is 1 replenishment in 40 production days, and the highest value is 518 replenishments in 40 production days.

The delivery tours the reach truck drivers make differ in duration due to the spread of the consumption locations, the differences in replenishment frequency, and replenishment moment. A delivery tour can be broken down into different components. Figure 2.13 shows a delivery tour breakdown. The delivery tour starts with the pick-up of pallets at the warehouse, requiring on average 39 seconds per pallet with a 95% confidence interval of [29, 48] seconds. The transportation time is the time required for driving to the locations of a tour and can be deducted from the driving speed of a reach truck and the length of the tour. Due to other logistic movements in the factory there sometimes is no space to continue driving, forcing the reach truck driver to wait, which results in waiting time. Based on measurements of the waiting time of representative tours we found that the average waiting time is 13% of the tour transportation time with a 95% confidence interval of [9%, 16%]. The drop-off time is the time required for unloading the pallet from the reach truck and placing the pallet at its consumption location. The drop-off time is on average 49 seconds per pallet with a 95% confidence interval of [37, 62] seconds. In the current process situation, reach truck drivers make an additional tour through the factory to spot consumption locations demanding a replenishment. This additional tour can be of any length as the reach truck drivers base this tour on experience. Besides the fact that this additional tour is not contributing to the productivity of the reach truck drivers, it is also risky to base replenishments on the content of a pallet at a consumption location. It happens that a part is still on the pallet while it is meant for a postponed chassis. The mechanics are supposed to remove such a part from the pallet, but this is sometimes forgotten. Through this, the reach truck driver assumes no replenishment is required at the consumption location while this is not true. The pick-up time, drop-off time, and waiting time are determined by performing measurements, as little information is present about this process at SPZ.

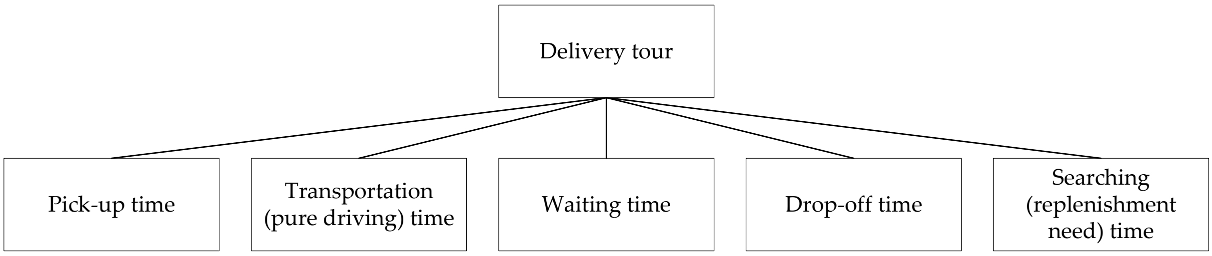

FIGURE 2.13: Internal sequencing delivery tour time breakdown.

Next to the pick-up time, transportation time, waiting time, drop-off time, and searching time there also is idle time. Idle time is the time the reach truck drivers are not busy with a delivery tour. As the duration of searching time and idle time are both unknown and depending on the reach truck driver, we merge these factors when calculating the theoretical productivity of the reach truck drivers. We define the productivity as the percentage of time available spent on the delivery tours excluding the searching times. We assume that on average 3 pallets are transported (2 pallets for the LB->LINE(2) flow due to pallet characteristics) in a delivery tour of 1200 meters. This is a representative tour length as observed during the measurements. The driving speed of reach trucks is 8 km/h. Furthermore, the productivity calculations are based on the time measurements and the number of pallets transported per day. For the HB->LINE reach truck drivers the productivity is 58%, for LB->LINE(1) 61% and LB-LINE(2) 60%.

2.6 Conclusions

This section presents the conclusions of the analysis about the current situation of the internal sequencing supply method at SPZ.

Scania Production Zwolle uses different part supply methods of which one of them is internal sequencing. With internal sequencing, an order picker picks parts and places them on pallets after which reach truck drivers transport these pallets to their consumption location. Reach truck drivers act on the planned consumption time that is on each pallet in the buffer and on the replenishment need they see while driving through the factory. The planned consumption times on the pallets to deliver are inaccurate due to the following causes:

- The standard time error (see Section 2.2).
- No updating of planned consumption times during the day.

The planned consumption time (the replenishment trigger) is one of the aspects that can be improved. Moreover, to increase the productivity of the reach truck drivers, a more accurate replenishment trigger provides the required reliable information by which the process can be improved.

The reach truck drivers responsible for the delivery of pallets from the HB warehouse to the assembly line and the reach truck drivers responsible for the delivery of pallets from the LB warehouse to the assembly line, belong in the current situation to different departments. Because of this, the delivery of pallets from these warehouses to the assembly line is also separated. As the consumption locations of the parts originating from both warehouses are spread through the factory, it happens that two consumption locations with a demand time close together are also located close together, while different reach truck drivers deliver the parts to these locations. This makes the combined delivery of pallets from both warehouses to the assembly line a viable aspect to contribute to the final solution. Besides, the transportation need per day depends on the production plan as not all chassis require the same parts. The consumption locations of these parts are also depending on the production plan. This makes every day unique in terms of pallet volumes and consumption locations, requiring a solution suitable for that day.

As the order pickers in the warehouse work push driven, the pallet buffer often contains a large number of pallets ready for transport. Reach truck drivers must search this buffer for the correct pallet to transport, resulting in additional material handling time. Another drawback of this full buffer is the possibility of early delivery of parts to the assembly line. When parts arrive early at their consumption location, there might be no space to place the parts at the consumption location as the preceding pallet with parts is not empty yet. The inaccurate replenishment signal is the main cause for the early delivery of pallets to the line. It causes the planned consumption time on the pallets to be inaccurate, resulting in wrong delivery moments.

The full buffer, combined with random delivery tours, can result in late delivery of pallets. In the current situation, there is no check for the reach truck drivers that they delivered everything they need to deliver. If they overlook a pallet in the buffer and they have not visually checked the location in the factory (spotted a replenishment need), it is possible that the pallet will be delivered late. When a part is late at its consumption location, a rush transport by the team leader of the warehouse is used. Obviously, this is not preferable.

The productivity of the reach truck drivers for the HB->LINE, LB->LINE(1), and LB->LINE(2) are 58%, 61%, and 60%, respectively. The main factors influencing this measure are the searching time, idle time, and the division of work among the reach truck drivers.

3 Literature review

This chapter describes the literature related to this research and investigates in what way it can contribute to our research. Section 3.1 describes the assembly line types described in literature and identifies the assembly line type at SPZ. Thereafter, the section describes the planning problems concerned with this assembly line type. Section 3.2 presents different process steps of in-house logistics and part supply methods described in literature. Section 3.3 describes push and pull part supply and thereafter it describes solution procedures to the problem identified in Section 3.1.

3.1 Assembly line types

In this section we present the different kind of assembly lines literature describes to identify the assembly line type of SPZ. Next, we elaborate the different planning problems associated with that assembly line type, in order to identify the problem type at hand.

An assembly line is a flow-oriented production system where operations are performed at sequential stations (Boysen, Fliedner, & Scholl, 2007). Literature distinguishes different kind of assembly line types: the Single-Model assembly line, the Multi-Model assembly line, and the Mixed-Model assembly line (Becker & Scholl, 2006; Kabir & Tabucanon, 1995). Single-Model assembly lines facilitate the production of one type of product; the assembly line is not designed for the production of another product type. Multi-Model assembly lines facilitate the production of multiple product types. The production of these products is typically organised in batches. The assembly line requires setup operations to produce the next batch. Mixed-Model assembly lines facilitate the production of multiple product types at random sequence. The design of the assembly line is such that no setup operations between different product types are necessary. Figure 3.1 schematically shows the three different types of assembly lines.

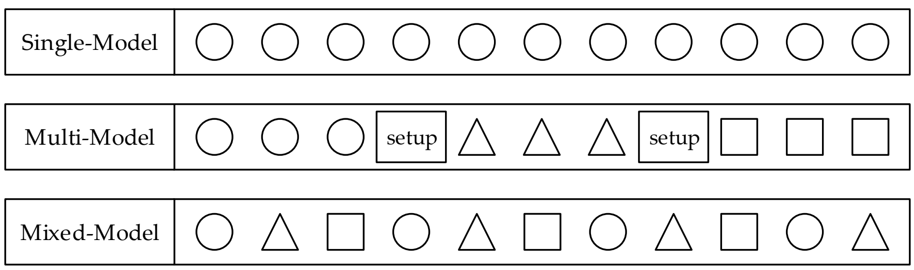

FIGURE 3.1: Different types of assembly lines. Adapted from: *Becker and Scholl, 2006*

Scania uses mixed-model assembly lines for the production of their trucks, as they produce different truck configurations and types in a mixed sequence on the same assembly line. Therefore, the remainder of this chapter only considers the mixed-model assembly line type.

Planning problems of Mixed-Model assembly lines
Where production of a lot of different products take place at the same assembly line, the Mixed-Model assembly line is often used as it can cope with almost every arbitrary production mix. However, planning problems arise with high-variant Mixed-Model assembly lines. The main planning problems associated with this type of assembly line are the following (Golz, Gujjula, Günther, Rinderer, & Ziegler, 2012):

- **Line balancing** – The determination of configuration of the assembly line including the takt time, the number of stations, where certain operations take place, and the type of equipment to use. The main objectives in literature are the reduction of stations together with the distribution of the workload over the stations.
- **Master production scheduling** – The assignment of production orders to time-slots over a planning horizon of several weeks. Scania's headquarters in Sweden determines the master production schedule for the different production plants. SPZ receives this master production schedule and starts making the production sequence.
- **Production sequencing** – The planning of production sequence for each time-slot available. Boysen, Fliedner, and Scholl (2009) performed a literature study on three alternative approaches for the production sequencing problem; *mixed-model sequencing, car sequencing, and level scheduling*. Typically, the mixed-model sequencing alternative balances the assembly line by averaging the different processing times of products to determine the takt time, whereas car sequencing considers the succession of work intensive operations to prevent work overload at the stations. These alternatives do not take the supply of parts in account as opposed to level scheduling. This alternative focuses on finding a production sequence that balances the part supply to facilitate just-in-time deliveries and minimise safety stocks. As the internal sequencing flow is just a small part of the existing internal supply flows at SPZ, level scheduling cannot be applied solely to the internal sequencing flow as it will result in disruptions in the other flows.
- **Resequencing** – The rescheduling of production in case of production disruptions due to, for instance, technical failures or late arrival of parts at the factory.
- **Material flow control** – Making sure parts arrive at the right place at the right time at the assembly line.

Section 3.3 explores the 'material flow control' planning problem as it is relevant to our research. The other planning problems defined by Golz et al. (2012) lie outside the scope of this research.

3.2 In-house logistics

As Section 3.1 presents, material flow control for mixed-model assembly lines is the planning problem at hand. Since the internal sequencing supply method is about the delivery of parts to their point-of-use, we now look into the process of in-house logistics for mixed-model assembly lines.

In-house logistics aims at getting the right parts at the right place at the right time. Boysen, Emde, Hoeck, and Kauderer (2015) set up a framework for the core process steps of in-house logistics. Figure 3.2 presents these core process steps of in-house logistics. In this figure, the assembly process takes place between 'line side presentation' and 'return of empties'. The return of empties comprises the return of empty packaging, such as pallets. In this framework, 'Delivery to line' is the scope of our research. Section 3.3 presents the relevant literature available on this topic.

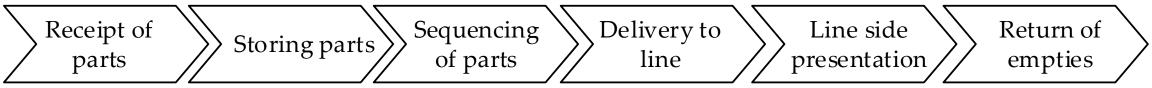

FIGURE 3.2: Core process steps of in-house logistics. Adapted from: *Boysen, Emde, Hoeck, and Kauderer, 2015*

Swaminathan and Nitsch (2007) introduce the concept of sequencing points in the logistic process of part supply. Sequencing is the placement of parts in the sequence final assembly requires and takes place at the supplier, on-site warehouse, or assembly line. Figure 3.3 schematically shows the sequencing points with their corresponding concept names JIS, JIT, and LOT:

- **Just-In-Sequence (JIS)** – Synchronisation of the suppliers' and buyers' production to make sequenced part delivery possible (Wagner & Silveira-Camargos, 2012). Just-in-sequence is complementary to just-in-time.
- **Just-In-Time (JIT)** – The delivery of parts to their consumption location in the right quality, quantity, and time (Heinecke, Lamparter, Lepratti, & Kunz, 2013).
- **Lot-wise (LOT)** – The supply of parts in homogeneous bins to the assembly line where assembly workers need to grab the correct part from the bin (Boysen et al., 2015).

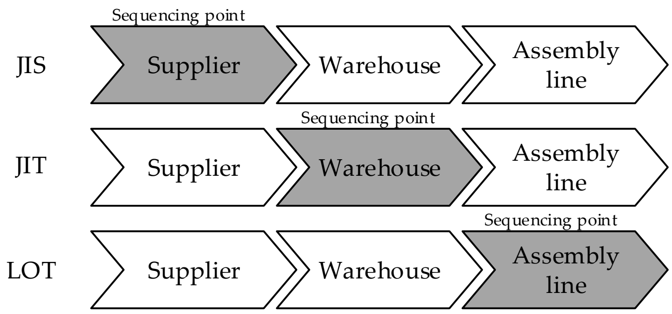

FIGURE 3.3: Different pathways through the logistics process. Adapted from: *Boysen, Emde, Hoeck, and Kauderer, 2015*

Literature describes several part supply methods applicable to mixed-model assembly lines. The main methods are the following:

- **Continuous supply** – Storage of all parts that the assembly process requires in individual boxes (lot-wise) at the assembly line (Sali, Sahin, & Patchong, 2015). This supply method is also referred to as line stocking in literature.
- **Kitting** – Boysen et al. (2015) describe kitting as the JIT supply of in-house sequenced parts. A kit is a container holding a specific assortment of parts, meant for one or more assembly operations (Bozer & McGinnis, 1992). Sali et al. (2015) distinguish two types of kits, namely:
  - **Stationary kit** – A kit is stationary if the consumption of parts from that kit take place at an unique workstation at the assembly line.

  - **Travelling kit** – A kit is travelling if the consumption of parts from that kit take place at different workstations along the assembly line while the kit travels with the end product requiring the parts through the assembly process.
- **Sequencing** – Sequencing is a particular form of the stationary kit where, in this case, the assortment is made of one and only one particular type of part (Sali et al., 2015).

We observe that the designation of the part supply methods in literature does not exactly match the designation of the part supply methods that Scania uses. For instance, continuous supply corresponds to Scania's unit supply and sequencing corresponds to Scania's batch picking (see Chapter 2). At Scania, a couple of different variants of kitting exist, but not like the travelling kit. Scania's internal sequencing supply method (the scope of this research) most closely matches a stationary kit in literature. The characteristic of a kit (as we saw in Figure 3.3) is that its sequencing point is at the in-house warehouse where picking of parts takes place.

3.3 Material flow control

In this section we present the relevant literature on material flow control for mixed-model assembly lines. We first discuss the concept of push and pull part supply. Thereafter, we present different solution procedures proposed in literature to the material flow control planning problem.

Push organised part supply systems are considered to be based on predictable events, extracted from, for instance, an MRP system (Pyke & Cohen, 1990). This means that the replenishment signal of parts is based on the predicted consumption of these parts. The counterpart of a push system is a pull system. A pull organised part supply system is a more service oriented and reactive system (Pyke & Cohen, 1990). Often, Kanban is applied to trigger a replenishment request. A Kanban can be any kind of signal (Rahman, Sharif, & Esa, 2013). The drawback of a pure Kanban system is that the deterministic information available through, for instance, an MRP system is not utilised as replenishments are based on a certain critical stock level. As a result, one can be "surprised" by replenishment requests (Emde & Boysen, 2012). The internal sequencing supply method at SPZ is partly push organised as the consumption times (and thereby their replenishment signal) of parts are determined during the night run. A weakness of this concept is that consumption times are not updated during the day. However, in the current situation, a replenishment need is visually checked at the consumption location, making it also partly a pull system.

For in-plant JIT delivery of parts to assembly lines, the milk run system is an often applied transportation concept. The milk run system is named after the traditional system of the milkman selling and delivering bottles filled with milk in a specified route from door to door combined with taking back empty bottles (Sadjadi, Jafari, & Amini, 2009). During a milk run for the in-plant JIT delivery of parts, multiple stations are supplied in a cycle. A supply cycle starts every certain period of time (Alnahhal & Noche, 2015). The delivery tours of the reach trucks closely matches a milk-run system, except the supply cycles of the reach trucks not starting every period of time. This is caused by the reach truck drivers choosing which pallet to transport when. To improve the current process, a higher level of information is required for making decisions about what to do when.

Klenk, Galka, and Günthner (2015) propose different strategies for handling peaks in the demand of milk-run systems. They aim at the delivery of all orders via the standard process, that is, the milk-run tours. However, if demand exceeds the capacity of a tour, exceeding orders must be delivered in a different way. The first strategy Klenk et al. (2015) propose to handle these orders is to initiate an exception transport. The exceeding order is transported immediately with a special vehicle dedicated for these transports. The second strategy proposed is an exception tour. The difference compared to the first strategy is that multiple orders exceeding the capacity of a tour are delivered in one run, rather than these orders being transported individually. The third and last strategy that Klenk et al. (2015) propose is to shift the order to the next tour by postponing it. This is possible if there is enough time to do so without violating the delivery time of that order. If it is not possible to postpone an order, the first strategy is applied to that order. The lowest total cost occur with the third strategy. The second strategy is found to be slightly more expensive, and operates at higher capacity utilisation making it more vulnerable to exceeding capacity in situations with higher variation in demand. If variation is low, the first strategy can be a good alternative. Also, the first strategy is useful when the lead-time of parts is critical. The main disadvantage of the strategies proposed by Klenk et al. (2015) is the assumption of fixed and equal travel times for all delivery tours.

Choi and Lee (2002) present a part feeding method that takes the actual production progress into account when dynamically assigning transport orders to transport vehicles. The dynamic feeding algorithm consists of two steps. In the first step the parts that require a replenishment, based on the production progress, are added to a 'parts to be fed' list. This list is then used as input for the second step of the algorithm in which transport orders for these parts are assigned to transport vehicles and routes are formed. Choi and Lee (2002) calculate an ideal feeding point in time for each part at a workstation and introduce a penalty function for early or late delivery of parts. An insertion heuristic method is proposed for the construction of delivery routes. This insertion heuristic takes the penalty function into account during route construction. The part feeding method presented approximately results in a 10% decrease in average inventory level in the system and 30% lesser feeding cycles.

Golz et al. (2012) state that the major disadvantage of a Kanban system is that a signal for part request is transmitted only if a certain stock level is reached, and that delivery tours are performed in a constant time interval and on predetermined routes (milk runs). Thereby, emergency tours are required in case of stock-outs due to no anticipation of future material demand. To overcome the weakness of a classical milk run system, Golz et al. (2012) propose a two-step heuristic solution procedure. In the first step they dynamically generate tours based on predicted transportation orders derived from the bill-of-materials of the products in the assembly sequence. This can be done per day or per shift, for example. Tour scheduling takes place in the second step. Golz et al. (2012) come up with this solution approach since a mixed-integer linear program (MILP) is impractical due to its excessive computational time for real-life problem instances. Their approach results, on average, in a 34% reduction of required drivers. The main conceptual difference between the approach of Golz et al. (2012) and a Kanban approach is that the latter reacts on replenishment signals while the approach proposed anticipates on the parts needed at an assembly station.

Table 3.1 gives an overview of the literature related to material flow control for mixed-model assembly lines, like the internal sequencing supply method of Scania. The commonality of the solutions proposed, is the utilisation of detailed data about the production sequence to schedule the part feeding process. In the current situation of the internal sequencing supply method at SPZ, there is no planning or scheduling of the delivery tours. Also, consumption times of the parts are not updated during the day, neglecting production progress.

Klenk et al. (2015)	Three alternative methods for handling peaks in stochastic Kanban orders. Two alternatives deploy exception transports, one alternative aims at shifting orders in case of standard transportation capacity shortage.
Choi and Lee (2002)	Part feeding method in which a parts to be fed list is updated according to production progress. An ideal feeding point in time is calculated by utilising demand estimates. An insertion heuristic constructs the delivery routes while taking the penalties regarding the ideal feeding point in time into account.
Golz et al. (2012)	Two-step heuristic solution procedure for generating tours, based on predictive orders derived from the bill-of-materials, and for scheduling the tours that can be deployed once a day or once a shift, for example.

TABLE 3.1: Overview of the methods proposed in literature for material flow control suitable for the internal sequencing supply method at SPZ.

In Chapter 4, we propose alternative methods, inspired by the literature found, to improve the productivity of the reach truck drivers while taking into account the bill-of-materials of a truck and the production progress in the factory.

4 Solution design

In this chapter we propose three alternative solution procedures to improve the internal sequencing supply method based on our findings from the previous chapters. In Section 4.1 we introduce the alternatives briefly. Section 4.2 elaborates the first alternative solution, Section 4.3 the second alternative solution, and Section 4.4 the third alternative solution. In Section 4.5 we give a short recap of the three alternatives.

4.1 Introduction of solution alternatives

In this section we first discuss shortcomings of the current situation and how we cope with them. Then, we introduce the alternative solution procedures. In the next sections we discuss these alternatives in detail.

In the current situation, reach truck drivers have no information available about the number of parts on a pallet at the consumption locations in the factory. Therefore, reach truck drivers observe if one of the two pallets at a certain consumption location is empty by driving along the consumption locations. As their delivery routes do not pass all consumption locations in the factory, but only the locations to replenish in the current tour and the locations on the route to these locations, reach truck drivers need to drive a larger route to also drive along other consumption locations. Next to the unknown depletion moment of pallets in the factory, the ERP system generates the scheduled consumption time for the parts to assemble after the night run of the system. These times are incorrect (see Chapter 2). Thereby, reach truck drivers must combine their observations in the factory with pallets ready for delivery in the warehouse to decide what pallets to deliver when. Improving the productivity of the reach truck drivers requires in the first place correct planned consumption times of parts. With wrong planned consumption times, it remains impossible to base pallet delivery choices on these times. The next step is to provide the reach truck drivers with more accurate consumption times of parts, based on the production progress. Thereby, we eliminate the need for the reach truck drivers to drive around to observe which consumption locations have space (an empty bin) for a replenishment. We do not consider the return flow of pallets, as the pallets either go to pallet breakdown after usage, or sometimes the reach truck drivers take the pallet back to the warehouse, which does not have significant impact on delivery times as the reach truck driver already has to drive to the warehouse.

Another characteristic of the current situation is the division of reach truck drivers over the different departments in the warehouses. Two reach truck drivers belong to the HB warehouse, and two to the LB warehouse. Reach truck drivers in the LB warehouse belong to different departments, we call them LB1 and LB2. Reach truck drivers do not assist another department but only serve, for example, from the HB warehouse. An advantage of the current situation is an easier to manage situation regarding the responsibilities of the reach truck drivers. For instance, if a pallet is delivered late, it is easier to remind the responsible reach truck driver its responsibilities. On the other hand, by assigning the reach truck drivers to different departments, the workload is not levelled over the reach truck drivers as they do not assist other departments. We investigate the effect of creating a pool of reach trucks serving the different warehouses in the simulation study in Chapter 5.

As an addition to correct planned consumption times of parts on pallets, we can also determine for the reach truck drivers what to deliver in a tour. Thereby, we make sure that good delivery tours are produced and less experienced reach truck drivers are able to do the job properly, since we found that this is not always the case. We can construct delivery tours for a period of time upfront the execution of the tour (offline planning) or construct tours just before the execution of the delivery tour (online planning). We choose to not construct delivery tours for a period of time (offline planning) due to the uncertainties to deal with in that case. One of them is stochastic delivery tour duration. We could deal with this by introducing slack time between every delivery moment to make sure pallets arrive in time at their destination. Another way to deal with the stochastic tour duration is to monitor the progress of the delivery tour and adjust or recalculate the next delivery tours. Dealing with stochastic tour duration when planning the delivery tours offline already is challenging, and we are not even considering deviations in production progress yet. For instance, assume that we have pallets with destinations at both assembly lines in the same delivery tour. If production on one of the assembly lines stops for a period of time, we have problems with the delivery tours with pallet destinations at both assembly lines as they are not consuming parts at the initially planned consumption times anymore. By having pallets for both assembly lines in separate tours, we can reduce this risk, but we will lose some productivity instead. Besides, we also need to deal with pallets with pre-assembly workplaces as destination. As it is possible for pre-assembly stations to work up to an hour ahead of schedule, it is hard to incorporate this deviation in the delivery tours when constructing them offline. For these reasons we do not design an alternative for offline planning of delivery tours.

We propose three different alternatives to improve the internal sequencing pallet delivery process. The alternatives in short:

1. Alternative 1 provides the reach truck drivers with improved information about the pallet depletion moment. We let the reach truck drivers themselves choose what pallets to transport when. The main difference between this alternative and the current situation is that we eliminate the need for visually checking the consumption locations in the factory for a replenishment need. By eliminating this need, a non-value adding process step is excluded from the internal sequencing supply method, saving the reach truck drivers time.
2. Alternative 2 constructs delivery tours just before the execution of the tour. Thereby, we can cope with unplanned line stops, stochastic tour duration, and pre-assembly stations working at varying paces. We have no restriction on combining different possible consumption locations in the delivery tours. For example, it is possible to have pallets for consumption locations of both assembly lines in the same delivery tour.
3. Alternative 3 replaces reach trucks by tugger trains. In this alternative we evaluate alternative 1 and 2 again, but now with tugger trains as means of transport. Tugger trains are able to transport up to 4 EUR-pallet positions or 8 half EUR-pallet positions in a delivery tour, without the need to stack the pallets. This results in the possibility to drop stacking height constraints, providing more flexibility in combining different packaging sizes in one delivery tour.

4.2 Alternative 1

This section describes the first alternative solution procedure. This alternative is close to the current situation. The main difference is that this alternative provides information to the reach truck drivers about what pallets can be transported to their consumption location, based on pallet depletion information in the factory. This eliminates the need for visually checking consumption locations for a replenishment need. The reach truck drivers still select the pallets to transport themselves.

We introduce this alternative by explaining the way reach truck drivers should work with it. After that, we elaborate design choices of the alternative. In this alternative, reach truck drivers are provided with a list with 'pallets released for delivery'. This 'pallets released for delivery' list contains the pallets ready for transport in the warehouse for which the consumption location in the factory is also released (i.e. there is space to receive a replenishment). The list is sorted on earliest due time of the pallets. The pallets with the highest delivery priority are thus on top of this list. Reach truck drivers use this list for selecting pallets to transport.

- The order picker gives feedback to the ERP system when he or she finishes picking the parts for a pallet. The status of that pallet changes to 'ready for transport' in the system.
- A list with the status of each consumption location in the factory tracks when one bin or both bins at a consumption location are available to receive a pallet. The status of that consumption location then changes from 'blocked' to 'unblocked' in the system.
- If the status of a pallet is 'ready for transport' and the status of its consumption location is 'unblocked', the pallet is added to the 'pallets released for delivery' list.
- When a reach truck driver starts a new delivery tour, he or she selects pallets from the 'pallets ready for delivery' list. After that, the list is updated and the reach truck driver can start with the delivery tour.

Reach truck drivers choose the pallets to deliver in a delivery tour based on the number of available pallets at the 'pallets ready for delivery' list, as this alternative does not provide additional information about which pallets to deliver in a delivery tour to reach truck drivers. In the current situation, reach truck drivers deliver between 2 and 6 pallets in a delivery tour, depending on their observations of empty bins in the factory, combined with the pallets they find in the warehouse. In this alternative, reach truck drivers can be certain that if there is a pallet on the 'pallets released for delivery' list, it can be delivered. Therefore, we believe reach truck drivers will try to pick-up as many pallets as the capacity of the reach truck allows for. As we provide reach truck drivers with the 'pallets released for delivery' list with pallets with the highest delivery priority (earliest consumption time of parts on the pallet) on top, we also believe reach truck drivers pick up pallets in a earliest due time first manner, as it is their job to make sure the pallets are at the consumption location in time. To make sure they do so, reach truck drivers can be instructed how to work with the system.

For the delivery of the pallets, we found that reach truck drivers deliver pallets in a delivery tour similar to constructing the route by using the nearest neighbour algorithm. The pallet for the consumption location that is the closest to the warehouse is visited first, then the pallet with a destination close to that consumption location, and so on. Therefore, we also apply this algorithm when simulating this alternative. Appendix A presents the flow chart of the delivery tour construction mechanism we designed for the simulation study.

We now make a distinction between the current situation regarding the division of reach truck drivers over the warehouses (1a), and an alternative division of reach truck drivers (1b). In the current situation, the reach truck drivers belong to either the HB, LB1, or LB2 warehouse. This is the situation in alternative 1a. In alternative 1b, we do not assign reach truck drivers to different warehouses, but we make a 'pool' of reach truck drivers serving the HB, LB1, and LB2 warehouses together. By means of this pool, we aim to utilise the effect of having replenishment requests for the pallets from the different warehouses more evenly spread in time. The two sub-alternatives:

1a: Reach truck drivers divided over warehouses (current situation).
1b: Reach truck drivers in a 'pool' serving the HB, LB1, and LB2 warehouses.

4.3 Alternative 2

This section describes the second alternative solution procedure. In this alternative, we shift the decision making about what pallets to transport in a delivery tour from the reach truck driver to an automated solution. Thereby, we can determine for the reach truck driver what pallets to deliver and in what sequence to deliver the pallets. We also generate delivery tours for the next arriving reach truck(s) if they return within a certain time. Thereby, we try to decrease the route lengths and improve the system performance. This alternative is an extension of Alternative 1 from Section 4.2, as we use the same 'pallets released for delivery' list also in this alternative, but now for generating the delivery tours.

In the current situation the reach truck drivers themselves make the choice for what to transport when. Alternative 2 proposes a method that selects the pallets to transport by the reach truck drivers. The idea is that when a reach truck returns to the warehouse, the system generates a new delivery tour for that reach truck. The reach truck driver receives a list with pallets to deliver in what sequence. By shifting the decision making for the tour content from the reach truck drivers to an automated solution that assigns the pallets to the reach trucks, efficient routes and division of work among the reach trucks is ensured. As this alternative informs the reach truck driver what pallets to take, there is no need for the division of reach trucks over the different warehouses. Therefore, we only consider the situation of the reach truck pool that aggregates the deliveries from the different warehouses. Alternative 2 also utilises the pallet depletion information in the factory, just like alternative 1. We use the 'pallets released for delivery' list for generating the delivery tours now.

As production does not always runs smoothly, line stops occur. This delays the consumption of parts resulting in a shift in the demand pattern of parts. Because there are two production lines in the SPZ factory, the standstill of one of the two production lines have great impact on the replenishment moment of pallets. Besides, there are many pre-assembly stations also supplying the assembly line. These pre-assembly stations can proceed working for a while in the event of a line stop, as there is buffer capacity between the pre-assembly station and the assembly line. This buffer is also causing the consumption pattern of the pre-assembly stations to fluctuate as they can work ahead schedule up to the point their buffer is full.

To handle this shifting demand pattern, we assign the pallets to reach trucks and generate the delivery sequence just before the start of a delivery tour. By doing so, there is no need for separating the delivery of pallets to the different assembly lines and pre-assembly stations in different tours. This results in having more flexibility for generating efficient tours. Another reason why we choose to generate tours only just before the start of a delivery tour is the variation in tour duration due to stochastic handling time of pallets and delays in the factory while driving. This alternative solution copes with this problem by assigning pallets to reach trucks at their return to the warehouse, instead of planning delivery tours long before the execution of a delivery tour. The following steps present the way we generate delivery tours for the reach trucks on return at the warehouse. After presenting these steps, we elaborate them in detail. Appendix A presents the flow chart of the delivery tour construction mechanism. We call the time at which a reach truck returns at the warehouse time t.

1. Evaluate the expected return time in the warehouse of the reach trucks still busy with their delivery tours. The expected return time of a reach truck is stored at the moment that reach truck started its delivery tour. If the difference between the expected return time of the next arriving reach truck and the current time t is lower than Bk minutes, we not only construct a delivery tour for the currently returned reach truck pending for a new delivery tour, but also for the first reach truck arriving within Bk minutes from time t.
2. In case of constructing 1 delivery tour: Start adding pallets to the delivery tour from the 'pallets released for delivery' list. Start on top of the list, as the 'pallets released for delivery' list is sorted on earliest due time. Continue doing so until the due time of the pallet being evaluated is later than T_{bound} minutes from the current time t. All pallets with a due time less than T_{bound} minutes from the current time t have priority on delivery as they are selected to add to the delivery tour based on their due time rather than selecting the pallet resulting in the least increase in tour length (step 3).

   In case of constructing 2 delivery tours: Select the first pallet for each delivery tour (the seed pallets) from the pallets with a due time less than T_{bound} such that they are far apart. By doing so, we aim to construct tours with destinations (consumption locations) clustered together and thereby reduce the tour lengths. Start adding pallets to the delivery tours from the 'pallets released for delivery' list. Start on top of the list, as the 'pallets released for delivery' list is sorted on earliest due time. The pallets are added to the tour resulting in the least increase in tour length based on the Cheapest Insertion heuristic. If there are no pallets with a due time less than T_{bound} minutes from time t, we select the seed pallets from the complete 'pallets released for delivery' list and proceed to the next step.
3. If the capacity of the reach truck is not reached after adding the pallets with a due time less than T_{Bound} minutes from time t, then completely evaluate the remainder of the 'pallets released for delivery' list to select the next pallet to add to the tour. Continue doing so until there are no pallets left or the tours are full. The pallet resulting in the least increase in tour length, based on the Cheapest Insertion heuristic, is added to the tour. In case of construction 2 delivery tours, only the tour(s) for which it is still able to add pallets to are evaluated.
4. For every pallet to add after the first pallet, we determine its insertion position in the delivery tour by using the Cheapest Insertion heuristic. Thereby, we try to keep the delivery tour length to a minimum.

If more than 1 reach truck arrive within T_{Bound} minutes from the current time t, we treat the 2nd extra returning reach truck as if it is the 1st reach truck pending a new delivery tour. Thus, we only construct a maximum of 2 tours in parallel. We do this to keep the construction of the tours relatively simple, and to reduce the risk of not having a reach truck available if a replenishment request pops up for a consumption location with a due time earlier than the expected return time of every reach truck.

We call the time it takes for a reach truck to finish its delivery tour and to return to the warehouse $k^t_{vehicle}$, where *vehicle* is a reach truck in this case and t the current time. For instance, if there are 2 reach trucks busy with their delivery tour and a 3rd reach truck is at the warehouse pending a new delivery tour (we call this vehicle i), two $k^t_{vehicle}$ times must be evaluated to find the minimum expected return time of all vehicles $\neq i$. Bk is the boundary on evaluating $k^t_{vehicle}$ of all vehicles $\neq i$ to construct a delivery tour for. Thus, if the return time of a reach truck is within Bk, we evaluate its time to finish its delivery tour. The first available reach truck $\neq i$ performs the new delivery tour. See Figure 4.1 for an graphical example. We evaluate $Bk \in \{1;\ 2;\ 3;\ 4;\ 5\}$ minutes as boundary to construct 1 or 2 delivery tours for sensitivity analysis.

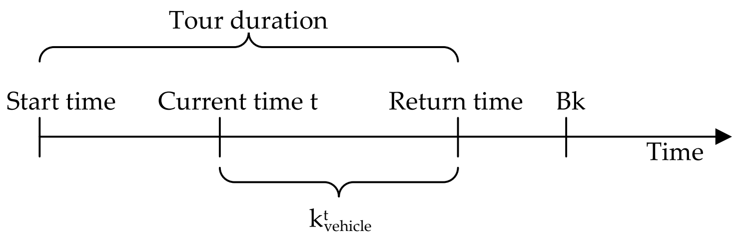

FIGURE 4.1: Return time situation of a reach truck given that there already is a reach truck at the warehouse pending a new tour. We evaluate all reach trucks that return within B_k minutes from time t to find the minimum expected return time of these reach trucks. In this example the reach truck returns within B_k minutes from time t.

To determine the distance between an arbitrary set of consumption locations in the factory, we divide the factory into zones of approximately equal size. We do this to simplify the determination of route lengths. Figure 4.2 shows how we determine the distance of the path between two zones (zone A and zone B in this case). A zone covers one side of multiple workstations of (in this case) multiple assembly lines. We use the centre of a zone to determine the distance from one zone to another. The distance of the path between zones is determined such that it equals the actual distance a vehicle needs to travel from a zone to another. The resulting map with all zones and paths between them is called a graph where the paths are called edges and the zone centres are called vertices. As reach trucks are able to make 180 degree turns on a path without having to drive to the end of that path to turn around and as reach trucks are allowed to drive on every path in every direction, we have a undirected graph. In such a graph, the vertices are linked symmetrically by edges.

Finding the minimum expected return time $k^t_{vehicle}$ of all vehicles $\neq i$, requires the expected tour duration of the delivery tours of these reach trucks. The duration of a delivery tour consists of the following components:

- Pick up time t_{pickup}: time in seconds required to pick up a pallet.
- Driving time d_T: the total net travel time in seconds of a reach truck to complete delivery tour T.

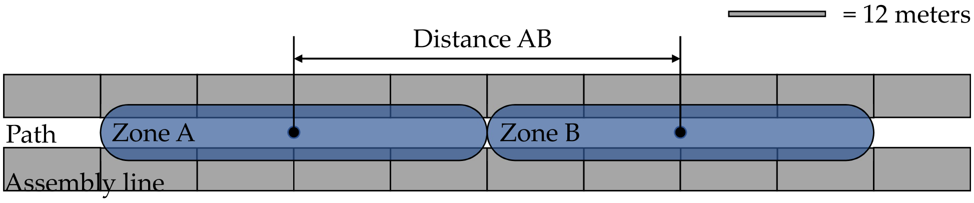

FIGURE 4.2: Delivery zone principle we use to calculate the distances between any pair of consumption locations in the factory.

- Waiting time fraction W: the time disturbances take (e.g. due to other traffic in the factory) as percentage of the net total driving time.
- Drop-off time $t_{dropoff}$: time in seconds required to drop off a pallet.
- Number of pallets p: the number of pallets to deliver in a delivery tour.

Equation 4.1 presents the formula to calculate the expected tour duration in seconds. For the pick up time, drop-off time, and waiting time, we use the expected value of these activities. By adding the expected tour duration to the start time of the delivery tour, we have the expected time of return of the reach truck in the warehouse.

$$Expected\ \ tour\ \ duration = (t_{pickup} + t_{dropoff}) \cdot p + d_T \cdot (1 + W) \tag{4.1}$$

For the construction of the routes we use the Cheapest Insertion heuristic (Rosenkrantz, Stearns, & Lewis, 1977). This heuristic calculates for a pallet to add to a tour the increase in tour length for every insertion position possible. We explain this with an example. Assume the tour being constructed already contains two pallets; pallet i and pallet j. Then, there are 3 insertion positions possible for the pallet to add; between the warehouse and pallet i, between pallet i and pallet j, or between pallet j and the warehouse. The algorithm calculates for these three options the new total tour length if the pallet is added to the tour. The pallet is allocated to the position that results in the least increase in total tour length. We use the Cheapest Insertion heuristic as route construction mechanism as we want to generate a good delivery sequence for the pallets in a fast way. There is no need to find the optimal delivery sequence in terms of driving distance, as this has not a lot of effect on the total tour duration compared to the sequence the Cheapest Insertion heuristic generates.

We first describe the principle when there is only 1 delivery tour being constructed, after which we describe the principle for the situation when 2 delivery tours are being constructed simultaneously. When constructing only 1 delivery tour at a time, we select the first pallet to add having the earliest consumption time among the pallets available to transport from the 'pallets released for delivery' list in case the consumption time is less than T_{bound}. We keep adding pallets to the delivery tour this way while keeping transportation capacity into account, as long as there are pallets with a consumption time less than T_{bound} on the 'pallets released for delivery' list. If the pallet under consideration is the pallet with the earliest consumption time but does not fit within the delivery tour, we continue with the next pallet from the 'pallets released for delivery' list while building the current delivery tour. If there are no pallets with a due time less than T_{bound} left, we continue adding pallets to the tour from the 'pallets released for delivery' list, such that the increase in delivery tour length is minimal. It is thus possible that a pallet not having the earliest due time is added to the delivery tour. In this way, we create more freedom when constructing delivery tours in terms of choosing the pallets resulting in shorter delivery tours, rather than just adding pallets to the delivery tour.

If we construct 2 delivery tours in parallel, the first pallet for each of the two tours (the 'seed' pallets) are preferably far apart. To select the seed pallets, we evaluate the intermediate distances of the pallets on the 'pallets released for delivery' list. The 2 pallets that are as far apart as possible and within T_{bound} are then selected as seeds, one for every delivery tour. The reason of doing this is that we want to generate routes utilising the effect of constructing 2 routes at the same time as good as possible, i.e. having pallets with a destination close together in the same delivery tour, without having too much overlap in the routes. In case there are not enough pallets with a due time less than T_{bound}, the whole 'pallets ready for delivery' list is evaluated. Figure 4.3 presents the idea behind selecting the seed pallets far apart. Assume that the pallets most left and most right in Figure 4.3 are the seed pallets, the pallets close to the seeds are added to the delivery tour with that seed pallet. Thereby, the pallets within a delivery tour are relatively close together, reducing the total driving distance.

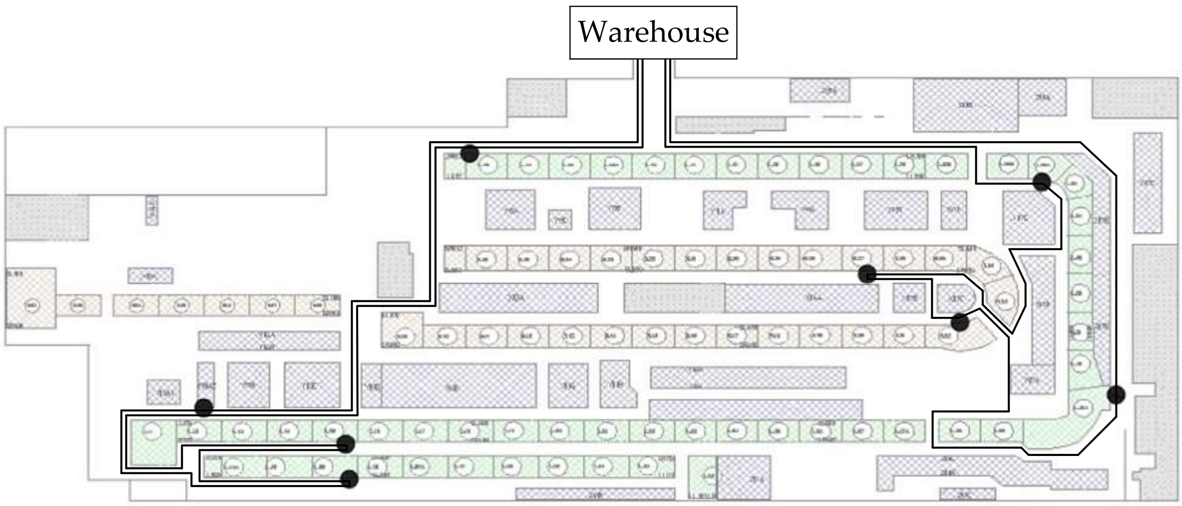

FIGURE 4.3: Two delivery tours constructed simultaneously. If the pallets most left and most right are the seed pallets (the black dots are the delivery locations), other pallets close to the delivery tour with that seed pallet are added to the corresponding delivery tour, aiming at decreasing the delivery tour lengths.

4.4 Alternative 3

This section describes the third alternative. In this alternative, we replace reach trucks by tugger trains. Tugger trains already are a common way of transport at SPZ. We investigate the effect of using tugger trains instead of reach trucks for the internal sequencing supply method, as reach trucks may be phased out as transport means in the future inside the SPZ factory.

With this alternative we investigate the use of tugger trains instead of reach trucks for the delivery of pallets to the factory. At SPZ, tugger trains take care of a lot of transport inside the factory already. The advantage of using tugger trains for the transport of pallets is not having stacking height constraints, the ease of use for the driver, and the improved safety compared to reach trucks. For these reasons we look into the effects of using tugger trains on the performance of the transportation of internal sequencing pallets.

A drawback of using tugger trains is the reduced freedom of movement in the factory. Where a reach truck is able to make a 180 degree turn at a path in the factory, giving it maximum manoeuvrability, a tugger train must continue driving in the same direction. Reversing with a tugger train is not possible due to the trolleys behind it. There already exists fixed driving directions at some places in the factory for tugger trains. This makes the graph with vertices and edges we introduced in the previous section a directed graph. As a result, route lengths will increase compared to the routes for reach trucks.

The assignment of pallets to tugger trains is the same as in alternative 1 and 2. The difference is that we respect the constraints of using a tugger train instead of a reach truck. The assignment of pallets is the same as in alternative 1 and 2, making this alternative a variant on these alternatives.

4.5 Summary of alternatives

This section gives a short recap of the alternatives we propose in this chapter.

Improving the internal sequencing supply method requires additional information about the depletion moment of pallets in the factory. With this information, we can eliminate the need to visually check the consumption locations if they can receive a replenishment pallet.

In alternative 1 we provide reach truck drivers with this pallet depletion information and let them select pallets to transport in a delivery tour. By means of this alternative, the reach truck drivers have still a lot of responsibility in doing their job in a good manner.

We shift the decision making about what to transport in a tour to an automated solution in alternative 2. By doing so, delivery tours can be generated in a way the workforce responsible for the delivery of internal sequencing pallets is provided with delivery tour information, such that efficient tours and division of work among reach truck drivers is ensured.

Alternative 3 evaluates tugger trains as means of transportation as it already is a common way of transportation at SPZ and it might happen in the future that reach trucks are not allowed inside the factory anymore. We evaluate alternative 1 and 2, but now with tugger trains instead of reach trucks.

5 Simulation study

This chapter describes the simulation model we use to evaluate the solution alternatives from Chapter 4. Section 5.1 describes the modelling choices and assumptions. Section 5.2 describes the input data and parameters for the model. Section 5.3 describes the output of the model. Section 5.4 describes the validation and verification of the model. Section 5.5 describes the design of the experiments. Section 5.6 presents the results of the simulation study and Section 5.7 draws conclusions based on the simulation results.

5.1 Model introduction

This section describes the simulation model and introduces the performance indicators we use to compare the alternatives. Next, we present modelling assumptions and choices.

5.1.1 Model description

To evaluate the effects of implementing the solution alternatives Chapter 4 proposes, we perform a simulation study. To perform this simulation study, we need to model pallet delivery requests for generating transportation need. We have several alternatives to generate these delivery requests, namely:

- Using historical delivery request data as direct input for the simulation model. The advantage of directly using historical data is that it represents the actual delivery request pattern. However, the drawback of directly using historical data is not having the possibility to evaluate different situations other than the specific events from the historical data. This, together with the lack of historical data, results in not selecting this approach for modelling the pallet delivery requests.
- Using demand rates of parts in the assembly process for generating pallets to transport. Generating delivery requests this way result in transportation need patterns that do not match the actual pattern due to the loss of the relation between parts (e.g. a left and a right bracket are required for the same chassis) and by violating chassis mixing rules. Therefore, we do not model the delivery request in this way.
- Generating delivery requests by creating part demand via the bill-of-materials of the trucks and the production sequence. In this way the part relations are respected and we have the possibility to generate situations other than the situations caused by the demand pattern from historical data, by drawing chassis from the production sequence while respecting mixing rules. As this is the most promising way to generate delivery requests, we apply it in our model.

To study the delivery of pallets from the warehouse to the assembly line, we require part demand at the correct locations in the factory in our model. With this demand, we deduct parts from the pallet at the corresponding consumption location (the line inventory). By moving the chassis from workstation to workstation while deducting the required materials according to its bill-of-materials at the correct workstation at the assembly line or pre-assembly workstation from the pallets with parts, we can track the moment a pallet depletes and a replenishment can be received. We model the assembly lines and pre-assembly workstations to do so. On the other hand, the pallets with parts must be picked in the warehouse. We generate pallets with parts based on the production sequence in our model and on pallet content settings from the ERP system. Figure 5.1 presents how the content of a pallet is determined. Engineers at SPZ determine these settings for every consumption location in the factory. We generate new production sequences in our model by drawing sets of chassis from the original sequence, while respecting the mixing rules as good as possible, thereby obtaining realistic part demand patterns and frequencies.

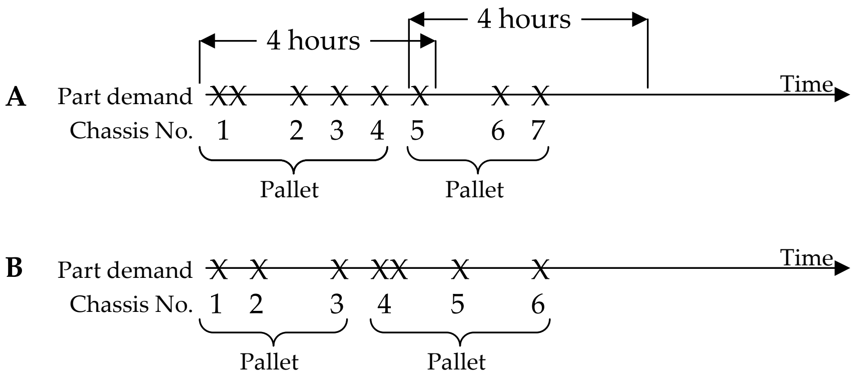

FIGURE 5.1: Different ERP system settings for limiting pallet contents for a specific consumption location. **A:** the pallet content is limited by an amount of time, in this case 4 hours, or by a number of parts, in this case 5 parts. The first criteria reached (4 hours or 5 parts), limits the pallet content. **B:** the pallet content is limited by a number of chassis, in this case 3 chassis. It does not matter how many parts a chassis requires.

We introduce the following performance indicators to compare and evaluate the different solution alternatives proposed in Chapter 4. Section 5.3 describes these performance indicators in detail:

- **Service level:** the percentage of pallets delivered in time.
- **Capacity utilisation:** the utilisation of the available capacity of the workforce responsible for delivering the pallets to consumption locations.
- **Lead time:** the average time between the moment the pallet is picked and the moment the pallet is delivered.
- **Distance per pallet:** the average distance travelled to deliver a pallet.

5.1.2 Model assumptions

A simulation model is an approximation of a complex real-world system. To model the internal sequencing supply method, we make the following choices and assumptions:

- Line stoppages are not included in the simulation model. Line stoppages decrease the transportation need temporarily, resulting in more time to transport the pallets. As it must be possible to deliver the pallets to their consumption location in time when there are few or no disruptions in the assembly process, we exclude line stoppages in our simulation model.

- Pre-assembly workstations can work up to 1 hour ahead of schedule.
- Chassis re-sequencing is not incorporated in the model.
- Part demand is based on the bill-of-materials of trucks produced in December 2018 and January 2019. Additional part demand is generated by drawing trucks from this set while respecting the mixing rules present.
- The production progress and part consumption is incorporated by simulating the two assembly lines and the pre-assembly stations.
- We include the order picking of pallets in the model by creating pallets in the warehouse between 4 and 6 hours before the consumption time of the first part in the pallet in our model.

5.2 Input of the model

This section describes the input data and parameters of the simulation model.

Bill-of-materials: The bill-of-materials contains every part that a chassis requires. We use the bill-of-materials from the ERP system of Scania in our simulation model to generate the correct number of parts per chassis. This influences the delivery frequency due to the limited pallet contents (see Figure 5.1).

Consumption location settings: Settings in the ERP system specify for every part at which consumption location mechanics require the part in the factory to assemble it. Each consumption location has its own packaging size and type. The ERP system determines, based on the consumption location settings, how many parts should be on a pallet (see Section 5.1). Mostly, a pallet contains different parts. The consumption location settings and the bill-of-materials, together with the production sequence, determine the replenishment frequency of a pallet.

Production sequence: The production sequence is a list with chassis to produce. Mixing rules determine the production sequence, trying to spread the chassis with special needs or with high part demand over time. We model the material flow of the internal sequencing supply method by combining the bill-of-materials, the consumption location settings, and the production sequence. Through this approach it is possible to come as close as possible to the real-world system.

Driving speed: At SPZ, reach trucks and tugger trains have a speed of 8 km/h inside the factory. We use this speed in our model.

Reach truck capacity: The capacity of reach trucks depends on the type of pallet and the number of collars. The maximum stacking height is 9 if the pallet itself counts as 1 and every collar of the pallet counts as 1. In case of half EUR-pallets it is possible to position 2 half EUR-pallets side by side. This requires the same space as 1 normal EUR-pallet. We evaluate every combination of pallet size and number of collars to generate a list with the maximum number of pallets of a type with a number of collars to add, given any possible loading situation at hand while assigning pallets to a delivery tour of a reach truck. With this list, we can easily check if it is possible to add the pallet being evaluated. This way we prevent having to perform complex calculations to check if a certain pallet may be added to the delivery tour based on its dimensions.

Tugger train capacity: The capacity of tugger trains is easier to determine for a given loading situation. We can ignore the height constraint as the pallets will not be stacked on a train. Therefore, the capacity of a tugger train is equal to 4 EUR-pallet positions. This means that at any position 1 EUR-pallet or 2 half EUR-pallets can be placed. For the tugger trains we also generate a list with pallets possible to add when having a certain loading situation at hand.

5.2.1 Delivery tour lengths

Calculating the duration of a delivery tour requires the distance between all consumption locations and the warehouses. To prevent the model slowing down by evaluating all possible routes to the next destination after visiting a consumption location, we calculate the route lengths between all pairs of destinations upfront. As there are many consumption locations in the factory, we divide the factory into delivery zones (see Chapter 4). To provide the simulation model with a matrix with the driving distances between all pairs of destinations, we use the Floyd-Warshall algorithm (Floyd, 1962). This algorithm calculates for every pair of vertices (in our case the zones) the shortest path, based on the weights of the edges (path lengths between zones). For reach trucks it is possible to drive every path in the factory in both directions, making the set of vertices and edges in this case an undirected graph. In case of using tugger trains, the graph is directed. This means, in our case, that it is not possible to drive a certain path in both directions, but that the direction of a path is fixed.

5.3 Output of the model

This section describes the output of the simulation model in performance indicators. We use the performance indicators to evaluate the outcomes of the different solution alternatives.

Service level: The service level is the percentage of pallets delivered in time. As late delivered pallets result in line stoppages, the service level is an important performance indicator in evaluating the model outcomes.

Capacity utilisation: The capacity utilisation of the workforce responsible for delivering the internal sequencing pallets to consumption locations is the time spent on the actual delivery of pallets as percentage of the total time available. This includes the pick-up of pallets, driving to the destinations, and the drop-off of pallets at the consumption locations (see Chapter 2). The lower the utilisation, the better the performance of the alternative, provided that the service level does not drop significantly. In case there is more than 1 vehicle available at the warehouse to start a new delivery tour, and only 1 tour can be constructed, the vehicle with the lowest *vehicle* number is chosen (e.g. we choose *RT1* over *RT2*). By doing so, the vehicle with the highest *vehicle* number has the most time available to perform other activities, like supporting the order pickers, if necessary.

Lead time per pallet: The lead time is the time between the moment the pallet is picked and the moment the pallet is delivered. We use this performance indicator to evaluate the extent to which an alternative is able to quickly deliver the pallets from the warehouses to their consumption locations. The shorter this time is, the smaller the chance of late deliveries and the lesser the impact of production sequence changes on already picked pallets.

Distance per pallet: The average distance travelled to deliver a pallet is a performance indicator to evaluate the effectiveness of the delivery routes. The less distance required per pallet, the more effective the delivery routes are. We calculate the distance per pallet by dividing the total distance driven by the total number of pallets delivered.

5.4 Validation and verification

This section describes the validation and verification of the simulation model. We elaborate how and with what techniques we validate and verify our model, to determine if it is an accurate representation of the real-world system.

Verification:
We verify the model by using different techniques Law (2015) proposes. One of the techniques is using a commercial simulation package. We build our model in the 13th version of Tecnomatix Plant Simulation. While programming our model, we debug every few lines written to be sure the model behaves the way we want to. In order to do so, we change the model in a way it is possible to test and debug the new programmed part of the model. This prevents large adjustments of the model if we notice a mistake later on. After programming the model, we use traces to check the behaviour of the model. A trace displays the state of the system just after an event occurs. By going through the model step by step, we check the model for mistakes. Next to that, we adjust some settings of the model, like the speed of the vehicles, and check if the results of these adjustments are in line with what we expect to happen. By slowing the vehicles down, we observe, as expected, an increase in late deliveries. We also make logs of the activities of the vehicles during the delivery tours, such that we can check for any unwanted behaviour. For instance, we check if the delivery tour content does not violate the capacity constraints of the vehicle and we check for anything that is not possible in real life. By doing so, we found and resolved a programming mistake in the capacity constraints. Next to that, we monitor pallet contents and count how many times a stock-out occurs. As each chassis contains its bill-of-materials in the model, we deduct the required number of parts for that chassis from the corresponding pallet at the assembly moment of these parts. By doing so, we observe programming mistakes quickly as the number of stock-outs increases fast in case of a programming mistake. Resolving errors and mismatches in the demand of parts and supply of parts to consumption locations of these parts took a lot of time. Not only due to programming errors, but also due to creating workarounds for some bugs in Tecnomatix Plant Simulation. We use the output of the model, animation of the model, tracing, and logs to verify if the model behaves as expected.

Validation:
We validate the model by comparing the simulation results with the real-world. The first thing we need to validate is the number of pallets the simulation model generates. The input of the model is the production sequence of the chassis, the consumption locations settings, and the bill-of-materials of each chassis produced in December 2018 and January 2019. We cannot compare the number of pallets the simulation model generates one-to-one with the real-world system due to production stops, re-sequencing of the chassis to produce, and changing consumption location settings over time. However, data extraction took place at several moments in time due to the limited planning horizon of the ERP system, lowering the aforementioned effects. Because of this, we expect the number of pallets the simulation generates is close to the amount in the real-world. We use the chi-square goodness-of-fit test for checking the number

of pallets the simulation model generates are of the same distribution as the values in the real-world. We choose the intervals the chi-square test requires in a way the probability of each bin containing the same number of observations of the real-world system is approximately equal. Exactly equal probabilities for each bin are not possible since our data is discrete. This method is called the equiprobable approach (Law, 2015). The minimum bin size is 5 observations of the real-world system. If the p-value of the chi-square test is above 0.05, we have no reason to believe the number of pallets the simulation model generates is of another distribution than the number of pallets in the real-world system. The p-values for the HB, LB1, and LB2 warehouses are all above 0.05. Appendix B presents the results of the statistical tests.

Another aspect of the simulation model we need to validate is the behaviour of the reach trucks. Due to the lack of real-world data about their movements and actions, we review the outcome of the simulation model with subject matter experts. The simulation model is consistent with perceived system behaviour and is said to have face validity (Law, 2015). By means of animation of the simulation model, we observe if there are any invalid model assumptions to improve the credibility of the model. We did not observe any weird behaviour of the model.

5.5 Experimental design

This section describes the design of the experiments we evaluate by means of the developed simulation model. This section also presents the warmup period, the run length, and the number of replications of the model.

5.5.1 Scenarios

We evaluate the following scenarios according to the alternatives we propose in Chapter 4.
Scenario 0: Current situation.
Scenario 1a: Providing the reach truck drivers with pallet depletion information while having the warehouses separated as in the current situation. (see Section 4.2). No usage of a delivery tour construction mechanism and no need to drive around to check for a replenishment need. We indicate this scenario as *'alternative 1 separated'* in the results.
Scenario 1b: Providing the reach truck drivers with pallet depletion information while having the reach truck drivers' departments merged (see Section 4.2). No usage of a delivery tour construction mechanism and no need to drive around to check for a replenishment need. We indicate this scenario as *'alternative 1 merged'* in the results.
Scenario 2: Using the pallet depletion information for constructing delivery tours on demand at the warehouse (see Section 4.3). Tour construction mechanism generates one or two tours at the same time. The reach truck drivers' departments are merged. We indicate this scenario as *'alternative 2 merged'* in the results.
Scenario 3: Usage of tugger trains as transport means instead of reach trucks (see Section 4.4). We evaluate tugger trains as transport means for alternatives 1a, 1b, and 2. As this scenario is an adaption of the preceding scenarios, we integrate the outcomes of this scenario in the results by differentiating between *'RTs'* when using reach trucks and *'TTs'* when using tugger trains.

5.5.2 Parameter settings

Alternative 2 provides delivery tours to the workforce responsible for the delivery of the internal sequencing pallets. As Chapter 4 describes, we have two parameters for which we tune their parameters. These parameters are T_{bound} and Bk.

T_{bound} represents the maximum difference in time between the current time t and the latest due time of a pallet in the 'pallets released for delivery' list. Pallets with a due time smaller than the current time t plus T_{bound} minutes are evaluated one by one to add to a delivery tour in sequence of the 'pallets released for delivery' list. The remaining pallets on the list are all evaluated on their increase in route length when adding the pallet to the tour, prior to adding a pallet to the tour. We evaluate $T_{bound} \in \{0;\ 30;\ 60;\ 90;\ 120;\ 150;\ 180;\ 210;\ 240;\ 270;\ 300;\ 330;\ 360\}$ minutes for parameter tuning.

Bk represents the boundary on the expected return time of the next arriving vehicles in the warehouse to determine if a second tour must be constructed or not. If a next vehicle is expected to arrive within the current time t plus Bk minutes, we not only construct a delivery tour for the current vehicle in the warehouse, but also for the next arriving vehicle. We evaluate $Bk \in \{1;\ 2;\ 3;\ 4;\ 5\}$ minutes for parameter tuning.

5.5.3 Warmup period

According to Law (2015), there are two simulation types: terminating and nonterminating. In a terminating simulation there is a natural event ending the simulation run. In a nonterminating simulation, there is no such event. A simulated system starts with transient behaviour, meaning the system behaviour depends on initial conditions. After a certain period of time, the transient behaviour changes to steady-state behaviour: the simulation model does not depend on the initial conditions anymore.

Our system is a nonterminating system as production continues at the start of the day with the same situation as they stopped with the previous day. To cope with the transient system behaviour, we use a warmup period to exclude the observations of the system during that behaviour. By doing so, we analyse the steady-state system performance in which we are interested. We use the lead time of pallets to determine the warmup period as an empty system influences this performance indicator a lot. The system starts with an empty factory and gradually fills with chassis on the production lines. This causes low part demand during the warmup period of the model, which translates to a low transportation need. As a result, the workforce can easily handle all the pallets, causing the lead times to drop drastically (see Figure 5.2).

The length of the warmup period is determined by using Welch's graphical procedure (Law, 2015). This procedure uses moving averages to determine when the system is running in steady-state, and thus how long the warmup period should be. To do so, we use windows of values to base the moving averages on. For example, a window can contain 10 values ($w = 10$). According to the procedure, the system shows steady-state behaviour after 1,5 production days. We set the warmup period to 2 days to be sure the model behaviour does not depend on its initial conditions anymore. Figure 5.2 shows the result of the graphical procedure.

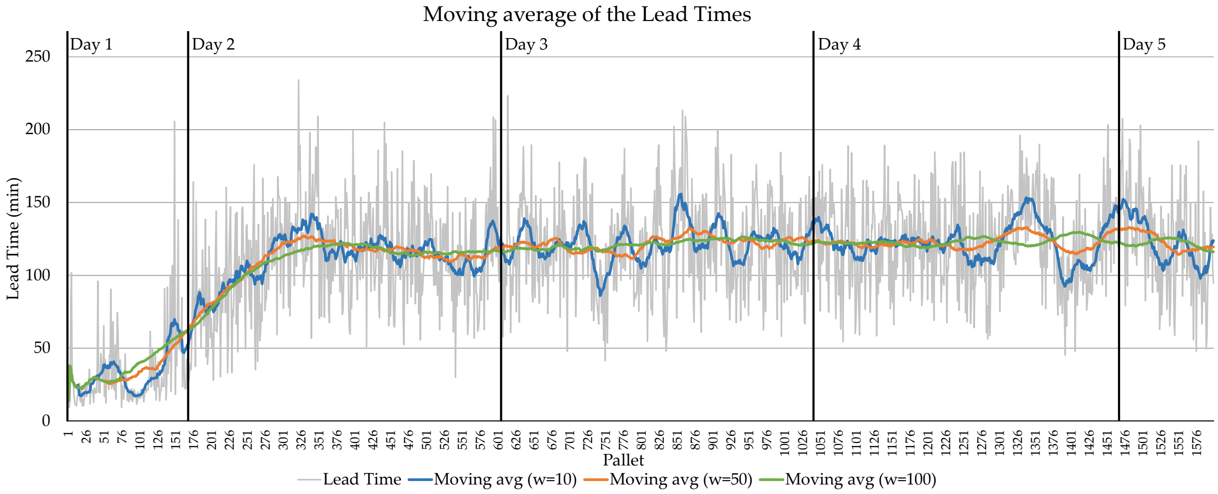

FIGURE 5.2: Welch's graphical procedure to determine the required warmup period of our simulation model. We use different window sizes (w=10, w=50, and w=100) to determine the required warmup period. We set the warmup period to 2 days as the system is then running in steady-state.

5.5.4 Run length and number of replications

To obtain sound statistics from our model, we use the replication/deletion approach (Law, 2015). The model is initialised and a warmup period is applied for every replication to make sure we gather the statistics during the steady-state behaviour of the model. By initialising the model for every run, correlation between runs is eliminated. This is the main advantage of using the replication/deletion approach over the batch means approach in which one long run is performed. The run length is set much longer than the warmup period to exclude any bias from the transient system behaviour. We set the run length to 30 days. To control the randomness of the model and be able to perform multiple experiments with the same situation, we use the common random numbers method. Every random event in the simulation model is based on a random number stream. By setting the random number stream to the same value in every run of an experiment, we can compare these experiments and only measure the impact of our interventions (the different alternatives) on the model behaviour.

To calculate the required number of replications to obtain a confidence level of 95%, we use the sequential procedure (Law, 2015). Every run of the simulation provides a point estimate of the mean of an output variable. These point estimates are used to calculate the required confidence level. Appendix C presents how we calculate the number of replications required. The number of replications is based on the lead times of pallets. The number of replications required is 5.

5.6 Simulation results

This section presents the results of the simulation study. We discuss the results from the different alternatives first, after which we discuss the results of tuning the parameters. Appendix C elaborates the statistical technique used for constructing 95% paired-t confidence intervals to analyse the results of the simulation study.

The service level represents the percentage of pallets delivered in time. This performance indicator is important as late delivery of pallets result in line stoppages if the destination of a pallet is a consumption location at the line, or potential line stoppages if the destination of a pallet is a consumption location at a pre-assembly station. A high service level is thus desirable. Figure 5.3 presents the service levels of the different alternatives. The service levels of the alternatives are significantly higher, based on 95% paired-t confidence intervals, compared to the current situation. If we compare the service levels of using reach trucks (RTs) or tugger trains (TTs) within the alternatives, only for *alternative 2 merged* there is no significant difference in service level. The service levels are above 99.9% for all alternatives, except the current situation and *alternative 1 separated* while using tugger trains. Reach truck drivers sometimes place the parts of two pallets for the same consumption location on one pallet, reducing the number of pallets to deliver. Also, the reach truck drivers sometimes place more than 2 pallets (bins) at a consumption location which reduces the risk of stock outs. However, these actions are not according to their instructions and rules. We simulate the current situation in compliance with the instructions and rules as the reach truck drivers should behave as they do these things only when they believe it is necessary and every individual reacts different to some situation.

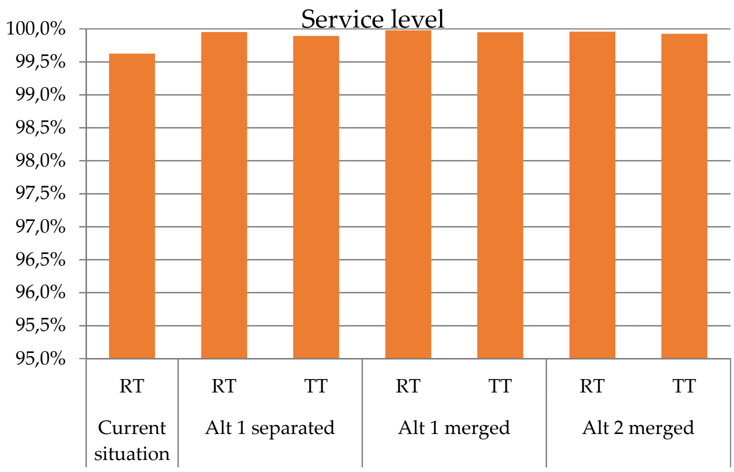

FIGURE 5.3: Service level of reach trucks and tugger trains under different scenarios.

Together with the lead time per pallet and the distance per pallet, the utilisation of the workforce responsible for the delivery of the internal sequencing pallets indicates the degree of productivity. A high utilisation of the workforce does not necessarily mean the workforce is spending their work time in a way that is also efficient. One could be very busy with the delivery of pallets if only 1 pallet is transported in a delivery tour. Then, the time spent on the delivery of pallets is high, resulting in a higher utilisation of the workforce. However, our aim is to improve the productivity of the workforce: doing more work in the same or less time. Reducing the number of FTEs responsible for the delivery of the pallets is one of the things that improves the productivity of the workforce if the system performance does not drop. Therefore, we evaluate the utilisation of the workforce, the lead time per pallet, and the distance travelled per pallet integrally to determine what results in the highest productivity.

In the current situation, there are a total of 7 FTEs responsible for the delivery of internal sequencing pallets. This is 0.5 FTE more than stated in Chapter 2 due to the increased production rate, as we evaluate the 'worst case' situation in which no line stoppages occur. This leads to an increase in availability of the 4th reach truck driver as this reach truck driver spends more time on the delivery of the pallets in case the workload increases. For *alternative 0* (the current situation) and *alternative 1 separated* (for RTs and TTs) the workforce is of equal size (7 FTEs in total). For *alternative 1 merged* and *alternative 2 merged* we reduce the number of FTEs to 6, as 7 FTEs results in too much overcapacity. Therefore, no data is available in the 'RT4' and 'TT4' columns for those alternatives.

Figure 5.4 presents the utilisation of reach trucks for the different alternatives if reach trucks are used as transport means and Figure 5.5 presents the utilisation of tugger trains for the different alternatives in case tugger trains are used as transport means. We observe a reduction in utilisation between *alternative 0* and *alternative 1 separated* when using reach trucks as transport means. This is mainly due to not having to drive through the factory to observe which consumption locations may receive a replenishment. These reductions in utilisation are, for every reach truck, significant. If we replace the reach trucks for tugger trains under *alternative 1 separated*, we observe a significant increase in utilisation. This is caused by the increase in route lengths as tugger trains are not able to turn around where and whenever they want, due to vehicle constraints and traffic rules.

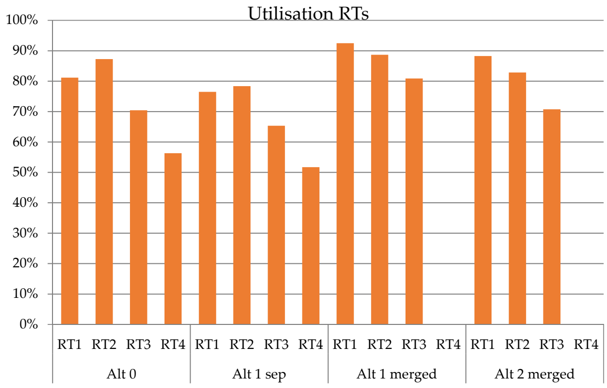

FIGURE 5.4: Utilisation of reach trucks under different scenarios.

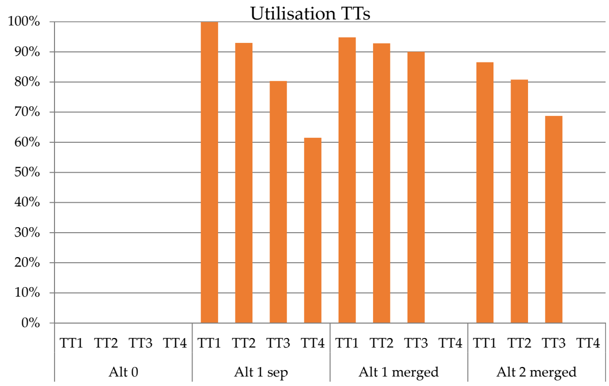

FIGURE 5.5: Utilisation of tugger trains under different scenarios.

If we merge the departments of the workforce responsible for the delivery of the internal sequencing pallets, we do not require 4 vehicles for pallet transportation per shift anymore. Then, 3 vehicles per shift are required to be able to transport the pallets, resulting in 6 FTEs in total. For *alternative 1 merged* the utilisation per vehicle increases, provided that we require 1 FTE less and that the service level is slightly higher than in the *alternative 1 separated* scenario. On the other hand, the lead time per pallet (see Figure 5.6) and the distance per pallet (see Figure 5.7) both increased due to having more pallets available to transport at a random moment. This is due to the workforce responsible for the delivery of the pallets cannot deliver the pallets as quick as in the *alternative 1 separated* scenario caused by the decrease in FTEs, resulting in more pallets in the buffer. This results in larger tours as no mechanism is in place to determine what pallets to take in a delivery tour while taking the delivery locations into account.

In the *alternative 2 merged* scenario, there is a mechanism in place to construct the delivery tours. Compared to *alternative 1 merged* (RT to RT and TT to TT), both the utilisation of reach trucks and tugger trains decreases (see Figure 5.4 and Figure 5.5). This is a good result as the lead time per pallet (see Figure 5.6) decreases and in particular the distance per pallet (see Figure 5.7) drops significantly. We therefore conclude the construction of delivery tours by the

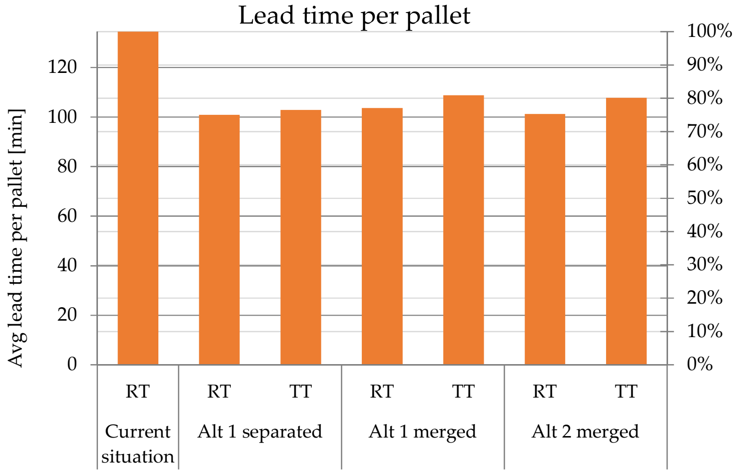

FIGURE 5.6: Lead time per pallet under different scenarios in minutes.

mechanism proposed in Chapter 4, combined with merging the departments, leads to the best results to improve the productivity of the workforce.

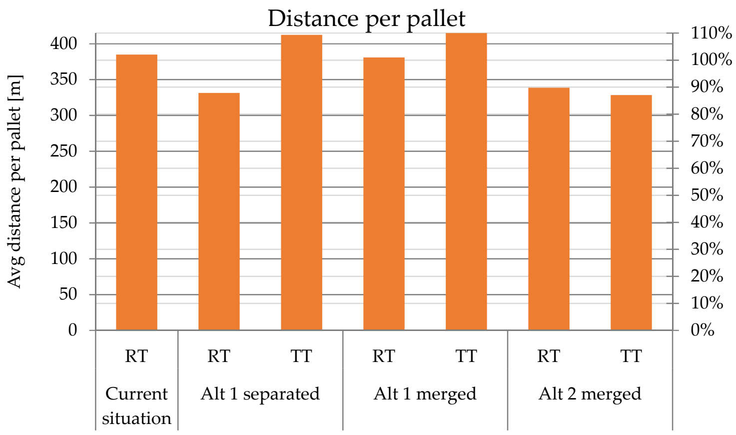

FIGURE 5.7: Distance per pallet under different scenarios in meters.

An additional advantage of using *alternative 2 merged* is the decrease in traffic intensity in the factory. The less meters required to deliver a pallet, the less delivery tours are required. This is true when using reach trucks as transport means, but especially true when using tugger trains as transport means. When using tugger trains, the delivery tours generally are longer as more pallets are delivered in a tour due to capacity constraints of the tugger train. As a result, the distance per pallet drops but the lead time per pallet slightly increases.

Parameter tuning

This subsection investigates how to tune the parameters Bk and T_{bound} for the 2nd scenario *alternative 2 merged* as these parameters only apply to this scenario. We first evaluate the tuning of parameters when using reach trucks as transport means, after which we do the same for tugger trains.

Figure 5.8 presents an overview of different performance indicators under different parameter settings of Bk and T_{bound} when using reach trucks as transport means. The first thing we notice is the pattern in the distance per pallet being lower around $T_{bound} = 3$ hours. This value of T_{bound} provides the best mix of pallets with a due time lower than T_{bound} and higher than T_{bound} measured from time i when constructing the delivery tours. The pallets with a due time higher than T_{bound} from the current time t are used to 'fill up' the delivery tour being constructed, if possible. If we set T_{bound} too low, the distance per pallet increases and if we set T_{bound} too high, the distance per pallet, the lead time per pallet and the average utilisation of the reach trucks increases. By taking a closer look at the Bk parameter setting around $T_{bound} = 3$ hours, we conclude that $Bk = 3$ minutes is a good setting. With this combination of parameter settings the distance per pallet, the lead time per pallet, and the average utilisation of the reach trucks are all low, while the service level is high. We advise to set T_{bound} around 3 hours and Bk at 3 minutes.

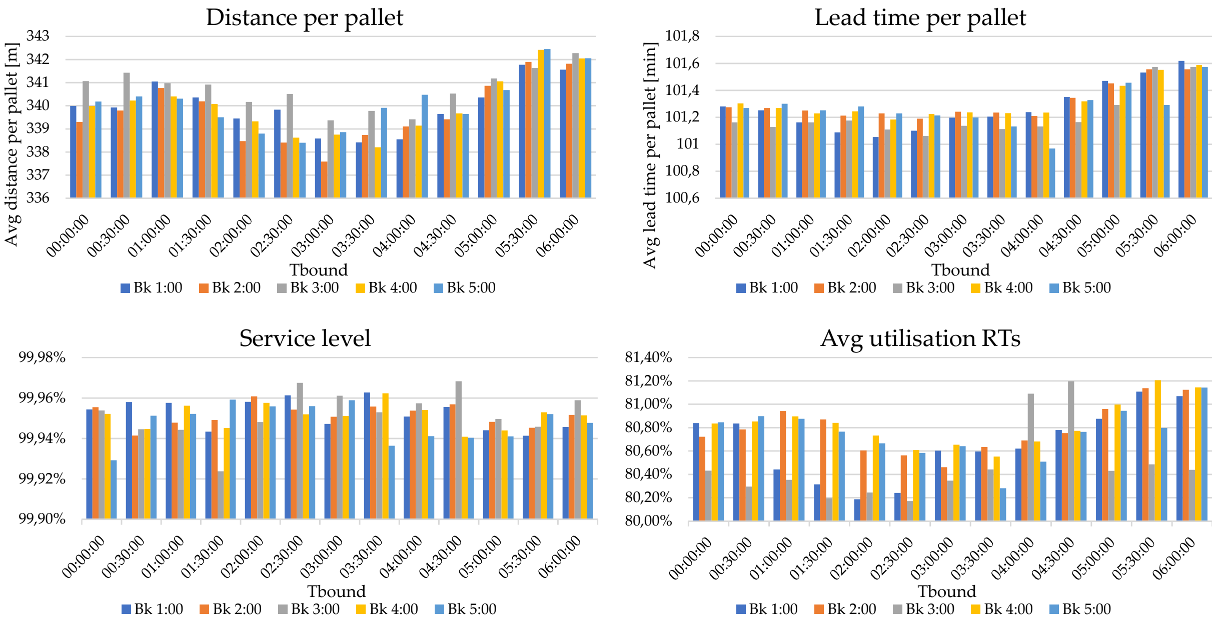

FIGURE 5.8: Overview of performance indicators for parameter tuning for reach trucks under different settings for T_{bound} and Bk.

Figure 5.9 presents an overview of different performance indicators under different parameter settings of Bk and T_{bound} when using tugger trains as transport means. We notice an increase in distance per pallet, lead time per pallet and utilisation of the tugger trains when T_{bound} is set lower than 3.5 hours. Furthermore, the service level slightly drops when T_{bound} is set around 1 hour. These observations happen as all pallets on the 'pallets released for delivery' list are evaluated when constructing the delivery tours when T_{bound} is set low. The result is that not always the pallets with the earliest due time are selected. This causes an increase in the lead times as the pallets remain longer in the buffer, on average. The drop in service level confirms that more often pallets are delivered late due to not selecting the pallets with earliest due time. The delivery tours are better in terms of closeness of the pallets, which reduces the tour lengths, but this also causes the tugger train to return earlier to the warehouse. Then, there are less pallets to choose from for the next tour, resulting in less pallets per tour which increases the distance per pallet and the utilisation of the tugger trains. This is not desirable, mainly because of the drop in service level. Therefore, we advise to set T_{bound} to 6 hours when using tugger trains as transport means, as this results in the shorter lead times, lower distances per pallet, and higher service levels. The utilisation of the tugger trains is also lower, which reduces the traffic intensity. This works for tugger trains as the height constraint of the pallets is of no influence on the remaining capacity when constructing a delivery tour. We advise to set *Bk* around 3 minutes when using tugger trains as transport means, as this provides the best overall performance if T_{bound} is set to 6 hours. Setting T_{bound} equal to 6 hours is the same as setting it to infinite, since picking of pallets finishes not earlier than 6 hours before the time the first part on the pallet is required for assembly due to ERP system settings.

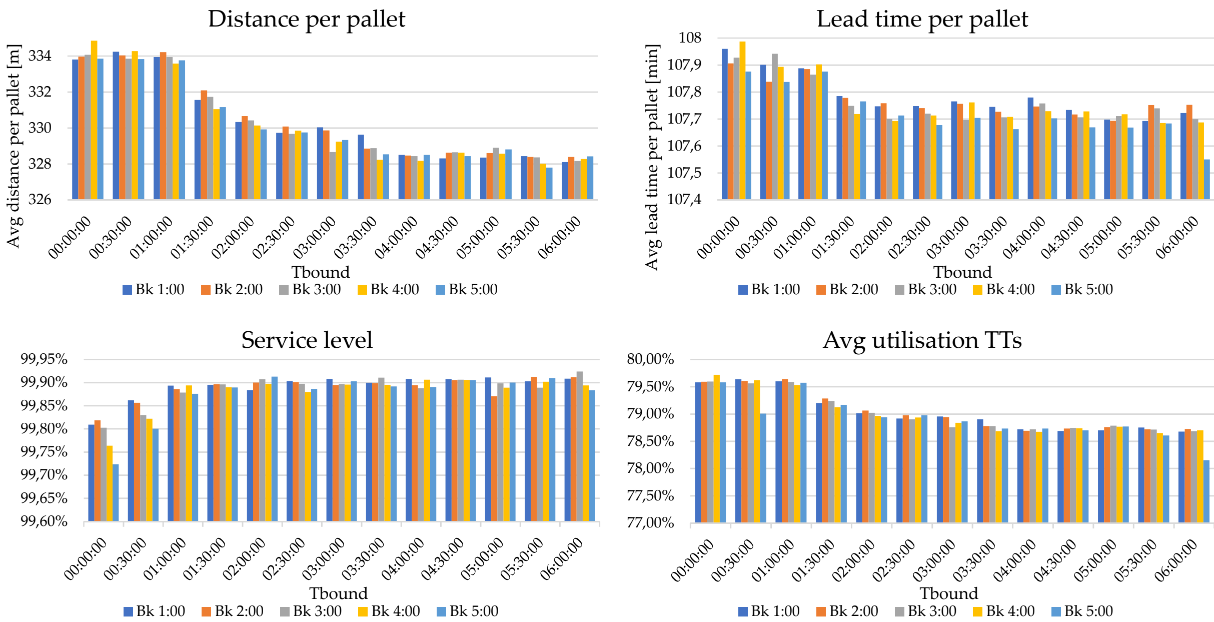

FIGURE 5.9: Overview of performance indicators for parameter tuning for tugger trains under different settings for parameters T_{bound} and *Bk*.

5.7 Conclusions

This section gives a short recap of the simulation study and presents the conclusions of the simulation model.

We evaluate the alternatives proposed in Chapter 4 by means of a simulation study. In our simulation model, we generate the internal sequencing pallets in the warehouses based on the production sequence, bill-of-materials of a truck, and the current ERP-system settings for the pallet contents for every consumption location. Reach trucks or tugger trains transport these pallets according to the solution alternative under consideration to their destination. To recall, we evaluate the following scenarios:

- **Scenario 0:** Current situation.
- **Scenario 1a:** Providing the reach truck drivers with pallet depletion information while having the warehouses separated as in the current situation. (see Section 4.2). No usage of a delivery tour construction mechanism.
- **Scenario 1b:** Providing the reach truck drivers with pallet depletion information while having the reach truck drivers' departments merged (see Section 4.2). No usage of a delivery tour construction mechanism.

- **Scenario 2:** Using the pallet depletion information for constructing delivery tours on demand at the warehouse (see Section 4.3). Tour construction mechanism generates one or two tours at the same time. The reach truck drivers' departments are merged.
- **Scenario 3:** Usage of tugger trains as transport means instead of reach trucks (see Section 4.4). We evaluate tugger trains as transport means for alternatives 1a, 1b, and 2. As this scenario is an adaption of the preceding scenarios, we integrate the outcomes of this scenario in the results by differentiating between *'RTs'* when reach trucks are used and *'TTs'* when tugger trains are used.

We evaluate the outcomes of the different scenarios on different performance indicators to determine if the productivity of the workforce responsible for the delivery of the internal sequencing pallets has improved. We evaluate the average lead time per pallet, average distance per pallet, service level, and utilisation of the available time of the workforce. Table 5.1 presents the results of the simulation study in comparison with the current situation.

	Reduction in				Increase in			
	lead time per pallet		distance per pallet		service level		average utilisation	
Alternative	RTs	TTs	RTs	TTs	RTs	TTs	RTs	TTs
1 separated	25.0%	23.4%	13.9%	-7.2%	0.33 p.p.	0.27 p.p.	0.9 p.p.	12.0 p.p.
1 merged	22.9%	19.1%	1.0%	-7.8%	0.36 p.p.	0.33 p.p.	20.3 p.p.	25.5 p.p.
2 merged	24.8%	19.9%	11.8%	14.7%	0.30 p.p.	0.30 p.p.	13.1 p.p.	11.6 p.p.

TABLE 5.1: Simulation results of the alternatives compared to the current situation. 'RTs' stands for reach trucks, 'TTs' for tugger trains, and p.p. for percent point.

The first thing we need to stress is the number of FTE in the current situation and for alternative 1 is equal to 7 (in total). For alternative 1 merged and alternative 2 merged, the total number of FTE is 6. This makes the latter two alternatives immediately interesting given the values for the performance indicators in Table 5.1 for these two alternatives when using reach trucks as well as tugger trains. By merging the departments of the workforce responsible for the delivery of the pallets, 1 FTE (in total) becomes redundant.

By providing the workforce with pallet depletion information, the lead time of the pallets improves. This is due to the redundancy of driving through the factory to evaluate the current stock levels at consumption locations and by being able to transport the pallet with the earliest due time. Hereby, the service level also increases. When the departments of the workforce are merged, the reduction in lead time per pallet and distance per pallet drop slightly and the average utilisation increases. However, merging the departments yields 1 FTE. If we generate tours for the workforce when the departments are merged, we are able to reduce the lead time per pallet and distance per pallet even further. Besides, the utilisation of the workforce decreases, which means there is capacity left if the transportation demand rises. Combing these figures leads to the conclusion that alternative 2 merged results in the largest increase in productivity of the workforce responsible for the delivery of the internal sequencing pallets. The performance when using tugger trains with this alternative is slightly lower, but is a good alternative to the reach trucks.

For alternative 2 merged there are two parameters that can be adjusted. These parameters are T_{bound} and Bk. Tuning the settings for these parameters result in the advise of setting T_{bound}

around 6 hours and Bk to 3 minutes when using reach trucks. When using tugger trains, we advise to set T_{bound} to 6 hours and Bk to 3 minutes. As the pallets do not need to be stacked when using a tugger train, the height constraint is of no influence to the capacity of the vehicle. Therefore, the pallets can be added to the delivery tour on sequence of earliest due time first. When using reach trucks, the height of the pallets is of importance. Therefore, it makes sense to 'fill up' the delivery tour with the pallet that still fits to the reach truck. This is what happens when setting T_{bound} around 3 hours. This also explains the difference in T_{bound} for reach trucks and tugger trains.

Given the results of the simulation study, we conclude that the productivity of the workforce can be improved when applying one of the proposed alternatives. The condition for applying these alternatives is the improvement of pallet depletion information. This is not possible to do within the current ERP-system. Therefore, a custom application as a complement to the current ERP-system is required. If the pallet depletion information is improved, we advise, based on the simulation results, to start merging the departments of the workforce responsible for the pallet transport while still using reach trucks as transport means. This reduces the required number of FTE from 7 to 6.

We conclude that the usage of tugger trains have the largest potential when applied under alternative 2 merged. That is, constructing delivery tours for the tugger trains. This is especially interesting to apply when the pallet transportation demand increases, as there is capacity left. A condition to apply tugger trains as transportation means is that all consumption locations in the factory (the pallet destinations) must be suitable to receive pallets from a tugger train. Currently, this is not the case.

6 Conclusions and Recommendations

This chapter presents the conclusions and recommendations from our research. Section 6.1 presents the conclusions about the internal sequencing supply method and Section 6.2 presents the recommendations for future research. The objective of our research is to create a method to increase the productivity of the workforce responsible for the delivery of internal sequencing parts to the assembly lines.

6.1 Conclusions

This section presents the conclusions from our research about the internal sequencing supply method.

Chapter 2 describes the analysis of the current situation and its outcomes. In the current situation, the workforce responsible for the delivery of internal sequencing pallets, base pallet replenishments on two indicators: on the cards on pallets in the warehouses containing the due time (consumption time) of that pallet and on physically checking the current stock level at the different locations in the factory pallets must be transported to. They do so as the times on the cards on the pallets in the warehouse are incorrect due to two reasons: the standard time error and the lack of updating these times during the day. The standard time error is the error caused by settings in the ERP system resulting in wrong consumption times after the night run of the ERP system. The consumption times should be correct after the night run, but they are wrong. By not updating these times during the day, the due time error will increase if production runs not as planned. Due to the lack of reliable information, the workforce responsible for the delivery of the internal sequencing pallets drive longer delivery tours to physically check different locations for a replenishment need. This leads to a decrease in productivity of the workforce. Also, the workforce is divided over different warehouses in the current situation, thereby not utilising the effect of combining pallets in delivery tours in a way the total system performance increases. We conclude that the productivity of the workforce can be improved by providing them with the correct pallet replenishment information combined with creating a workforce 'pool' for the delivery of pallets from both the HB and LB warehouses. By providing the workforce with information about what pallet to deliver in a delivery tour, we expect the productivity of the workforce to increase even further. Chapter 1 identifies the lack of an accurate replenishment signal and random delivery routes as the core problems of our research.

By means of a literature study we investigate the possibilities of improving the delivery tour contents and routes the workforce drive to deliver internal sequencing pallets. Different strategies on constructing and dispatching the delivery tours are proposed in literature. The main disadvantages of the proposed solutions are; the assumption of equal driving times for all delivery tours, the assumption of fixed consumption rates of parts, and the assumption of deterministic part demand. However, these assumptions do not correspond with the situation at Scania. We therefore propose solution alternatives that cope with these assumptions.

The solution alternatives that we propose in Chapter 4, provide the workforce responsible for the delivery of the internal sequencing pallets with information about the pallets to deliver. Through this, we improve the productivity of the workforce by eliminating the need to check for replenishment needs and by making the right decisions on what pallet to deliver when. We distinguish between the workforce themselves choosing the pallets to deliver and a computer program making this decisions for the workforce, and the type of vehicle to deliver the pallets: reach trucks or tugger trains. The proposed alternatives are not only applicable at Scania; they are applicable in all environments where transportation need for pallets (or other units to move) exists where the choice on what pallets to deliver takes place shortly before execution of transport at, for instance, a company assembling a product on an assembly line.

By means of a simulation study we evaluate the proposed alternatives on the utilisation of the workforce, the service level, the distance per pallet, and the lead time of pallets. Table 6.1 presents the results of the simulation study. Keeping the workforce separated over the warehouses, as in the current situation, requires 7 FTEs in total. By providing the workforce with information about what pallets must be transported when (*alternative 1 separated*), result in an increase in utilisation of 0.9 p.p. compared to the current situation in case of using reach trucks as transport means and 12.0 p.p. in case of using tugger trains. The biggest change is the reduction of the lead time per pallet: 25% for reach trucks and 23.4% for tugger trains. These values are the highest among the alternatives due to having an overcapacity situation as the workforce is separated over the warehouses.

By creating a workforce 'pool' serving both the HB and LB warehouse (*alternative 1 merged*), the total number of FTEs can be lowered to 6 which results in and increase of 20.3 p.p. in average utilisation when using reach trucks and 25.5 p.p. when using tugger trains. This means the workforce is more productive, given the lead time per pallet, distance per pallet, and service level all improved when using reach trucks or tugger trains and a workforce of 6 FTEs instead of 7 FTEs. The only exception is the increase in distance per pallet when using tugger trains, caused by internal traffic rules for tugger trains. When providing the workforce with information about the pallets to transport in a delivery tour (*alternative 2 merged*), the average utilisation increases with 13.1 p.p. when using reach trucks and 11.6 p.p. when using tugger trains, both compared to the current situation. The reduction in lead time per pallet and distance per pallet is the largest under this alternative. These figures indicate this alternative can handle the pallets in the most effective way, using reach trucks or using tugger trains.

	Reduction in				Increase in			
	lead time per pallet		distance per pallet		service level		average utilisation	
Alternative	RTs	TTs	RTs	TTs	RTs	TTs	RTs	TTs
1 separated	25.0%	23.4%	13.9%	-7.2%	0.33 p.p.	0.27 p.p.	0.9 p.p.	12.0 p.p.
1 merged	22.9%	19.1%	1.0%	-7.8%	0.36 p.p.	0.33 p.p.	20.3 p.p.	25.5 p.p.
2 merged	24.8%	19.9%	11.8%	14.7%	0.30 p.p.	0.30 p.p.	13.1 p.p.	11.6 p.p.

TABLE 6.1: Simulation results of the alternatives compared to the current situation. 'RTs' stands for reach trucks, 'TTs' for tugger trains, and p.p. for percent point.

We advise to start with the implementation of *alternative 1 merged* while using reach trucks as transport means and later expand this to *alternative 2 merged*, also using reach trucks as transport means. By doing so, Scania has an intermediate phase in which the performance of the system can be evaluated and ERP system settings can be adjusted if required before programming the complete application for the assignment of pallets to delivery tours. We advise to use reach trucks as the performance improvement when using tugger trains compared to reach trucks is not that large, reach trucks are already present resulting in lower investment costs, and not all pallet destinations in the factory are suitable for supply by tugger trains yet. If the use of tugger trains becomes mandatory or preferable, the change to tugger trains can easily be made as the proposed solution procedures can handle both transportation means. Implementing a solution alternative requires real time production progress information from the factory. Section 6.2 elaborates how to achieve this.

6.2 Recommendations

Section 6.1 advises to implement alternative 1 merged and expand this later to alternative 2 merged. In this section we provide Scania with recommendations on the implementation of alternative 1 merged and/or alternative 2 merged and we propose recommendations for future research.

Recommendations on alternatives

- Tracking the production progress in the factory requires feedback to the ERP system about the current state of production. We recommend Scania to obtain the production progress at the line by means of an identification tag at each chassis. Scanning this tag at a couple of stations spread over the assembly line, results in an accurate overview of the production situation in the factory. We recommend to exclude human interaction in the scanning process of the chassis to prevent any mistakes as this is a critical step to obtain real time production progress information for the supply of parts.
- We recommend to revise the trigger times of the required parts in the ERP system for all workstations to match the production progress more closely as we found that there are some incorrect settings for workstations at the assembly line as well as for workstations at pre-assembly stations. By making sure these times are correct, the bias in due time of pallets are improved resulting in accurate times to base the replenishment moment on.
- The vehicles delivering the pallets to their destination require a device on which a list with the pallets ready for delivery is visible. The vehicle driver sees the priority of the pallets to deliver and either make the choice on what pallets to take (*alternative 1 merged*) or let the system decide what pallets to take for a delivery tour (*alternative 2 merged*).
- An intermediate application is required to provide the workforce with information about the pallets to deliver. This application also needs to track the stock level of every pallet destination by matching the production progress with the parts on the pallet. In this way, it is known when a pallet is empty, i.e. one of the two bins is available for a replenishment. The application matches the picked pallets in the warehouse with pallet destinations in the factory that are available to receive a replenishment. By combining this information with the due time of every picked pallet in the warehouse, a list with the pallets to transport sorted on priority can be made and provided to the workforce. The workforce should provide feedback to the system when a certain pallet is picked up for transport by means of a scanner. In this way the system can prevent others to try to find the pallet already in transport. By scanning the pallet again on delivery, the application knows the pallet has arrived at its destination and can add the pallet loading to the inventory of that location. An additional advantage of this is the possibility to analyse travel times and delivery tour contents. We advise to have specialists from the IT-department of Scania involved in the design and realisation of the required application as connections to the existing system are required.

Recommendations on future research

- We recommend to investigate the possibilities to include other logistic flows originating from the HB and LB warehouses that are not 100% flows (i.e. the parts not required for every chassis) in the internal sequencing flow of this research. Adding these pallets to the internal sequencing flow of pallets may increase the benefits of creating a workforce 'pool' we observed in our research.
- Currently, reach trucks are the transport means for the delivery of internal sequencing pallets. We recommend to investigate if the use of AGVs for the delivery of the internal sequencing pallets is suitable for this supply method and what kind of implications arise. By using AGVs, it is likely to be possible to reduce the required workforce for the delivery of the internal sequencing pallets as no drivers are required anymore.

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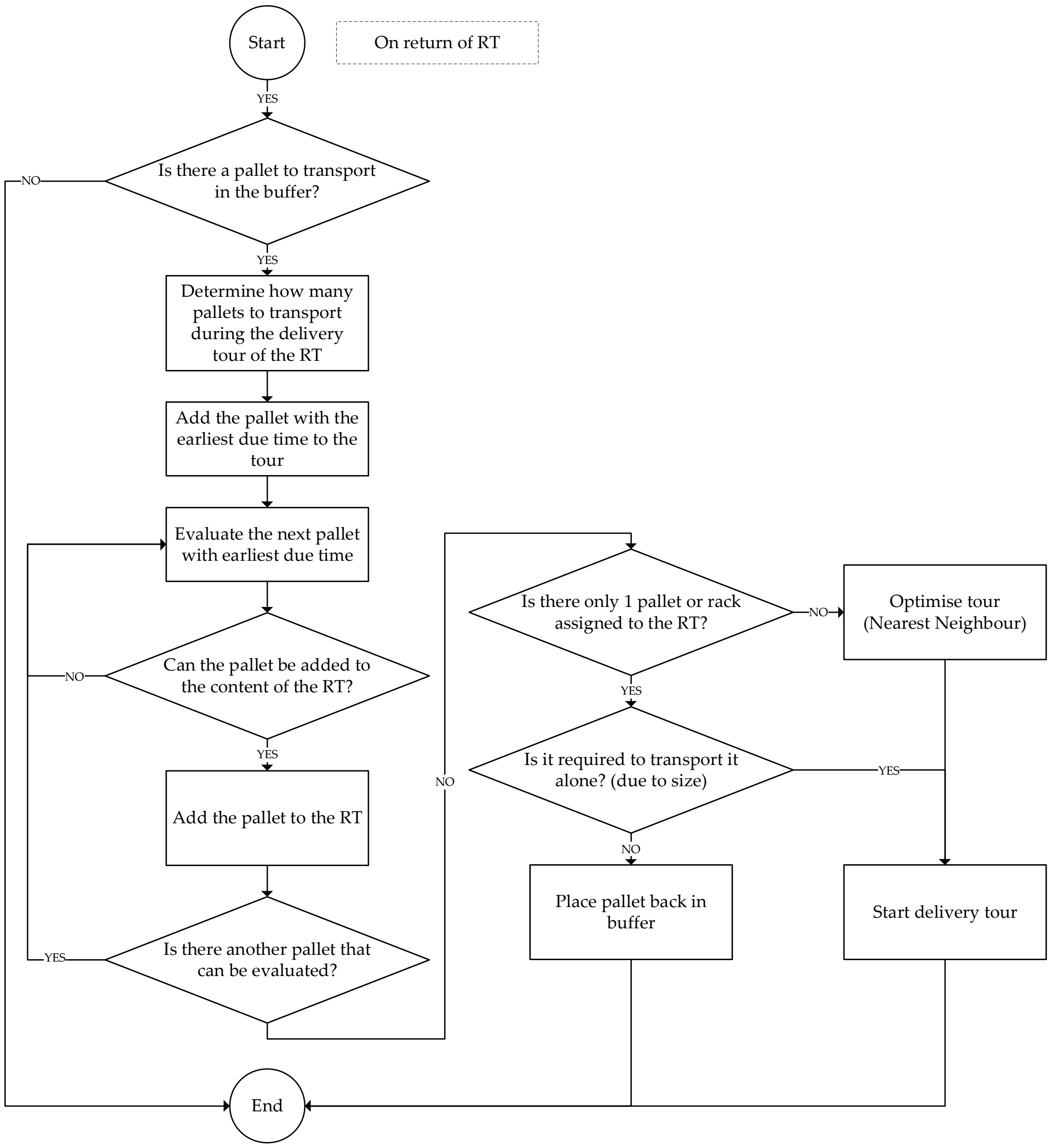
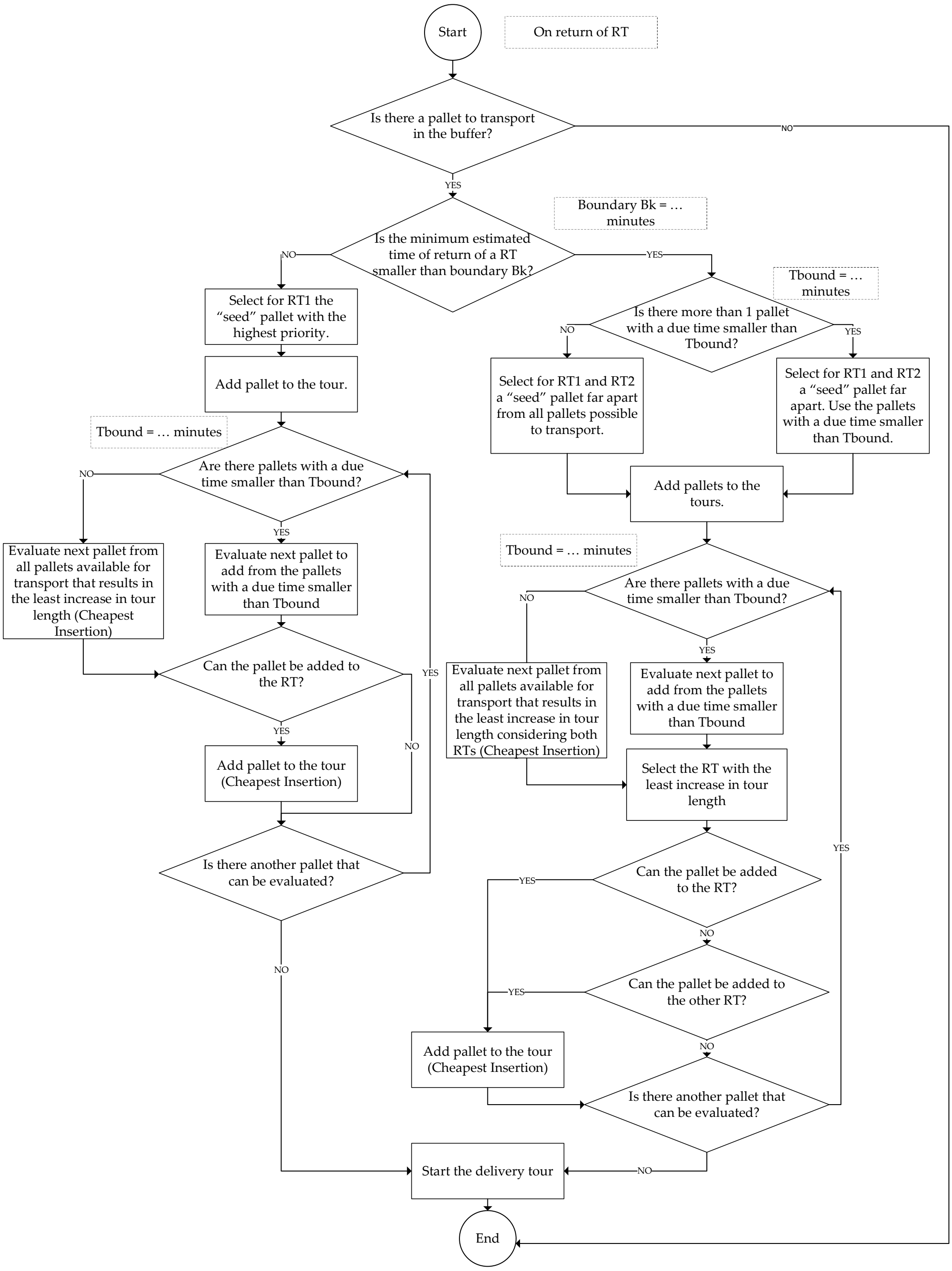
A Flowcharts of alternatives

This appendix presents the flowcharts of the different solution alternatives.

A.1 Flowchart alternative 1



A.2 Flowchart alternative 2



B Model validation

This appendix presents the results of the chi-square goodness-of-fit test to evaluate the number of pallets generated in the warehouses in our model compared to the actual number of pallets.

B.1 Goodness-of-fit test

Section 5.4 describes the approach for validating the simulation model. This appendix presents the results of the chi-square goodness-of-fit test of the number of pallets used on a production day. Figure B.1 shows the result of the test for the number of pallets from the HB warehouse. The expected number of observations represents the real world system and the observed number of observations the simulation model. The test results in a p-value of 0.354. If the p-value is above 0.05, we have no reason to believe that the data from the simulation model does not fit the real world data. Table B.1 presents all p-values of the tests.

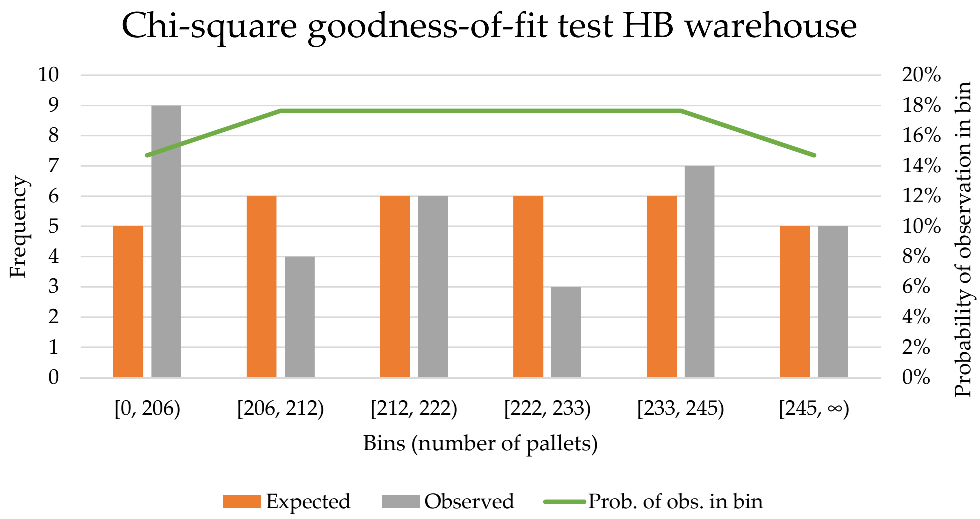


FIGURE B.1: Chi-square goodness-of-fit test result HB warehouse.

Warehouse	p-value
HB	0.354
LB1	0.310
LB2	0.122

TABLE B.1: Chi-square goodness-of-fit test results.

C Statistical techniques

This appendix presents the statistical techniques used. Section C.1 presents the sequential procedure used for determining the required number of replications in the simulation model and Section C.2 describes the paired-t confidence intervals for comparing the outcomes of the simulation model.

C.1 Sequential procedure

We use the sequential procedure to determine the required number of replications to obtain a confidence level of 95%. In the sequential procedure, replications of the model are added one at the time, until the confidence level is high enough. To calculate a confidence interval for the mean when the variance is unknown, Formula C.1 is used.

$$[\overline{X} - t_{n-1,1-\frac{\alpha}{2}} \cdot \frac{S}{\sqrt{n}}, \overline{X} + t_{n-1,1-\frac{\alpha}{2}} \cdot \frac{S}{\sqrt{n}}] \quad \textit{in which} \tag{C.1}$$

$\overline{X}$ = the sample mean
S = the sample standard deviation
n = the number of replications
α = the confidence level
$t_{n-1,1-\frac{\alpha}{2}}$ = t-value from the Student's t-distribution with
$n-1$ = the degrees of freedom
$1-\frac{\alpha}{2}$ = the significance level of one tail

When calculating the confidence intervals, the confidence interval half-width relative to the sample mean indicates how good or bad the estimation of the mean is. For example, lets assume we have a confidence interval half-width of 20. When having a sample mean of 35, the confidence interval is [15, 55]. When having a sample mean of 400, the confidence interval is [380, 420]. In the latter case, the prediction is better. To deal with this difference in the confidence interval half-width relative to the mean, we calculate the relative error.

The relative error is the confidence interval half-width relative to the mean. We use the Formula C.2 from Law (2015) as a stopping criterion on the relative error for performing more replications.

$$\frac{t_{n-1,1-\frac{\alpha}{2}} \cdot \frac{S}{\sqrt{n}}}{\overline{X}} < \gamma' \quad \textit{in which} \tag{C.2}$$

$\gamma' = \frac{\gamma}{1+\gamma}$ is the adjusted relative error
γ = the actual relative error

The actual relative error should be lower than 0.15 (Law, 2015). We use a relative error of 5% ($\gamma = 0.05$) and a confidence level of 95% ($\alpha = 0.05$) to determine the number of replications.

C.2 Paired-t Confidence Interval

To compare the outcomes of the simulation model with each other, we use a paired-t confidence interval of the difference in outcomes (Law, 2015). This is possible due to the use of common random numbers in our simulation model. To compare the outcome of scenario X with the outcome of scenario Y, we calculate the differences between the replications i of these scenarios. This means we calculate for every replication $Z_i = X_i - Y_i$, where Z_i is the difference in outcome for the i^{th} replication. We calculate the 95% confidence intervals with Formula C.3.

$$[\overline{Z} - t_{n-1,1-\frac{\alpha}{2}} \cdot \frac{S}{\sqrt{n}}, \overline{Z} + t_{n-1,1-\frac{\alpha}{2}} \cdot \frac{S}{\sqrt{n}}] \quad \textit{in which} \tag{C.3}$$

$\overline{Z}$ = the mean of the differences
S = the sample standard deviation
n = the number of replications
α = the confidence level
$t_{n-1,1-\frac{\alpha}{2}}$ = t-value from the Student's t-distribution with
$n-1$ = the degrees of freedom
$1-\frac{\alpha}{2}$ = the significance level of one tail

If the confidence interval includes 0, there is no significant difference between the outcomes of scenario X and scenario Y. If the confidence interval does not contain 0 and is positive, the outcome of scenario X is significantly higher than the outcome of scenario Y. If the confidence interval does not contain 0 and is negative, the outcome of scenario X is significantly lower than the outcome of scenario Y.