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SCANIA

Improving internal routing operations in the automotive industry

Master graduation assignment at Scania Production Zwolle

Author: N.H.D. Koopman, BSc

Supervisors

Dr. ir. E.A. Lalla (1st supervisor University of Twente)
Dr. ir. J.M.J. Schutten (2nd supervisor University of Twente)
Drs. ing. G. Stoffers (Head Logistics Engineering at Scania Production Zwolle)
MSc K. Grit (Logistics Engineer at Scania Production Zwolle)

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University of Twente
Industrial Engineering and Management
Drienerlolaan 5
7522 NB Enschede
Tel.: 053 489911

Scania Production Zwolle
Department of Logistics Engineering
Russenweg 5
8041 AL Zwolle
Tel.: 038 4977611

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Author:
N.H.D. Koopman, BSc
Master student Industrial Engineering & Management, University of Twente

Supervisors University of Twente:
Dr. ir. E.A. Lalla (1st supervisor)
Dr. ir. J.M.J. Schutten (2nd supervisor)

Supervisors Scania Production Zwolle:
Drs. ing. G. Stoffers (Head Logistics Engineering)
MSc K. Grit (Logistics Engineer)

Management summary

This thesis is about the Batch/Sequence/Kit flow (BSK flow), which is part of the internal logistics process at Scania Production Zwolle (SPZ). In this thesis we create a future-proof solution approach that improves the internal routing operations at SPZ, in comparison to the manually created train schemes. The results from our solution approach, while using the current settings of the BSK flow, show that our solution approach improves the performance of the BSK flow. Further improvements of the BSK flow performance are possible by changing some of the used planning restrictions.

Context analysis

SPZ produces a wide variety of trucks and the BSK flow is used for a part of their internal logistics process. The BSK flow consists of parts that are transported on fixtures from the on-site warehouses to the assembly lines by tugger trains on a regular tact. The BSK flow parts are first picked as batch, sequence, or kit, and are placed on fixtures in the warehouses. The BSK flow currently uses 12 tugger trains, and each tugger train has 4 fixed routes. A tugger train uses 4 trailers, and each trailer can transport one 1-euro size fixture or two ½-euro size fixtures. In the current manual routing method, the BSK flow uses 2 types of trailers, fixed warehouse locations, and 5 principles. Regarding the planning restrictions, we have observed the following possibilities to improve the BSK flow: use of 1 type of trailer, use of a marshalling area, and use of 1 principle. For each route of the BSK flow, the Total Route consists of the route inside the warehouse to pick up full fixtures, the route at the assembly line to deliver full fixtures and to pick up empty fixtures, and the route inside the warehouse to deliver empty fixtures. Our analysis of the three datasets of the BSK flow showed that there are discrepancies in each train of the BSK flow, when we compared datasets 1 and 2 (real data from practice), with dataset 3. Therefore, for the evaluation of our solution approach we have only used dataset 3, which is the artificially generated dataset resembling the normal situation of the BSK flow.

Core problem and main research question

The current routing method of the BSK flow results in a productivity loss, which is observed via the Key Performance Indicators of this flow that are below their target of 80%: the average physical fill rate (71.7%) and the average time fill rate (72.6%). The physical fill rate shows the percentage of used capacity, compared to the available capacity in a route. Moreover, the time fill rate shows the percentage of used travel time in comparison to the available time, which is the logistical tact time of a route. Using a problem cluster, we have defined the core problem of the BSK flow as:

> The manual routing method of the BSK flow is not efficient because of the increased complexity of this flow and the labour intensity of this method, affecting the ability to cope with changes in tact times and the ability to exploit its potential, which results in a productivity loss of the BSK flow.

Furthermore, we have defined our research objective, which is to advise SPZ on how to improve the routing of the BSK flow. We have translated the research goal into the main research question:

> How can the routing of the BSK flow be optimised, to increase the productivity of the BSK flow?

Proposed methodology based on literature

Using a Systematic Literature Review, we have identified the problem faced at SPZ as a Vehicle Routing Problem (VRP): the BSK flow-VRP is the Vehicle Routing Problem with Pickup and Delivery and loading constraints for internal logistics. The objective of the BSK flow-VRP is to minimise the total travel distance, which might result in a reduction in the number of trains. Using fewer trains results in a cost reduction which is the economic advantage SPZ wants. We have observed that for each route of the BSK flow, either the Partial LIFO or the Strict LIFO loading constraints are present in the current routes. Furthermore, we have observed the possibility to adapt the partial LIFO from the literature to the BSK flow, resulting in the Adapted Partial LIFO strategy. Adapted Partial LIFO entails that only the last pickup fixture is the first fixture that is delivered to the assembly line, whereas Strict LIFO entails that the route at the assembly line is the reverse of the route inside the warehouse to pick up the full fixtures. Based on the preceding, we have incorporated the following loading constraints in our solution approach: No Policy, Adapted Partial LIFO, and Strict LIFO. VRPs can be solved exactly, via heuristics or via metaheuristics. Based on the advantages and disadvantages of each solution approach, metaheuristics is the best option to solve the BSK flow-VRP. From the metaheuristics we have chosen Tabu Search since this is the most advisable choice for solving the BSK flow-VRP. We have chosen the Nearest Neighbour Heuristic (NNH) to generate the initial solution.

Solution approach

Our solution approach to solve the BSK flow-VRP consists of: importing the BSK flow data; executing the NNH and Tabu Search, that are both adapted to the BSK flow-VRP; generating the output. The standard NNH starts and ends at the depot, while the routes of the BSK flow start and end inside the warehouse. Therefore, we have tailored the NNH to the BSK flow-VRP: the NNH constructs the Total Route, which consists of the route to pick up full fixtures inside the warehouse (Route_WH), the route to deliver full fixtures at the assembly line and to pick up empty fixtures at the same line location (Route_LL), and the route to deliver empty fixtures to the warehouse (Route_WHBack). So, the NNH constructs for each train the Total Route: Total Route = Route_WH + Route_LL + Route_WHBack. Similarly, the new route of each candidate after executing a swap or move during Tabu Search, also consists of the preceding Total Route. This way, we have also tailored Tabu Search to the BSK flow-VRP. All in all, we have tailored the concepts and methods from literature to our problem. For verification we have used debugging, visualisation of output, and meetings with the stakeholders of SPZ. Furthermore, we have used those meetings, and the current trains schemes, for validation.

Results and conclusions

Based on the experimental results of experiments 1 to 4, we have substantiated the choices of our solution approach. Afterwards, we have evaluated our solution approach by running experiments 5 to 12, which has shown that our solution approach solves the core problem of the BSK flow. Table 1 shows the NNH results of experiment 5, and the Tabu Search results of experiments 9, 10, and 12.

Experiment	Experiment Name	Used loading constraints	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Average Just-In-Time percentage	Computational Time
E5. NNH	Current settings of the BSK flow	No Policy	659.8	5.22	12	6	10.64	74.97%	68.61%	35.93%	00:04:43
		Adapted Partial LIFO	688.3	5.37	12	6	10.81	73.74%	69.14%	37.29%	00:03:37
		Strict LIFO	693.4	5.40	12	6	10.75	74.14%	69.95%	38.66%	00:03:30
E9. TS	Use of a marshalling area and 1 type of trailer	No Policy	359.9	3.63	11	5	9.38	85.52%	54.40%	28.45%	01:59:07
		Adapted Partial LIFO	357.3	3.62	11	5	9.38	85.52%	54.20%	28.45%	01:49:28
		Strict LIFO	354.1	3.60	11	5	9.38	85.52%	53.94%	28.45%	01:50:13
E10. TS	Use of a marshalling area and 1 principle	No Policy	371.3	3.70	10	5	7.39	96.53%	76.57%	38.26%	01:59:16
		Adapted Partial LIFO	368.7	3.68	10	5	7.39	96.53%	76.29%	38.26%	01:59:44
		Strict LIFO	366.1	3.67	10	5	7.39	96.53%	76.02%	38.26%	01:58:41
E12. TS	Use of a marshalling area, 1 principle and 1 type of trailer	No Policy	350.9	3.58	10	4	7.03	92.35%	70.95%	34.77%	01:59:41
		Adapted Partial LIFO	347.9	3.57	10	4	7.03	92.35%	70.63%	34.77%	01:59:57
		Strict LIFO	345.2	3.55	10	4	7.03	92.35%	70.34%	34.77%	01:59:33

Table 1. Results of experiments 5 (NNH), and the Tabu Search results of experiments 9, 10, and 12

Below are the most important findings of experiments 5, 9, 10, and 12.

- The most important findings of experiment 5, in comparison to the current train schemes, are: lower average number of trains; increase of the average physical fill rate; decrease in the total travel distance and the total travel time; decrease of average time fill rate, which is traced back to the lower average number of trains and the lower total travel time.
- The most important findings of experiments 9, 10, and 12 are the reductions in the required number of trains: experiment 9 needs one train less and has no large fluctuations of needed trains during the day; experiments 10 and 12 both yielded a decrease of 2 trains, but they have fluctuations in the number of trains needed during the day. Experiments 9, 10, and 12 have the

following Return on Investment: 3.09 years (experiment 9), 1.23 years (experiment 10), and 1.64 years (experiment 12).

Overall, our research shows that our solution approach solves the core problem in the following ways:

- the increased complexity of this flow: our solution approach can cope with the increased complexity of the BSK flow. Moreover, our solution approach can cope with the current planning restrictions, but it can also deal with changes in the used planning restrictions.
- the labour intensity of this method: the use of our solution approach is less labour intensive since our solution approach solves the BSK flow-VRP and automatically generates the desired outputs.
- affecting the ability to cope with changes in tact times: by changing the logistical tact time in the input data and changing the maximum travel time in the solution approach, our solution approach copes with changes in tact times.
- the ability to exploit its potential: Tabu Search optimises the initial solution from the NNH, which shows that our solution approach is able to exploit the potential of the BSK flow.
- Productivity: the increased average physical fill rates (experiments 5 to 12), and the increased average time fill rates in the experiments that use 1 principle, resemble the desired increase in productivity.

Recommendations

We recommend SPZ to use our solution approach for the route creation of the BSK flow. Moreover, we recommend SPZ to look for other internal logistics flows that could use our solution approach in an adapted form. It is possible that a route of our solution approach is not desired due to safety or congestion inside the factory, even though the result is better. Therefore, we advise SPZ to check this before implementing the solution. Lastly, we advise SPZ to gather more data about the BSK flow, which should be accurate to prevent the discrepancies that our analysis of the current datasets showed.

Based on the evaluation of our solution approach, we have recommendations that are based on the three planning levels: operational (short-term), tactical (mid-term), and strategic (long-term).

- Operational level: we recommend SPZ to use our solution approach for creating the fixed routes. By using input data of only 4 time periods, the solution approach will make 4 fixed routes.
- Tactical level: we advise SPZ to start testing the use of the flexible routes that the solution evaluation of experiments 5 to 12 generated.
- Strategic level: SPZ needs to decide which of the used planning restrictions from experiments 5 to 12 are implemented. Furthermore, in the long-term we advise SPZ to use an advanced navigation system that can show the flexible routes instead of using the printed fixed routes.

Limitations of our research, contributions of our research, and future research

Limitations of our research are: the maximum computational time of 2 hours for Tabu Search; since there were many discrepancies between datasets 1 and 2, in comparison with dataset 3, we have only used dataset 3 for the solution evaluation.

Our research contributes to theory in the following ways: the adaption of the NNH and Tabu Search to the BSK flow-VRP; use of multiple loading constraints in our solution approach. Furthermore, our research contributes to practice in the following ways: the use of decomposing the big problem into smaller instances; solving the core problem.

Possibilities for future research are: incorporation of different layouts of the warehouse; experiment with different number of chassis per fixture; incorporate the different frame types from practice; use of another heuristic to generate the initial solution, which might result in a better initial solution; incorporate the extra time from the special crossings differently.

Preface

With great pleasure, I present to you my master thesis “Improving internal routing operations in the automotive industry”. This report is the result of my master thesis project at Scania Production Zwolle to finalise my study Industrial Engineering and Management at the University of Twente.

First of all, I would like to express my gratitude to my colleagues at the department of Logistics Engineering at Scania Production Zwolle. They were always willing to help me with my graduation project. I also look back on a pleasant period at the department of Logistics Engineering, because of the great working environment they offered me. In particular, I would like to thank my company supervisor, Gerben Stoffers, for his enthusiasm, advice, and feedback during my graduation project. Furthermore, I would like to thank my supervisors Eduardo Lalla and Marco Schutten from the University of Twente for their critical view, guidance, and support. The feedback helped me to improve the quality of my thesis. Finally, I would like to thank my family and friends for their support during my graduation project.

During my graduation project I learned a lot about myself, and I look forward to the future in which I hope to continue to improve myself and keep on learning. For now, I hope that you enjoy your reading.

Nathalie Koopman
Apeldoorn, January 2023

Content

List of definitions

- *Batch supply*: supply method; a fixture is split up into multiple boxes and each box contains a certain batch size of each part number. The batch size is calculated based on the consumption and some extra safety margin.
- Batch/Sequence/Kit flow: the Batch/Sequence/Kit flow (BSK flow) consists of parts that are transported on fixtures from the on-site warehouses to the assembly lines by tugger trains on a regular tact. Those parts are first picked as batch, sequence, or kit, and are placed on fixtures in the warehouses.
- *Factory Feeding:* delivery of parts; Factory Feeding consists of unloading the supplying trailers and afterwards delivering the parts directly to the assembly line or transporting the parts to a warehouse.
- *Fixture*: a fixture is used as a carrier, where the parts of the BSK flow are transported on.
- *Fixture overview*: overview that shows the distribution of fixtures over trains and shows relevant information for each fixture.
- *Individual train scheme*: overview of fixtures that are delivered by an individual train, in each delivery route of this train.
- *Instance*: an instance is a combination of a time period, a principle, and a type of trailer.
- *Kit supply*: supply method; a kit is a composition of several parts that are used for the assembly of one truck, which is based on the chassis number. These kits are picked based on an order picking list, which shows what needs to be picked for the next *k* chassis.
- *Line Feeding*: delivery of parts; Line Feeding entails picking parts from the warehouse and delivering those parts to the assembly line.
- *Logistical tact time:* the logistical tact time is the time the tugger train has for a route. The logistical tact time is calculated as the tact time multiplied by the principle the train is in.
- *On a regular tact*: process that is based on the tact time.
- *Physical fill rate:* the physical fill rate shows the percentage of used capacity, compared to the available capacity in a route.
- *Principle*: the BSK flow uses in the current routing schemes 5 principles. The used principles are: Principle 1, Principle 2, Principle 3, Principle 4, and Principle 6.
- *Routing scheme*: delivery routes per train; showing the train driver where to stop for the pickup and the delivery of each fixture in their routes.
- *Sequence supply*: supply method; the parts are picked based on an order list and are placed on fixtures. By using this list, the parts are placed on the fixture by their chassis number, which is in the sequence of the production.
- *Sub dataset*: we use sub datasets to execute our solution approach and each sub dataset contains all time periods. We have created the following sub datasets, which are based on the principle and the type of trailer: Principle15minutes_Type1; Principle15minutes_Type2; Principle3_Type1; Principle3_Type2; Principle4_Type2; Principle6_Type1.
- *Tact time*: the available time per workstation; if the tact time is 15 minutes, every 15 minutes all trucks in progress will go to the next workstation and the finished truck at the last workstation goes to the parking.
- *Time fill rate:* the time fill rate shows the percentage of used travel time in comparison to the available time, which is the logistical tact time of a route.
- *Tugger trains*: mode of transport; trains that transport the BSK flow fixtures, by 'clicking' the fixtures in the Rothar or Still trailer. A tugger train uses 4 trailers, and each trailer can transport one 1-euro size fixture or two ½-euro size fixtures. Each tugger train has currently 4 fixed routes.
- *Unit supply*: supply method; highly consumed parts are supplied to the assembly line without repacking or order picking. The parts are delivered in their original package, which is in pallets or bins.

1. Introduction

This chapter introduces the research on the Batch/Sequence/Kit flow that we have performed at Scania Production Zwolle (SPZ). In the remainder of this report, we shorten the Batch/Sequence/Kit flow to the BSK flow. First, Section 1.1 introduces SPZ by explaining the information that is needed for this research. Next, Section 1.2 explains the internal logistics at SPZ. The BSK flow is one of the internal logistics flows at SPZ and is therefore also introduced in Section 1.2. Afterwards, Section 1.3 addresses the assignment and the motivation for this research. Next, Section 1.4 explains the problem cluster of the BSK flow, which is used to identify the core problem of the BSK flow. Afterwards, Section 1.5 addresses the research goal and the main research question. Next, Section 1.6 addresses the research scope. Afterwards, Section 1.7 addresses the research questions with the used approach and structure of this report. Lastly, Section 1.8 summarises the research design as the conclusion of this chapter.

1.1. Scania Production Zwolle

Scania is a world-leading manufacturer of trucks, busses, coaches, and engines, and has a production location in Zwolle. Each year, Scania produces more than 80,000 trucks, 8,000 coaches, and 8,000 engines. Figure 1.1 depicts the products that Scania produces, and Scania delivers trucks to more than 80 countries worldwide. Scania has more than 50,000 employees in about 100 countries. More than 2,000 employees work at Scania Production Zwolle.

Figure 1. 1. Overview of Scania products

The production location in Zwolle, SPZ, has two U-formed assembly lines, the Castor line and the Pollux line, where the assembly of trucks takes place. The assembly lines consist of multiple consecutive workstations. SPZ also delivers Knockdown Trucks. Those Knockdown Trucks are transported as a kit to the country of destination where assembly takes place. SPZ is Scania's biggest and most modern assembly factory in Europe. This location is responsible for 60% of the yearly production of Scania.

1.1.1. Scania Production System

Scania wants to be the leader in sustainable transport, which creates a world of mobility that is better for business, society, and the environment. Scania uses the Scania Production System (SPS) to achieve this vision. The SPS is based on Lean Production, which was inspired by the Toyota Production System (Scania Production Zwolle, 2022). Lean Production or Lean Manufacturing is characterised as "a traditional approach to eliminate waste in the value stream and ensure the efficiency of the production processes" (Valamede & Akkari, 2020). Scania applies Lean Production to its whole supply chain, which results in a lean supply network (Scania Production Zwolle, 2022).

Figure 1.2 depicts the Lean Production of Scania by showing the SPS. Appendix A describes the whole SPS. The rest of this section only describes the relevant implications of the SPS. One layer of the SPS-house is the normal situation. For Scania, the normal situation consists of standardisation, tact time, levelled flow, balanced flow, visualisation, and real-time management. Scania has demand-driven output, which means that trucks are only produced after the order is placed. Based on the modular design and the customer's first core value, the customer can customise their truck. Due to the customisation, there is a large variety of possible configurations of a truck. The truck production mix is not the same each day because of the demand-driven output and the modular design. This results in a variation in the type of produced trucks. Moreover, this also results in a variation in the number of produced trucks. A core concept of Lean Production is the elimination of waste, which is translated into the Just-In-Time (JIT) delivery of parts. JIT means that precise amounts of materials are provided just when they are required, which minimises inventory and waste in the process (Goh & Goh, 2019); (Ruffa, 2008). The use of the JIT principle, in combination with the limited space at the assembly lines, translates to a high amount of traffic around the assembly lines as Section 1.4.2 explains. The production of trucks can only continue when the right parts are delivered at the right place at the right time. Therefore, the logistical process is closely linked to the production of trucks, as Section 1.2 describes the organisation of the internal logistics at SPZ.

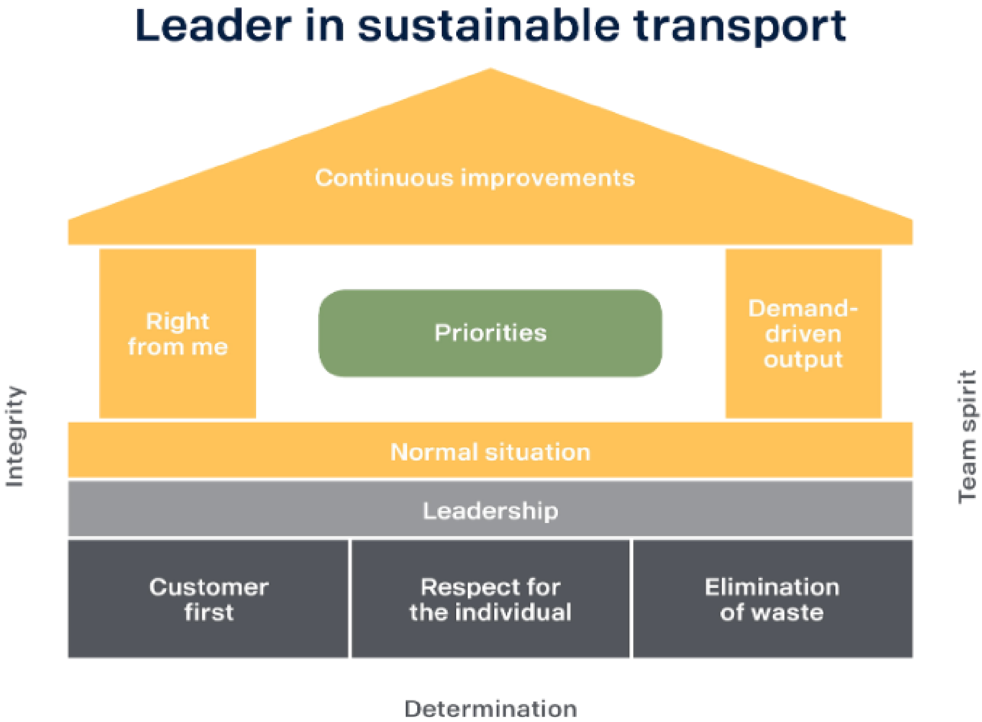

Figure 1. 2. The Scania Production System

1.2. Internal logistics at Scania Production Zwolle

This section explains how the internal logistics at Scania Production Zwolle are organised. The departments of Factory Feeding and Line Feeding are responsible for the internal logistics at SPZ, as Section 1.2.1 explains. Section 1.2.2 briefly explains the BSK flow, which is one of the Line Feeding flows. Chapter 2 explains the BSK flow in more detail by describing the current situation.

1.2.1. Factory Feeding and Line Feeding

The production process of trucks is based on the actual placed orders by customers and the assembly of trucks takes place *in sequence*. The logistical process is closely linked to the production of trucks. Regarding the delivery of parts, both external and internal delivery, Scania uses the JIT principle. With regards to internal logistics, there are two types of logistical processes. Figure 1.3 depicts these two types of internal logistics: Factory Feeding and Line Feeding. Chapter 2 divides the two main logistical processes of Factory Feeding and Line Feeding into more specific supply methods.

Factory Feeding consists of unloading the supplying trailers and afterwards delivering the parts directly to the assembly lines or transporting the parts to a warehouse. The direct delivery of parts from the trailers to the assembly lines is mainly used for large parts, like motors, cabins, tires, and fuel tanks.

On the other hand, when Line Feeding is used, the parts are picked from the warehouses and are delivered to the assembly lines. The BSK flow is one of the Line Feeding flows as Section 1.2.2 explains.

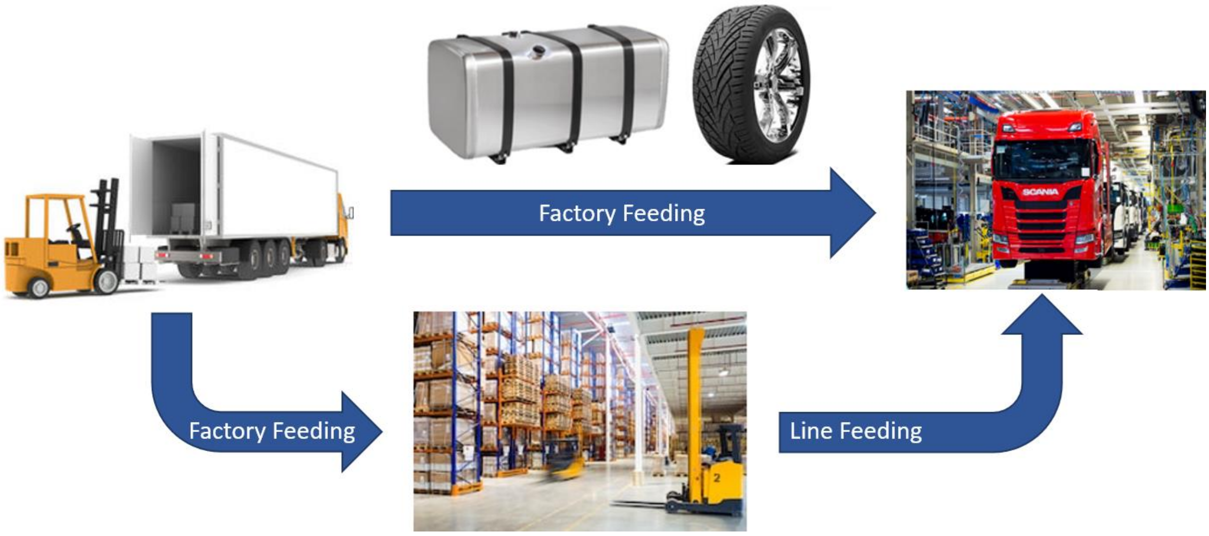

Figure 1. 3. Internal logistics performed as Factory Feeding and Line Feeding at Scania Production Zwolle

1.2.2. Introduction of the BSK flow

The BSK flow consists of parts that are transported on fixtures from the on-site warehouses to the assembly lines by tugger trains on a regular tact. Those parts are first picked as batch, sequence, or kit, and are placed on fixtures in the warehouses. The tact time is the available time per workstation: if the tact time is 15 minutes, every 15 minutes all trucks in progress will go to the next workstation and the finished truck at the last workstation goes to the parking. The BSK flow transports parts on fixtures from the warehouses to the assembly lines by tugger trains because it is not possible to have enough (palleted) stock at the assembly lines.

The BSK flow uses 117 fixtures, some of these fixtures are ½-euro size, but most fixtures are 1-euro size. The sizes of the fixtures, 1-euro and ½-euro, are based on 1-euro pallets and ½-euro pallets. Each fixture is dedicated to transporting specific parts, for example Figure 1.4 shows the motor fans fixture. This figure shows that the motor fans fixture is transported on a Still trailer by the Linde tugger train. Besides this combination, Scania Production Zwolle also uses Rothar trailers with the Toyota tugger train. Chapter 2 explains the BSK flow in more detail.

Figure 1. 4. Build-up of tugger trains for motor fans fixture

1.3. Assignment and research motivation

The routes of the BSK flow are manually created and optimised. Scania Production Zwolle is not satisfied with the manual routing method of this flow, because of the productivity loss. Since SPZ is not satisfied with the current routing method, the assignment is to design a new method for routing the BSK flow, given the restrictions of this flow. This assignment is thus based on the need of SPZ to design a new routing method for the BSK flow. Within SPZ, this assignment is conducted at the department of Logistics Engineering.

1.4. Core problem

The BSK flow is part of the internal logistics at Scania Production Zwolle and this section identifies the core problem of the BSK flow. We have observed and interviewed employees who are responsible for the BSK flow to identify problems with this flow. Based on those observations and interviews, we made a problem cluster. Figure 1.5 shows this problem cluster, which is used to identify the core problem. The problem cluster visualises the causal relationships between the problems. In case some causes are hard to change or have little impact, they cannot be the core problem (Heerkens & Van Winden, 2012). These kinds of causes are marked yellow in Figure 1.5. The core problem is identified by going back in the problem cluster, which means that we have to find the problem that does not have a preceding cause (Heerkens & Van Winden, 2012).

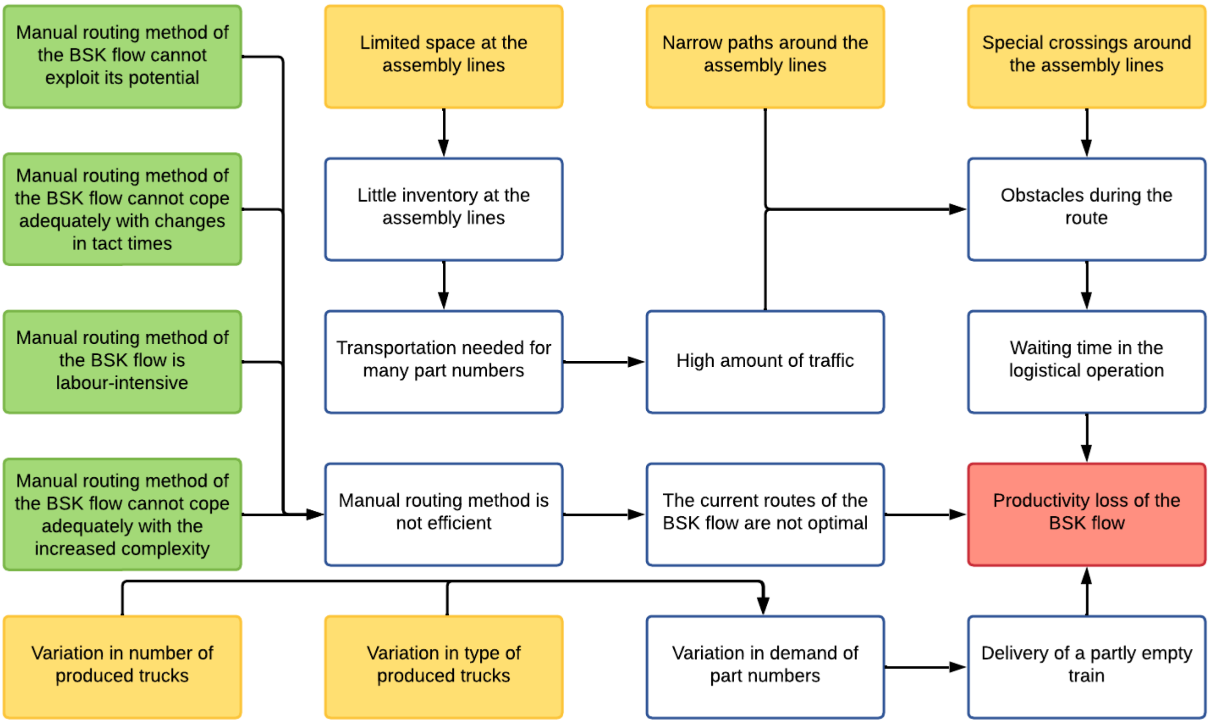

Figure 1. 5. Problem cluster of the BSK flow. Green = core problem. Red = experienced problem. Yellow = problem with little impact or hard to influence.

The experienced problem, marked in red, is the productivity loss of the BSK flow. The first cause of the productivity loss is the manual routing method that results in non-optimal routes (Section 1.4.1). The two other causes of the productivity loss are the waiting time in the logistical operation (Section 1.4.2) and the delivery of a partly empty tugger train (Section 1.4.3).

1.4.1. Productivity loss – Manual routing method

Creation and optimisation of the routes of the BSK flow is done manually. However, it is experienced by employees of Scania Production Zwolle that the routes of the BSK flow are not optimal because of the manual routing method, resulting in productivity loss. The Key Performance Indicators (KPIs) of the BSK flow, shown in Section 2.4, are below their targets. Therefore, these KPIs show the non-optimality of the current routes of the BSK flow. The non-optimal routes are caused by the inefficient manual routing method of the BSK flow.

We have identified the following four causes regarding the inefficient manual routing method:

- The manual routing method cannot cope adequately with the increased complexity;
- The manual routing method is labour intensive;
- The manual routing method cannot cope adequately with changes in tact times;
- The manual routing method cannot exploit the potential of the BSK flow.

First of all, the manual routing method cannot cope adequately with the increased complexity of the BSK flow. The increased complexity consists of the increased number of planning restrictions and the increased size of the BSK flow. The increased size of the BSK flow means that the number of fixtures, the pickup and the delivery locations of the BSK flow have increased over time. Although the BSK flow has changed over time, the routing method remained manual. The increased number of planning restrictions, as well as the increased size of the BSK flow, are given and are therefore hard to influence. The used planning restrictions at the beginning of the BSK flow were to deliver all fixtures from their warehouse location to their line location (assembly line), given the available tugger train capacity and the logistical tact time. The logistical tact time is calculated as the tact time multiplied by the principle the tugger train is in, shortened to *principle*: $Logistical\ tact\ time = tact\ time * principle$. The increase in the number of planning restrictions is a result of the following new planning restrictions: used type of trailer (Rothar or Still); if possible, a separate delivery to the Castor line and the Pollux line; Regular and Special fixtures; 1:2:4 supply method. Section 2.3.1 explains the current planning restrictions in more detail.

The second cause of the inefficient manual routing method is the labour intensity. The cause of the labour intensity is that the lead time of the manual method is long. The lead time being long is hard to change when using a manual routing method. Therefore, the long lead time is given and hard to influence. The lead time is long because of the increased number of planning restrictions described earlier. Section 2.2.3 explains the process of the manual routing method by using a flowchart, which shows that the manual routing method is labour intensive.

The third cause of the inefficient manual routing method is that the BSK flow cannot adequately cope with changes in tact times. This means that the BSK flow is currently not flexible regarding changes in tact times. The inability to cope with changes in tact times is also caused by the long lead time for changing the BSK flow. The last cause of the inefficient manual routing method is that the manual routing method cannot exploit the potential of the BSK flow. The used KPIs for the BSK flow are based on a theoretical calculation, as Section 2.4 explains in more detail. The KPIs are below their target which indicates that improvements are necessary and possible, but the manual routing method is not able to exploit that potential. Furthermore, it is not possible to know the exact fill rates since this flow is not monitored in real-time. Although there are plans for setting up a real-time monitoring system, at the moment this is not available.

1.4.2. Productivity loss – waiting time

Section 1.4.1 identified four causes of the inefficient manual routing method that contribute to the productivity loss of the BSK flow. Another cause of the productivity loss of the BSK flow is the waiting time in the logistical operation. This consists of the waiting time of the order pickers and the waiting time of the tugger train drivers, where the focus is on the waiting time of the tugger train drivers. Waiting time of the order pickers and the tugger train drivers lead to productivity loss: instead of contributing to the logistical process, they are waiting until they can start picking orders or start delivering fixtures.

The waiting time of tugger train drivers is caused by obstacles during their routes. There are three types of obstacles that tugger train drivers can encounter: high amount of traffic, narrow paths, and special crossings. The special crossings are crossings where for example the cabin or the motor crosses the road. These special crossings are hard to change and are therefore marked yellow in Figure 1.5. The paths around the assembly lines are narrow. Therefore, tugger train drivers must sometimes wait because there is another vehicle in front of them. Passing other vehicles is dangerous because of the narrow paths and the high amount of traffic.

Besides the narrow paths and the special crossings, the high amount of traffic is also a contributor to the waiting time of tugger train drivers. The high amount of traffic can be traced back to the Just-In-Time principle and the limited space at the assembly lines. The limited space at the assembly lines is marked yellow because it is hard to change. Because of the JIT principle and the limited space, there is little inventory possible at the assembly lines. Therefore, transportation is needed for many parts, which results in a high amount of traffic around the assembly lines. Besides the tugger trains, there are also pallet trailers, forklift trucks, order picker vehicles, and reach trucks. Although the JIT principle is a contributor to having little inventory at the assembly lines, JIT is not resembled in the problem cluster since it is not experienced as a problem. So, narrow paths, special crossings, and a high amount of traffic result in waiting time and thus productivity loss. Another cause of the productivity loss is the delivery of partly empty tugger trains as Section 1.4.3 explains.

1.4.3. Productivity loss – Delivery of partly empty tugger trains

This section explains the last cause of the productivity loss: the delivery of a partly empty tugger train also contributes to the productivity loss. A tugger train is partly empty if at least 1 fixture cannot be delivered, fewer fixtures than the capacity of the tugger train are delivered, or when a fixture is not completely filled. Sometimes a fixture cannot be delivered because the previous one is not consumed at the assembly line. Because of the non-optimal routes, the fixtures are not optimally distributed among the routes. This results in sometimes delivering fewer fixtures than the tugger train capacity, for example only delivering 3 fixtures in a route while there is available capacity for 4 fixtures. Another option is that fixtures are partly empty delivered. This means having space for example for 4 parts per part number but only delivering 2 parts per part number. The cause of delivering partly empty tugger trains is the variation in demand of part numbers. As explained in Section 1.1.1, Scania experiences a variation in the type of produced trucks and a variation in the number of produced trucks. The cause of this is the demand-driven output and customisation from the Scania Production System. However, the SPS is not resembled in the problem cluster since this is not experienced as a problem. The variation in the number of produced trucks and the variation in the type of produced trucks are therefore given and marked yellow. These variations result in a variation in the demand of part numbers.

1.4.4. Definition of the core problem

Section 1.4.1 described the four green boxes of the problem cluster. Based on those descriptions, this section defines the core problem. Because the identification of the core problem is based on going upstream, it consists of problems without a preceding cause (Heerkens & Van Winden, 2012). The green boxes resemble the problems regarding the manual routing method of the BSK flow, which results in a productivity loss of the BSK flow: the increased complexity of this flow, the labour intensity of this method, the ability to cope with changes in tact times, and the ability to exploit its potential. An important notion is that the increased complexity of this flow consists of both the increased number of planning restrictions as well as the increase in the number of fixtures, the pickup and the delivery locations of this flow. Therefore, the core problem is defined as:

> The manual routing method of the BSK flow is not efficient because of the increased complexity of this flow and the labour intensity of this method, affecting the ability to cope with changes in tact times and the ability to exploit its potential, which results in a productivity loss of the BSK flow.

1.5. Research goal and main research question

Based on the core problem, the objective of this research is to advise Scania Production Zwolle on how to improve the routing of the BSK flow, in a way that meets the requirements. This advice is based on the new routing method of the BSK flow that will be created. This new routing method of the BSK flow should be able to cope with the changes in tact times and the increased complexity, it should be able to exploits its potential, and it should be less labour-intensive. The improved routing should increase the productivity of the BSK flow, which is currently measured via the physical fill rate and the time fill rate that Section 2.4 explains. The research goal is translated in the following main research question:

How can the routing of the BSK flow be optimised, to increase the productivity of the BSK flow?

1.6. Research scope

This research is about the BSK flow at Scania Production Zwolle. Therefore, the scope of this research is the BSK flow. The BSK flow consists of fixtures that have a usage of 100%, which are the 'Regular' fixtures. However, the 'Special' fixtures, which have a usage between 0-90%, will also be incorporated in the new routing method. Currently, the BSK flow delivers to both the Castor line and the Pollux line. Therefore, both lines are in the scope of this research. Changes in the layout of the warehouses are possible, but for this assignment, the layout is set to be fixed so that we focus on the routing of the BSK flow. Besides the tugger trains that the BSK flow uses, the following modes of transportation are also used at SPZ: pallet trailers, forklift trucks, order picking vehicles, and reach trucks. However, these modes of transport are outside the scope of this research project. Moreover, the High Bay warehouse is currently outside the scope of this assignment, because parts from this warehouse are transported by reach trucks. One of the input parameters of the BSK flow is the number of chassis that can be placed on one fixture. By changing the layout of a fixture, the number of chassis per fixture can be changed. However, the number of chassis per fixture is set to be fixed for this assignment. This is because the current layout of the fixtures is ergonomically safe and fits the 1:2:4 supply method.

1.7. Research questions and approach

This section elaborates on the research questions with the approach that we use to answer the questions. This way, the main research question can be answered.

1.7.1. Analysis of the current situation of the BSK flow

The first set of research questions is about the current situation of the BSK flow. Chapter 2 answers the first research question (RQ1). The customer's first view is an important aspect of the Scania Production System. Therefore, the most important stakeholder of the BSK flow are the assembly lines, since it is the customer of the BSK flow. Other important actors of the BSK flow are the operators (both the warehouse order pickers and the tugger train drivers), the team leaders, the supervisors, and the employees of the department of Logistics Engineering. Therefore, we interview and/or observe these different actors to find out what the bottlenecks are in the BSK flow. Moreover, gathering information from the intranet of SPZ is used for answering (some of) the sub-questions. Besides that, we gather data from the Enterprise Resource Planning system to measure the current performance.

RQ1: What is the current situation regarding the BSK flow?

- What steps are taken in the assembly process at Scania Production Zwolle?
- What is the production planning process?
- What storage locations and supply methods does Scania Production Zwolle use for their internal logistics?
- How is the BSK flow organised?
- What are the complexities of the manual routing method of the BSK flow?
- What is the current performance of the BSK flow?
- What are the requirements for the solution design of the BSK flow?

1.7.2. Literature review on routing of (internal) logistics

The second set of research questions identifies solution approaches in the literature that can be used for improving the routing of the BSK flow, which we explain in Chapter 3. The literature review is performed to find methods that improve the routing of the BSK flow.

RQ2: What concepts and methods described in the literature can be used to improve the routing of the BSK flow?

- What concepts and methods have been proposed in the literature for solving an internal logistics problem?
- What solution approach is suitable for the BSK flow of Scania Production Zwolle?
- What are the advantages and disadvantages of the considered solution approach?

1.7.3. Solution design

Chapter 4 proposes a solution design for routing the BSK flow. This solution design is based on tailoring the concepts and methods found in the literature from Chapter 3. The solution design is based on a mathematical model that Chapter 4 explains. Also, Chapter 4 explains the flowchart of the solution design. During this process, there will be a close cooperation with the end-users for validation and to make sure that the created method is practically useful.

RQ3: How does the proposed solution design for routing the BSK flow look like?

- How can the concepts and methods from the literature be tailored to our problem?
- How does the mathematical model of the solution design look like?
- How does the flowchart of the solution design look like?

1.7.4. Solution evaluation

Chapter 4 describes the solution design phase. Once the solution design phase is finished, the performance of the solution approach will be evaluated for different experiments. Chapter 5 describes the results of this solution evaluation, by answering research question 4 (RQ4).

RQ4: How does the solution approach perform for different experiments?

- What are the different experiments that we evaluate?
- How does the solution approach perform for each experiment?

1.7.5. Recommendations and conclusions

Chapter 5 describes the results of the solution evaluation. Based on those results, we describe the conclusions and the recommendations to Scania Production Zwolle. We use these recommendations and conclusions in Chapter 6 to answer the last research question (RQ5).

RQ5: What are the recommendations and conclusions based on the results of the different experiments?

- What are the conclusions of this research?
- What recommendations do we provide to Scania Production Zwolle, based on the results of the solution evaluation?

1.8. Conclusion

This chapter introduced the research on the BSK flow at Scania Production Zwolle. The BSK flow consists of parts that are transported on fixtures from the on-site warehouses to the assembly lines by tugger trains on a regular tact. Those parts are first picked as batch, sequence, or kit, and are placed on fixtures in the warehouses. The assignment is to design a new routing method for the BSK flow, given the restrictions of this flow. The motivation for this research is that SPZ is not satisfied with the current routing method, because of the productivity loss. The core problem of the BSK flow has been identified as: the manual routing method of the BSK flow is not efficient because of the increased complexity of this flow and the labour intensity of this method, affecting the ability to cope with changes in tact times and the ability to exploit its potential, which results in a productivity loss of the BSK flow. Moreover, the research goal is to advise SPZ on how to improve the routing of the BSK flow, based on the new routing method. Besides that, we have also provided the scope of the research. To answer the main research question, the required (sub)research questions and used approach were formulated. Figure 1.6 shows the research design, summarising the (main) research questions and the used approach.

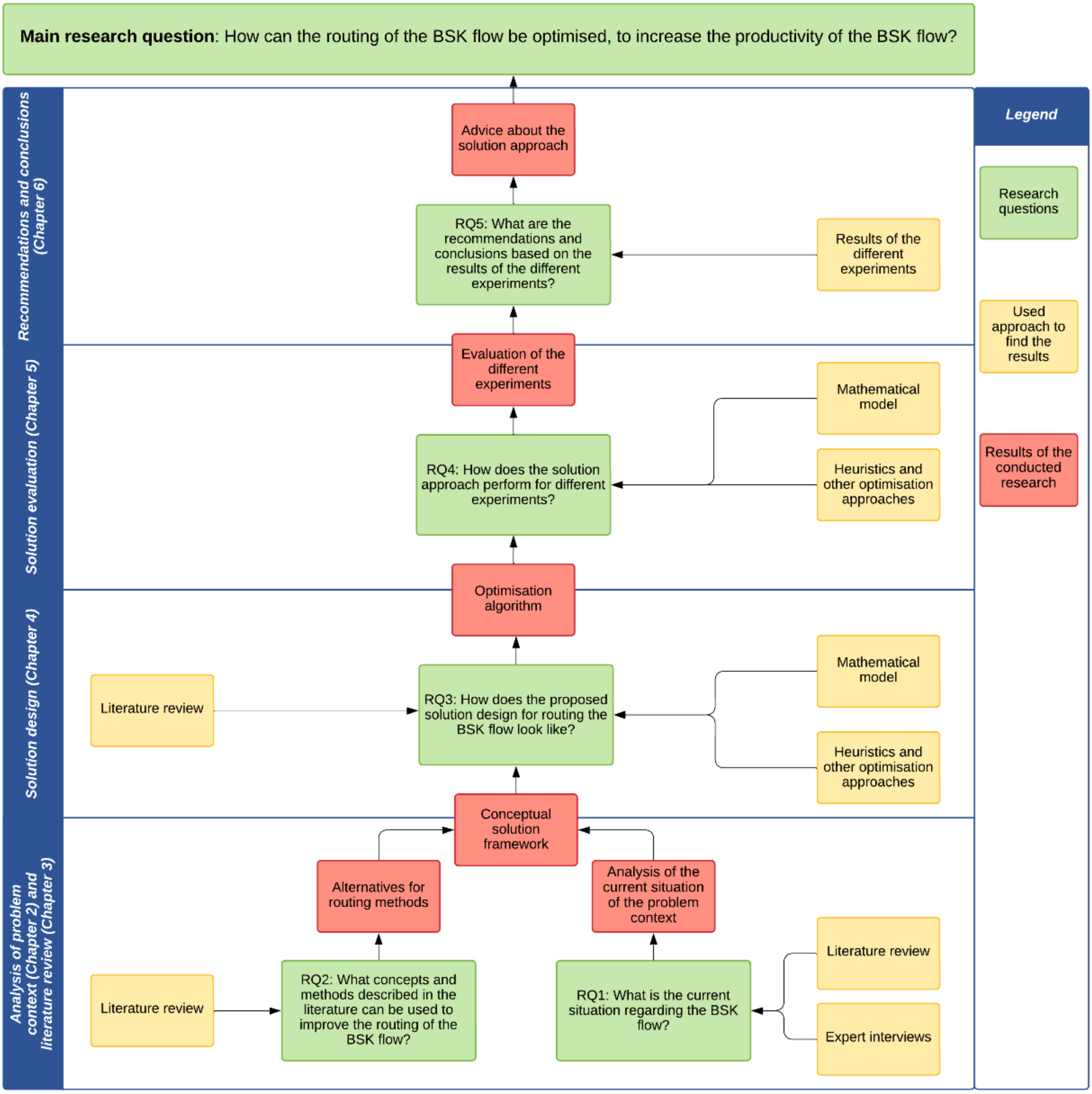

Figure 1. 6. Research design: research questions and used approach

2. Current situation of the BSK flow

In Chapter 1, we defined the core problem of this thesis. Moreover, we defined the research goal, the main research question, and the (sub)research questions. In this chapter, we answer the first set of research questions.

RQ1: What is the current situation regarding the BSK flow?

- What steps are taken in the assembly process at Scania Production Zwolle?
- What is the production planning process?
- What storage locations and supply methods does Scania Production Zwolle use for their internal logistics?
- How is the BSK flow organised?
- What are the complexities of the manual routing method of the BSK flow?
- What is the current performance of the BSK flow?
- What are the requirements for the solution design of the BSK flow?

To answer Research Question 1, this chapter explains the current situation of the BSK flow by explaining how the BSK flow is organised (Section 2.2), the complexities of the current routing method (Section 2.3), and the current performance of the BSK flow (Section 2.4). Next, Section 2.5 explains the available datasets. Afterwards, Section 2.6 explains the requirements for the solution design of the BSK flow, which we consider during the Systematic Literature Review in Chapter 3. Finally, Section 2.7 concludes this chapter by answering RQ1. Before we explain the BSK flow, Section 2.1 starts by explaining the production process at Scania Production Zwolle.

2.1. Production process at Scania Production Zwolle

Our research at Scania Production Zwolle is about the BSK flow, which is part of the internal logistics process. Since the logistical process is closely linked to the production of trucks, this section explains the production process at SPZ. Here, we explain the layout of SPZ (Section 2.1.1), the used supply and storage methods (Section 2.1.2), and the production planning process (Section 2.1.3)

2.1.1. Layout of Scania Production Zwolle

Section 1.1 explained that Scania Production Zwolle has two assembly lines: the Castor and the Pollux lines. Figure 2.1 depicts the layout of the factory, where the Castor line is coloured in green, and the Pollux line is in blue. Both assembly lines consist of a large number of workstations, where assembly takes place on a regular time period: the tact time. The tact time is the available time per workstation: it is the time a truck is at a workstation while executing all standardised tasks of that workstation.

The parking depicted inside the factory is the parking area for the tugger trains of the BSK flow. Moreover, the yellow arrow shows the entrance to or the exit from the warehouses (W). The assembly lines are divided into 8 function areas (FAs) of which the most important production steps are: frame assembly (FA0); pipes and cables (FA1); axles (FA2); engine (FA3); cabin (FA4); tires (FA5); test & repair (FA6); Fit For Use (FA7). Figure 2.1 depicts the FAs for the Castor line and Appendix B gives a more detailed explanation of the FAs.

The Castor line produces the highest number of trucks whereas the Pollux line is used for special trucks, or when extra production capacity is needed. This is because the Castor line is always in use, and usually has a tact time that is lower than the Pollux line. This means that the Castor line produces more trucks per hour. Both lines have a different tact time, which is in the used datasets 7:30 minutes for the Castor line and 15:00 minutes for the Pollux line. The tact time is dependent on the number of trucks that are assembled, which means that the tact time can variate. The lower the tact time, the higher the production rate is and vice versa.

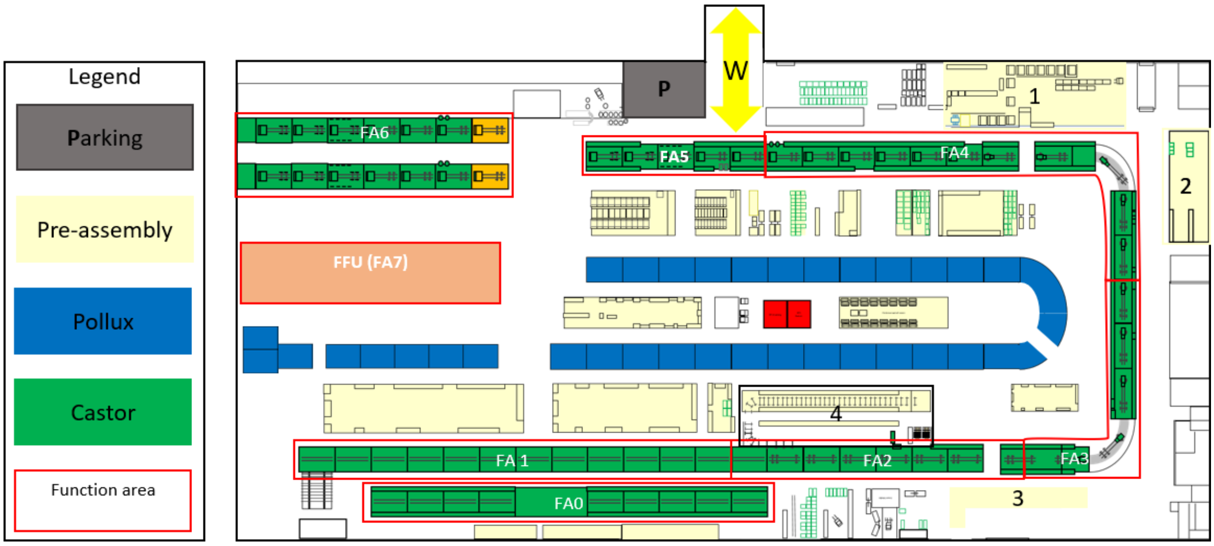

Figure 2. 1. Layout of the factory at Scania Production Zwolle with the function areas

Besides the two assembly lines, Figure 2.1 also shows pre-assembly areas. By using pre-assembled parts, the truck needs less time on the assembly line. There are many pre-assembly areas of which four pre-assembly areas are numbered. These are the areas that pre-assemble the cabins (1), the muffles (2), the engines (3) and the axles (4). Inventory of parts can be found at each workstation and pre-assembly area. Moreover, at the workstations, the highly consumed parts are kept in stock. For most of these parts the two-bin principle is used. Furthermore, the Just-In-Time principle is used for lowly consumed parts.

Figure 2.2 gives an overview of where the warehouses are with reference to the assembly lines. The warehouses consist of the unit supply warehouse, Platform LB1, Platform LB2, and the High Bay warehouse. Moreover, inside the warehouse is also a pre-assembly area. This pre-assembly area assembles parts for the BSK flow. The pallet breakdown is also shown in this figure, but this is outside the scope of this assignment. Line Feeding entails picking up the parts from the warehouses and delivering those parts to the assembly lines. The BSK flow uses Platforms LB1 and LB2 to pick up the parts: full pallets are placed in racks in the aisles of Platforms LB1 and LB2. More specifically, as can be seen in Figure 2.3, the BSK flow uses Platform LB1 and Platform LB2 for the bulk BSK flow parts. The special parts of the BSK flow are stored in the LB1 Special, which consists of parts that are big and/or heavy. The low volume kits are stored at the High Bay warehouse and are transported by reach trucks, which is outside the scope.

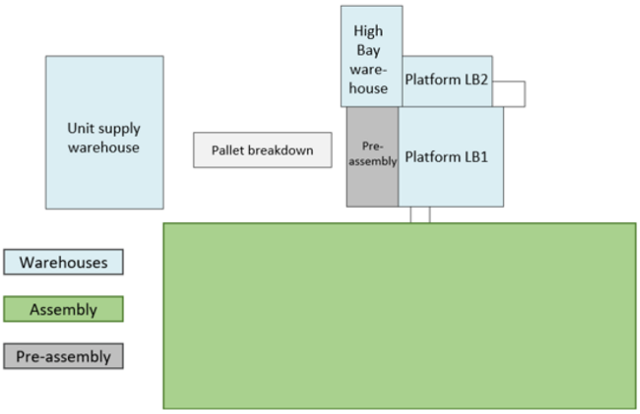

Figure 2. 2. Overview of warehouses with reference to assembly area

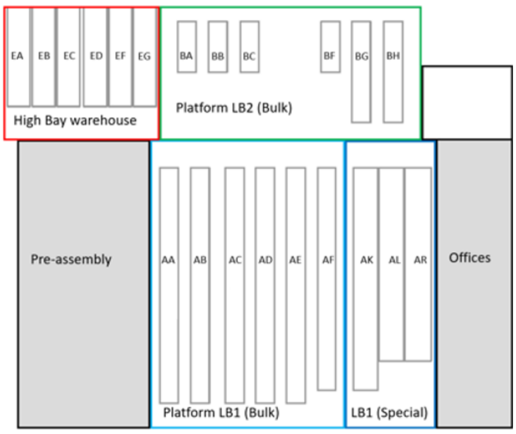

Figure 2. 3. Overview of Line Feeding warehouses

Based on Figure 2.1, the possible roads that can be used for transportation are marked blue in Figure 2.4. Moreover, the 14 special crossings are added in red. These special crossings make the routing of the BSK flow more complex because of the possible waiting times. Appendix C gives an overview of the special crossings.

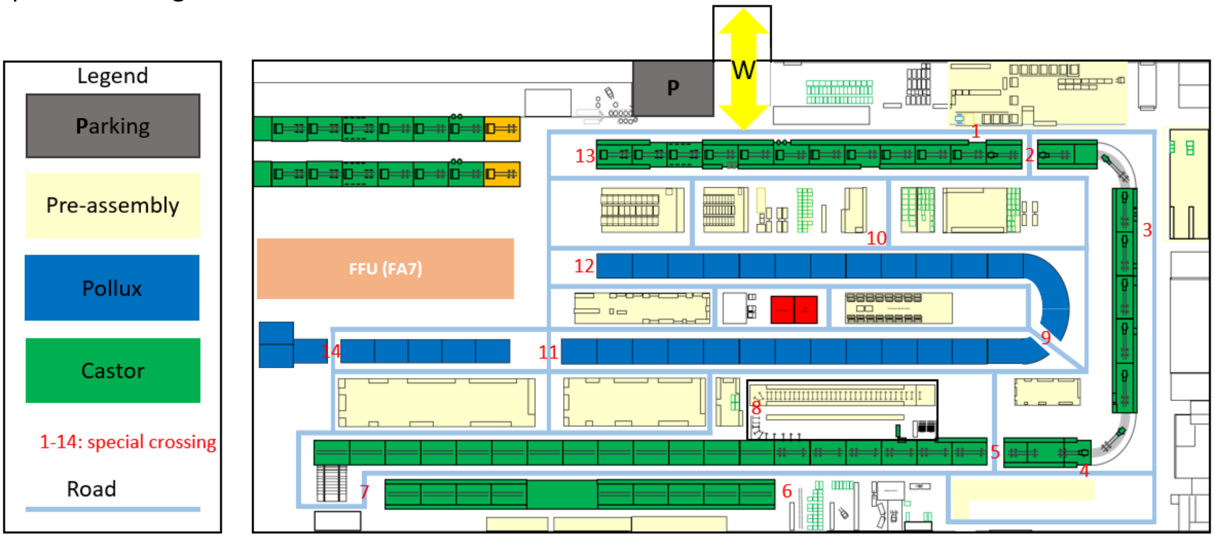

Figure 2. 4. Layout of Scania Production Zwolle with roads for transportation and special crossings

2.1.2. Supply methods and storage locations

Scania Production Zwolle uses the following supply methods: unit supply, batch picking, sequencing, and kitting. Unit supply is Factory Feeding, while the other supply methods are Line Feeding. The unit supply parts are stored in the unit supply warehouse, while the Line Feeding parts are stored at Platforms LB1 or LB2. The low volume kits are stored at the High Bay warehouse.

- Unit supply: highly consumed parts are supplied to the assembly lines without repacking or order picking. The parts are thus delivered in their original package, which are pallets or boxes. The replenishment of these pallets and boxes is based on the two-bin principle, which means that at the workstation there is an inventory of two pallets/boxes: when the first one empties, a replenishment is requested and during the lead time of that replenishment, the other pallet/box is consumed.
- Batch picking: static batch picking is used as a supply method for small batches of one type of part number. A fixture is split up into multiple boxes and each box contains a certain batch size for each type of part number. The batch size is calculated based on the consumption and some extra safety. The parts in one box of the static batch picking fixture are the same and can be used for all trucks. At the assembly lines, the whole fixtures are swapped, even when the current fixture is not yet completely empty.
- Sequencing: the parts are picked based on an order list and are placed, with a sticker, on fixtures. By using this list, the parts are placed on the fixture by their chassis number, which is in sequence of the production order.
- Kitting: a kit is a composition of several parts that are used for the assembly of one truck, which is based on the chassis number. These kits are picked based on an order picking list, which shows what needs to be picked for the next *k* chassis. These kits are placed on fixtures and are transported by tugger trains. Besides the kits that are linked to the tact time, there are also low volume kits. These are picked 4-6 hours before they are used at the assembly lines.

2.1.3. Production planning process

Section 1.1.1 explained the Scania Production System. Based on the SPS, trucks are only produced after the order is placed. Therefore, the planning of the production starts when a truck is sold. Based on the agreed delivery period, the production period for the truck is determined. At the headquarters in Sweden, global planning allocates the trucks to the production plants. Based on that, Scania Production Zwolle receives an overview of production orders. A planning program proposes a production sequence for each production period. Multiple sequence constraints, the so-called mixing rules, are considered for the production sequence. For example, the length of the frame is customisable. Producing a longer frame is more complex than a short frame. Moreover, the mechanics at the assembly lines have the same tact time for each truck, regardless of their configuration. Therefore, Scania uses a mixing rule, which implies that at most 1 out of 3 trucks can have a long frame. Figure 2.5 depicts an example of this mixing rule, showing that the last truck violates this mixing rule.

Figure 2. 5. Example of a mixing rule violation where at most 1 out of 3 trucks can be a long truck

Based on the mixing rule, a production sequence is proposed by the planning program that minimises the number of violations. A production planner makes manual changes, after which the production sequence is approved for production and the sequence cannot be changed anymore. However, it is possible that because of late or incorrect delivery, the approved production sequence is not possible since parts are missing. If this is the case, a truck that cannot be produced will be postponed without changing the planned sequence of the other trucks. To overcome these mutations in the production sequence, the production schedule is daily updated. Figure 2.6 summarises the whole process.

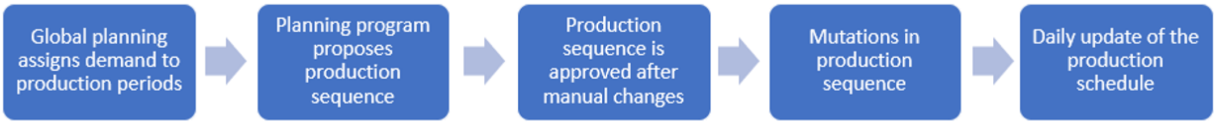

Figure 2. 6. Summary of the production planning process at Scania

2.2. Current organisation of the BSK flow

This section focusses on the BSK flow, by explaining the current organisation of this flow. First, Section 2.2.1 describes the BSK flow in more detail. Next, Section 2.2.2 explains the supply timing. Afterwards, we use flowcharts to describe the BSK flow delivery process and the manual routing method (Section 2.2.3). Lastly, Section 2.2.4 explains the special characteristics of the BSK flow.

2.2.1. The BSK flow

As introduced in Section 1.2.2, the BSK flow consists of parts that are transported on fixtures from the on-site warehouses to the assembly lines by tugger trains on a regular tact. Those parts are first picked as batch, sequence, or kit, and are placed on fixtures in the warehouses. Figure 2.7 shows the build-up of tugger trains for the motor fans.

Figure 2. 7. Build-up of tugger trains for motor fans fixture

In general, the build-up of the tugger trains for the BSK flow is as follows: the parts are placed in or on a fixture that is designed specifically for those parts. In Figure 2.7, the parts are the motor fans. It is easy to move the fixture during order picking or delivering, because the fixture has wheels, as can be seen in Figure 2.7. The fixture fits in a trailer, by 'clicking' it in the trailer. In this example, the used trailer is a Still trailer. Regarding the trailers, different frame types are available. Next, each tugger train normally has 4 trailers behind it. In the current train schemes, 2 of the 12 tugger trains only use 3 trailers, while 10 tugger trains use 4 trailers. Each trailer can transport one 1-euro size fixture or two

½-euro size fixtures. Scania Production Zwolle uses Linde tugger trains and Toyota tugger trains. Still trailers are combined with the Linde tugger train, and Rothar trailers are combined with the Toyota tugger train. Therefore, using a type of trailer implies which type of tugger train is used. In the fixture overview from SPZ, the type of trailer is mentioned. Since information on the type of trailer is available in the fixture overview, we use the type of trailer instead of using the type of tugger train. In the remainder of this report, we shorten the tugger train that the BSK flow uses to train. All in all, a fixture is used as a carrier, where the parts of the BSK flow are transported on.

The current routing method of the BSK flow is manual. This method results in the fixture overview, the individual train schemes, and the individual routing schemes.

- Fixture overview: overview that shows the distribution of fixtures over trains and shows relevant information for each fixture. At SPZ, this overview is placed on a physical whiteboard and there is also a digital version in Excel. Table 2.1 shows the information about the fixtures that are delivered by the Castor Train 1. Another name for the Castor Train 1 is the AD1 Train. Based on the fixture overview, SPZ makes the individual train schemes and the individual routing schemes.

Fixture number	Fixture name	Description (in Dutch)	Warehouse location	Aisle	Line	Regular(100%) or Special (0-90%)	Trailer	Train	Max chassis	Size
35	LR388-DBP-AD	Div. steunen CA	AD3601A	AD	C	100%	Rothar	Castor train 1	6	0.5
36	LR364-DBP-AD	Div. leidingen CA	AD3601B	AD	C	100%	Rothar	Castor train 1	6	1
37	LR455-DBP-AD	Schokbrekers CA	AD4601B	AD	C	100%	Rothar	Castor train 1	6	0.5
40	LR318-DBP-AD	Stootrubbers CA	AD4001A	AD	C	100%	Rothar	Castor train 1	12	1
41	LR170-AD	Kantelcillinder CA	AD4001B	AD	C	100%	Rothar	Castor train 1	12	1
57	LR314-DBP-AD	Kantelslangen CA	AD4601A	AD	C	100%	Rothar	Castor train 1	12	1

Table 2. 1. Fixture overview of the AD1 train

- Individual train scheme: overview of fixtures that are delivered by an individual train, in each delivery route of this train. This overview is placed on each train, so that the train driver knows which fixtures are delivered per route. Figure 2.8 shows this scheme of the AD1 train.

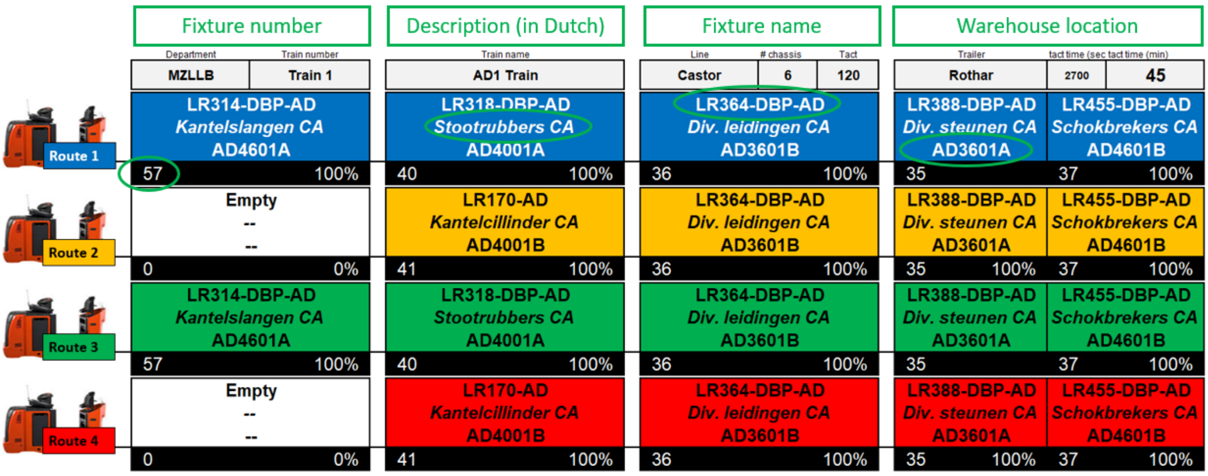

Figure 2. 8. Individual train scheme of the AD1 train

- Individual routing scheme: delivery routes per train; showing the train driver where to stop for the pickup and the delivery of each fixture in their routes. This overview is placed on each train, so that the train driver knows their routes.

Figure 2.9 shows route 1 of the individual routing scheme of the AD1 train. Likewise, there are also delivery routes for the other three routes of the AD1 train, which Appendix D shows. For each route of the BSK flow, the Total Route consists of the route inside the warehouse for the pickup of full fixtures, the route at the assembly line for the delivery of full fixtures and the pickup of empty fixtures, and the route inside the warehouse for the delivery of empty fixtures.

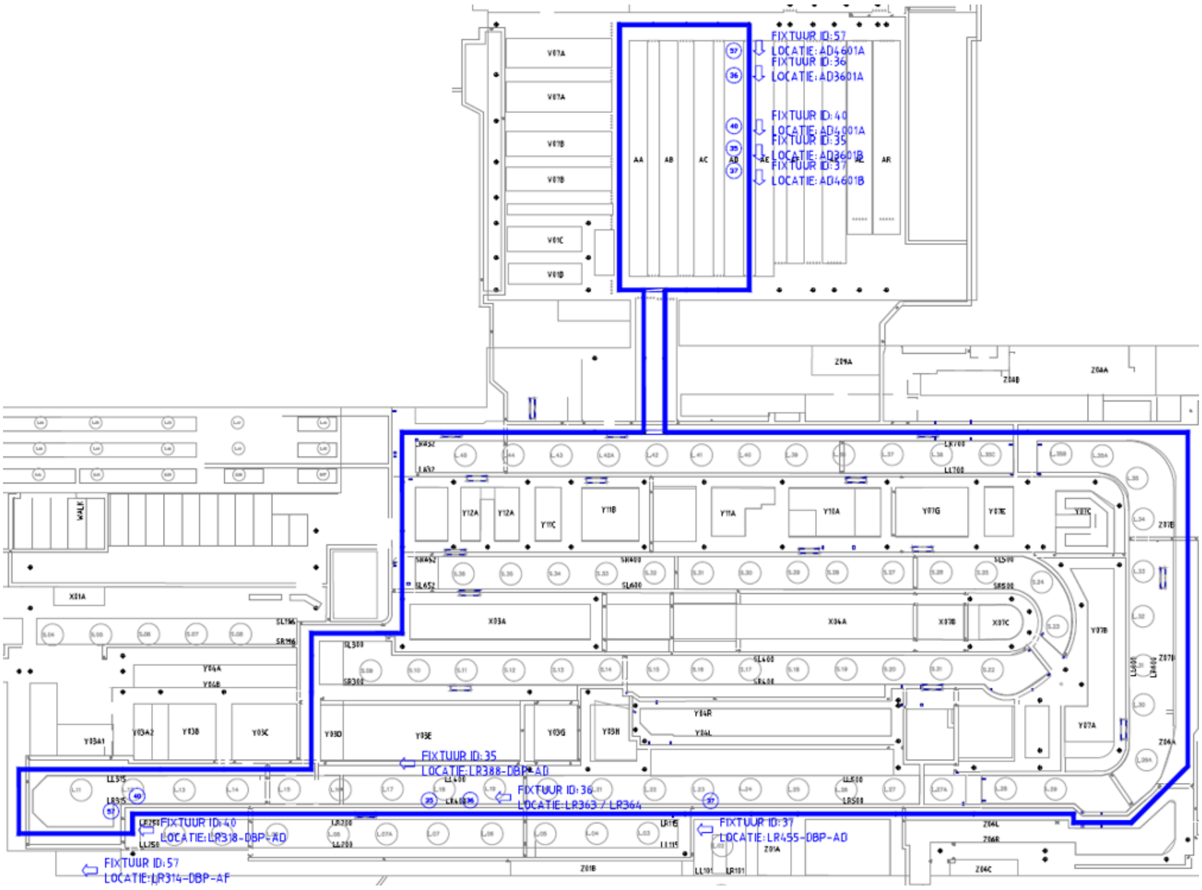

Figure 2. 9. Individual routing scheme of Route 1 of the AD1 train

2.2.2. Supply timing – 1:2:4 supply method

Scania Production Zwolle uses supply timing, which is their foundation for an effective logistics flow. Using this method results in levelling material flow to production and supporting delivery of parts when they are needed (Scania Production Zwolle, 2022). This method is used for the BSK flow, for example when designing the routing schemes of the trains. In the current routing scheme, the 1:2:4 supply method is translated into the use of the following principles: Principle 1 (Pollux; 1:2:4), Principle 2 (Castor; 2:4:8), Principle 3 (Castor; 3:6:12), Principle 4 (Castor, 4:8:16), Principle 6 (Castor; 6:12:24). The current tact time is 7:30 for the Castor line and 15:00 for the Pollux line. Based on that, the logistical tact time of Principle 1 (Pollux) and Principle 2 (Castor) is both 15:00, which results in Principle15minutes.

Each train of the BSK flow has 4 routes and the 1:2:4 supply method is used to set up each route of the BSK flow trains. Table 2.2 shows for each of the used principles the 1:2:4 supply method in practice. The base frequency of 1:2:4 is used for Principle 1 (Pollux), with a tact time of 15 minutes, which also results in a logistical tact time of 15 minutes. Instead of using the base frequency, we can also use a multiple of 1:2:4. In case the base frequency of 1:2:4 is set to 2 tact times, we get a setup of 2:4:8, which is the setup of Principle 2 (Castor). Similarly, setting the base frequency to 3, 4, or 6 tact times results in Principle 3 (3:6:12), Principle 4 (4:8:16), or Principle 6 (6:12:24).

Principle	Used setup (base frequency * Principle)	Tact time	Logistical tact time (tact time * Principle)	Every time (fixture A)	Every second time (fixtures B and C)	Every fourth time (fixtures D, E, F, G)
Principle 1 (Pollux)	1:2:4	00:15:00	00:15:00	1	2	4
Principle 2 (Castor)	2:4:8	00:07:30	00:15:00	2	4	8
Principle 3 (Castor)	3:6:12	00:07:30	00:22:30	3	6	12
Principle 4 (Castor)	4:8:16	00:07:30	00:30:00	4	8	16
Principle 6 (Castor)	6:12:24	00:07:30	00:45:00	6	12	24

Table 2. 2. The 1:2:4 supply method in practice for the used principles

The number of chassis that fit on the fixture determines how often that fixture needs to be transported. Based on the base frequency of 1:2:4, a fixture in Principle 1 can be transported every tact time (1), every second tact time (2), or every fourth tact time (4):

- A fixture with place for one chassis, needs to be transported every logistical tact time (1)
- A fixture with place for two chassis, needs to be transported every second logistical tact time (2)
- A fixture with place for four chassis, needs to be transported every fourth logistical tact time (4)

Figure 2.10 translates the 1:2:4 supply method into an overview of routes, which also includes the configurations of Principle 2 (2:4:8) and Principle 3 (3:6:12). For this example, we use the base frequency of 1:2:4, which results in Principle 1. Figure 2.10 shows for Principle 1 that fixture A is delivered every logistical tact time (1), fixtures B and C are delivered every second logistical tact time (2), and fixtures D, E, F, and G are delivered every fourth logistical tact time (4). We shorten in the remainder of this report the different configurations from the 1:2:4 supply method to their corresponding principle.

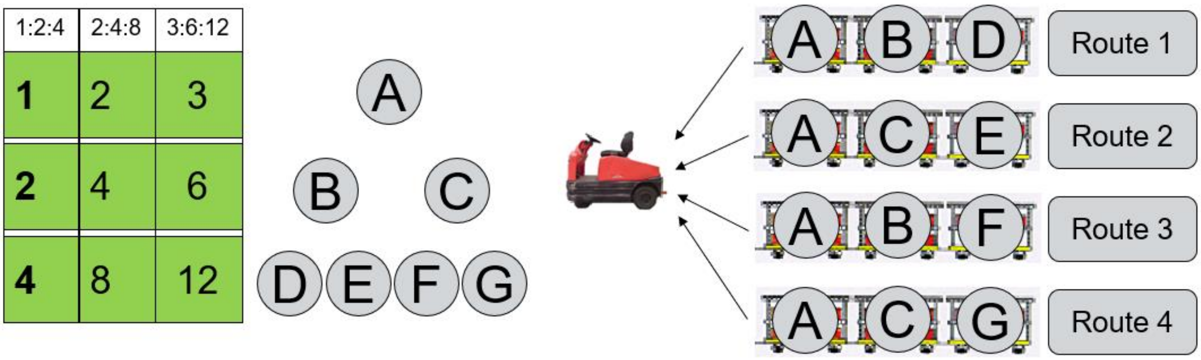

Figure 2. 10. Supply timing – 1:2:4 supply method in practice

2.2.3. Flowcharts of the BSK flow delivery process and the manual routing method

Figure 2.11 shows via a flowchart the helicopter view of the delivery process of the BSK flow. This figure shows two stakeholders that interact with each other: the train driver and the warehouse order picker. In the delivery process by the train, the fixture is assumed to be prepared by the warehouse order picker. The interaction between these stakeholders is when the train driver switches an empty fixture for a full fixture at the pickup location. The start of a new delivery cycle by the train driver is based on PRIDE. PRIDE stands for Part Requirement Indicator Device. At Scania Production Zwolle, this is the standardised tool to visualise the logistical tact time and the departure time for logistics (Scania Production Zwolle, 2022).

Figure 2.12 shows the manual routing method that is used when changes are needed, which is most of the time caused by a change in tact time. Another reason for changing the routes is when the team leaders or the supervisors request changes. The starting point for this method is based on all individual train schemes, which gives an overview of the fixtures that are delivered by each train for each route. Figure 2.8 shows an example of this scheme. An important step is the calculation of the logistical tact time of the route, which is calculated as: $Logistical\ tact\ time = tact\ time * principle$. Suppose the tact time is 7:30 and each fixture of the train is in Principle 4, then the logistical tact time of that route is 30:00. For example, when the tact time is lowered to 7:00, the logistical tact time is also lowered. In this case, the logistical tact time of this route is lowered to 28:00.

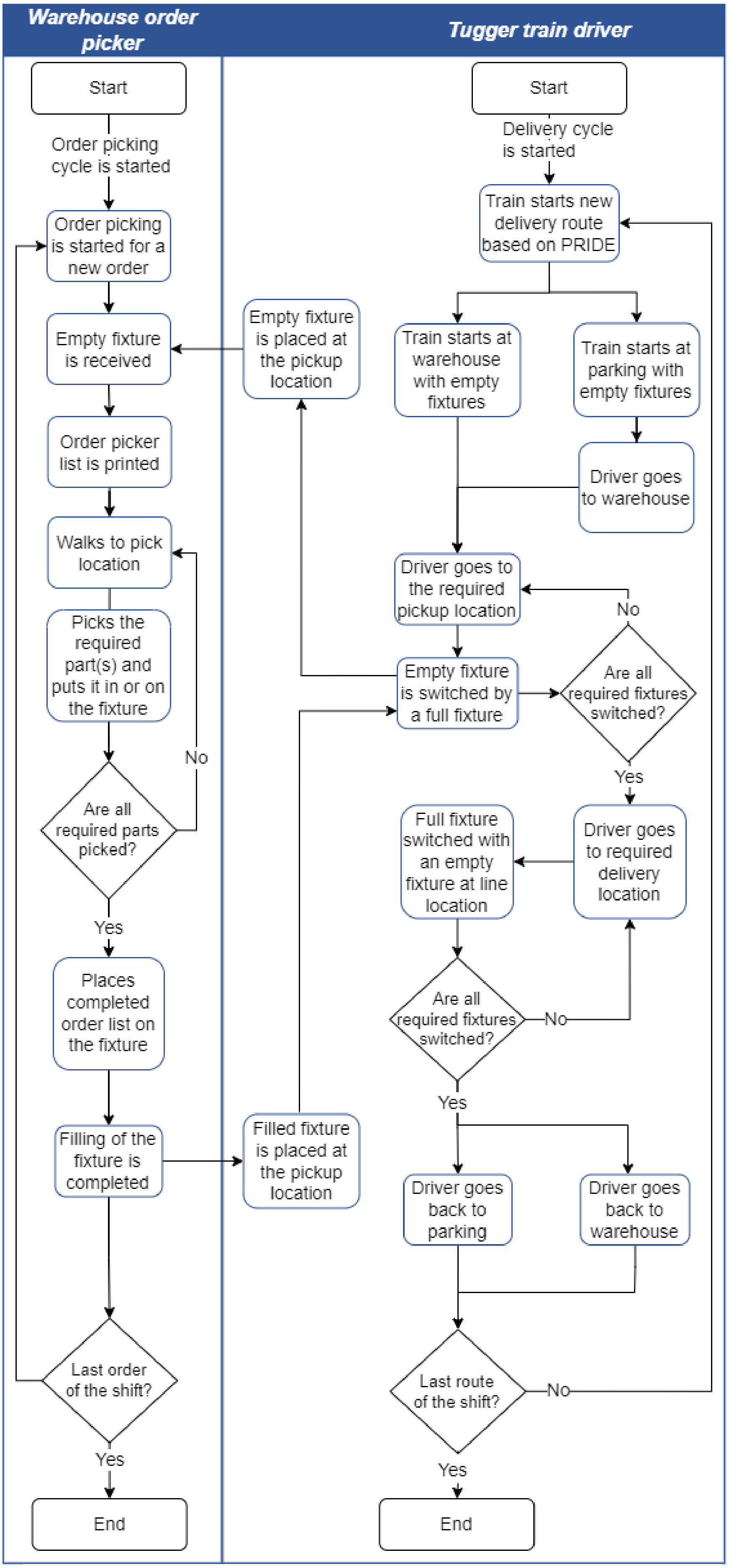

Figure 2. 11. Helicopter view of the delivery process of the BSK flow

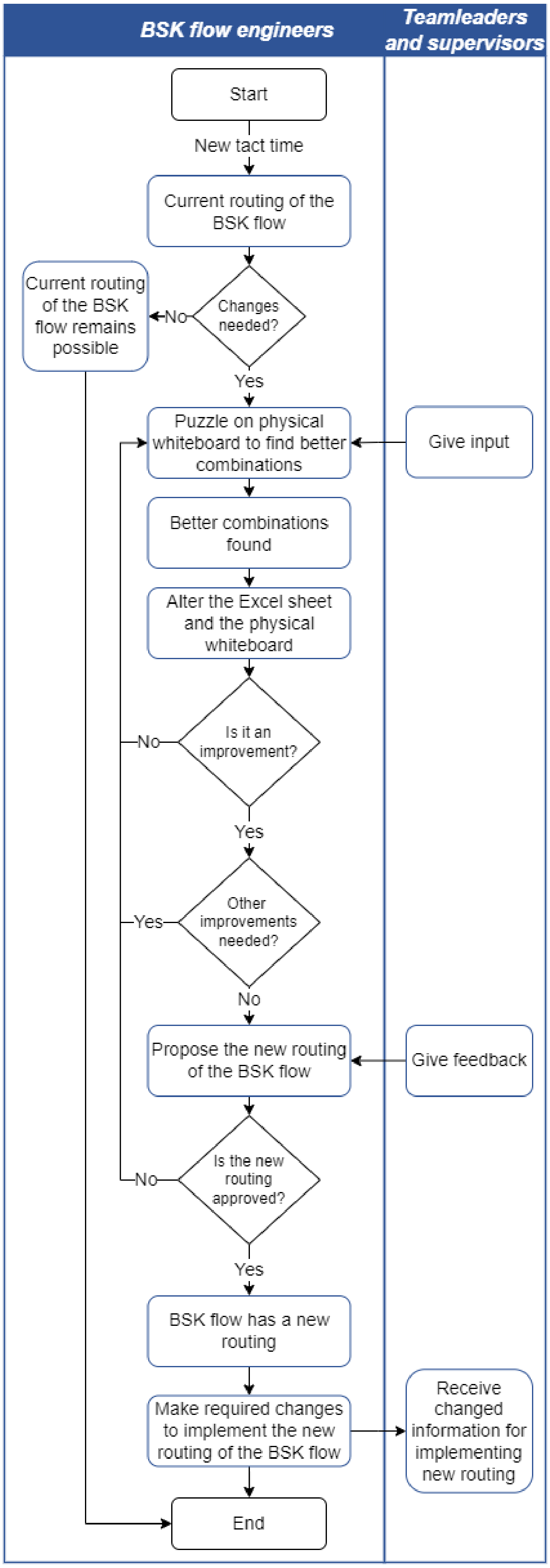

Figure 2. 12. Flowchart of the manual routing method

2.2.4. Special characteristics of the BSK flow

During the analysis of the current train schemes, we noted that for some routes, the sequence of deliveries is the reverse order of the pickup sequence. In literature, this is known as Last-In-First-Out (LIFO) loading constraints. The LIFO loading constraints means that, "considering all shipments that are currently on board a vehicle, one must deliver the shipment that is most recently picked" (Toth & Vigo, 2014). Besides LIFO, partial LIFO is described once in literature as a variant of the LIFO policy which entails that the LIFO policy is only partially followed: with partial LIFO, the LIFO policy may be violated within a given reloading depth (Chagas et al., 2020). The partial LIFO uses rearrangements during the pickup and the delivery. All current train schemes of the BSK flow match with the partial LIFO, and some routes meet the strict LIFO policy. During our observations of the BSK flow, we observed a possibility to adapt the partial LIFO from literature to the BSK flow. The Partial LIFO adapted to the BSK flow, shortened to Adapted Partial LIFO, entails that only the last pickup fixture is the first fixture that is delivered to the assembly line. Chapter 4 elaborates on the incorporation of different loading policies into our solution approach.

2.3. Complexities of the current routing method of the BSK flow

One aspect of the core problem, defined in Section 1.4.4, is the increased complexity of the BSK flow. An important notion is that the increased complexity of this flow consists of the increased number of planning restrictions (Section 2.3.1) as well as the increased size of the BSK flow (Section 2.3.2). Afterwards, Sections 2.3.3, 2.3.4, and 2.3.5 describe possibilities to improve the BSK flow.

2.3.1. Planning restrictions of the BSK flow

When the BSK flow started, the planning restrictions were to deliver all fixtures from the warehouses to the assembly lines, given the available train capacity and the logistical tact time. These planning restrictions result in on-time delivery and the delivery of all required fixtures. At some point, the second type of trailer was introduced, resulting in an additional planning restriction that a train can only use 1 type of trailer. Scania Production Zwolle would like the trains to deliver only to the Castor line or to the Pollux line. This is an additional planning restriction that is assumed to be fixed. However, since some of the current routes deliver to both lines, this is also possible in the new routing method. Another additional planning restriction is about the type of fixture, whether it is a Regular or a Special fixture. The Regular and the Special fixtures are also assumed to be fixed and result in high usage of fixtures versus low(er) usage. Moreover, the introduction of the 1:2:4 supply method, resulting in the use of 5 principles, is also an additional planning restriction. This method results in fixed routes and fixed logistical tact times. Lastly, the number of chassis per fixture results in how many supplies are needed. This is assumed to be fixed, because the current layout of the fixtures is ergonomically safe and fit the 1:2:4 supply method. Table 2.3 shows the results of all planning restrictions and the influence we have on each planning restriction. Overall, the increase in the number of planning restrictions has led to an increase in complexity of the BSK flow.

Planning restriction	Result	Influence
Logistical tact time	On-time delivery	Assumed to be fixed (Principle x tact time)
Train capacity	Delivery of all required fixtures	Assumed to be fixed (4 trailers and each trailer can transport one 1-euro size or two ½-euro size fixtures)
Pick-up locations (warehouse locations)	Pick-up from all required locations	Experiment with a marshalling area
Delivery locations (line locations)	Delivery to all required locations	Assumed to be fixed
Used trailer (Rothar or Still)	A train can only use one type of trailer	Experiment with only one type of trailer
Desire for separate delivery to the Castor line and the Pollux line	Desire for a train to only deliver to the Castor line or the Pollux line	Assumed to be fixed
Regular and Special fixtures	High usage vs low(er) usage	Assumed to be fixed
1:2:4 supply method	Fixed routes and fixed logistical tact times; use of 5 Principles	Experiment that uses only 1 Principle
Number of chassis per fixture	How many supplies are needed	Assumed to be fixed

Table 2. 3. Planning restrictions of the BSK flow

2.3.2. Size of the BSK flow

The increased size of the BSK flow means that the number of fixtures has increased over time. Each fixture has a pickup and a delivery location so therefore the number of pickup and delivery locations have also increased over time. When the BSK flow started, it was used for the transportation of only a few fixtures, that were picked up from a few places in the warehouses and were delivered to only a few places at the assembly lines. Moreover, in the beginning only a few trains were needed for this flow. Now, 12 trains are needed for this flow and this flow delivers 117 fixtures. Because of the increased size of the BSK flow, more trains were needed to deliver all fixtures of this flow on time. Therefore, the increase in the number of fixtures, the pickup and the delivery locations has led to an increase in the complexity of this flow.

2.3.3. Possibility to improve the BSK flow: use of 1 type of trailer

Scania Production Zwolle uses in the current routing schemes 2 types of trailers, and 5 principles that are based on the 1:2:4 supply method. Because of that, the fixtures can only be transported by a train that is in the same principle and uses the same type of trailer. Figure 2.13 shows the current routes of the trains in Principle 3, of which trains 6 and 9 use the Still trailer and train 8 uses the Rothar trailer. This figure shows that some parts of the routes of Principle 3 trains overlap. Similar overlaps are found in the figures with the routes of Principle15minutes in Appendix E, which shows train 2 (Rothar), train 5 (Rothar), train 10 (Still), and train 11 (Still).

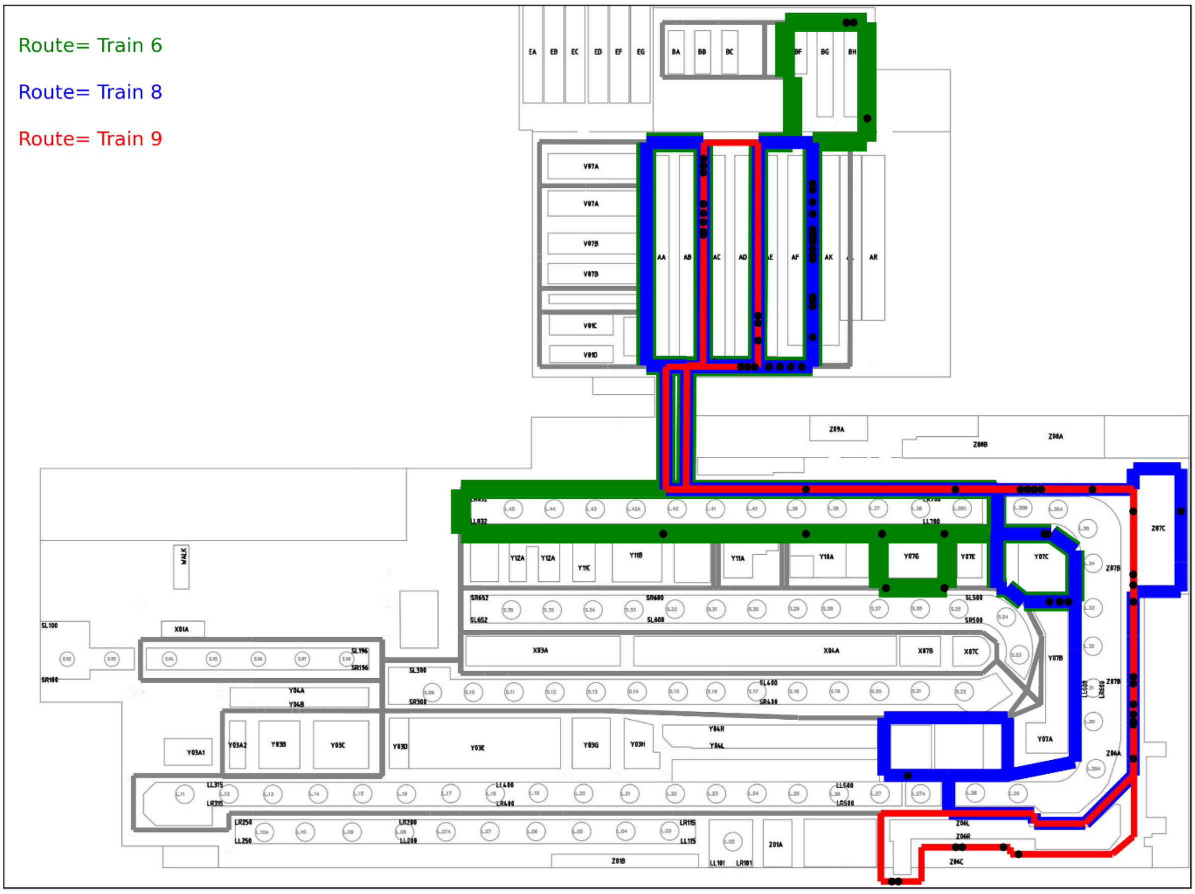

Figure 2. 13. Current routes of trains in Principle 3

We expect that one of the possibilities to improve the BSK flow is to use 1 type of trailer instead of 2 types of trailers. When only 1 type of trailer is used, we expect that better routes become possible. These better routes are currently not possible because of the different trailer types. In case the routes improve, we observe a decrease in the total distance travelled and this might result in a reduction in the required number of trains. To find out if our expectation is correct, Section 5.7 shows the results of the experiments that use only 1 type of trailer.

Besides the possible improvement of the BSK flow, using 1 type of trailer would be easier for Scania operators. There are currently 2 types of trailers, and each requires a different driving style: 1 type of trailer needs sharp turns while the other one needs wide turns. This difference in required driving style is learned to new operators, but it would be easier for the operators if there was only 1 type of trailer.

2.3.4. Possibility to improve the BSK flow: use of a marshalling area

In the current routes of the BSK flow, the fixtures have fixed locations inside the warehouses. However, we observe the possibility to construct a marshalling area, which becomes a central pickup location for full fixtures and a delivery location for empty fixtures. In case Scania Production Zwolle uses a marshalling area, the trains do not need to go to individual warehouse locations. Instead, the trains go to the marshalling area to pick up full fixtures and to deliver the empty fixtures.

Figure 2.14 shows the location of the marshalling area, where the assembly lines and the BSK flow warehouses (Platforms LB1 and LB2) are also visible. This figure shows that the location of the marshalling area is closer to the assembly lines than the fixed warehouse locations. Based on that, we expect that by using a marshalling area the total distance travelled decreases and this might result in a reduction in the required number of trains. To find out if our expectation is correct, Section 5.7 shows the results of the experiments that uses a marshalling area.

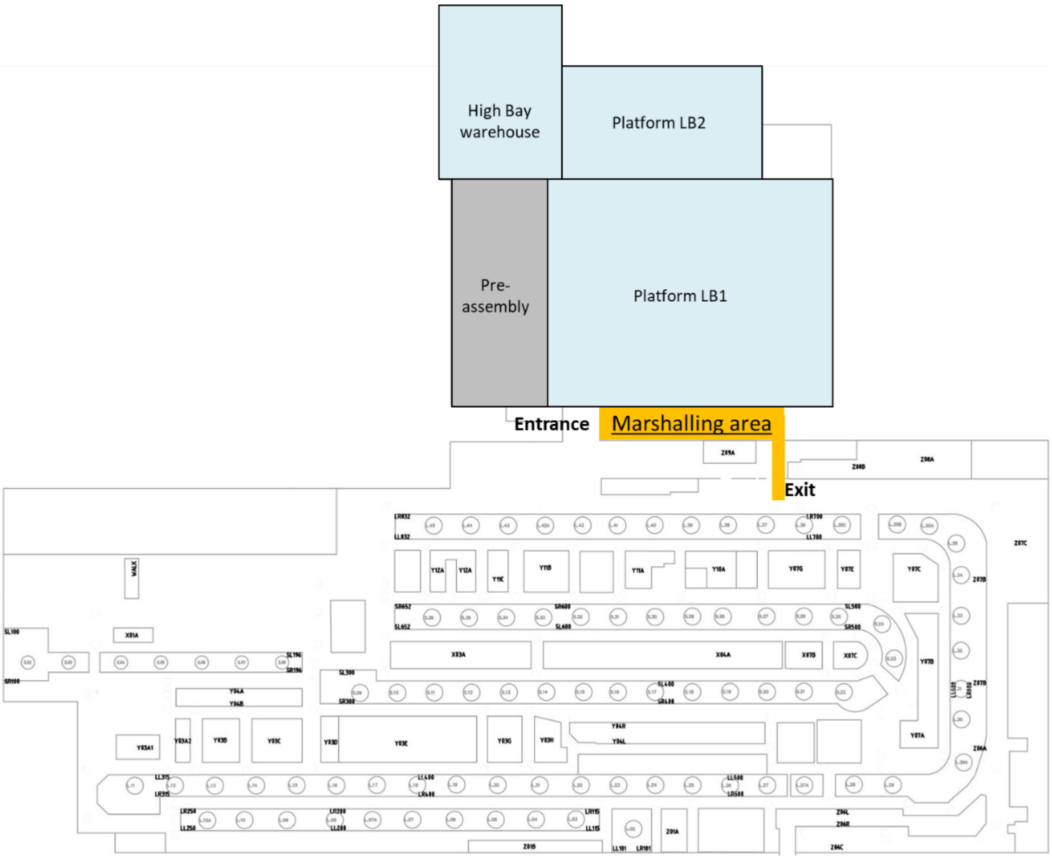

Figure 2. 14. Location of the marshalling area

2.3.5. Possibility to improve the BSK flow: use of 1 principle

The 1:2:4 supply method is translated in the use of the following 5 principles in the current routing schemes: Principle 1 (Pollux), Principle 2 (Castor), Principle 3 (Castor), Principle 4 (Castor), Principle 6 (Castor). Principle 1 (Pollux) and Principle 2 (Castor) both have 15 minutes as their logistical tact times, which results in Principle15minutes.

We observe two possibilities for improving the BSK flow by using 1 principle. The first possible improvement is that we expect that better routes are possible when 1 principle is used. Section 4.5.2

explains that 15 minutes becomes the new logistical tact time for all fixtures when we use 1 principle. When 15 minutes is the new logistical tact time for all fixtures, we expect that better routes become possible. These better routes are currently not possible because of the different logistical tact times due to the different principles. In case the routes improve, we observe a decrease in the total distance travelled and this might result in a reduction of the required number of trains. Although we expect an improvement when we use 1 principle, the BSK flow engineers expect that using 1 principle leads to a fluctuation of required number of trains during the workday. To find out if our expectation is correct, Section 5.7 shows the results of the experiments that uses 1 principle.

Another possibility to improve the BSK flow by using 1 principle is that, for some fixtures, we can increase the number of parts per fixture. In the current routing schemes, there are fixtures that could transport more parts than what they currently transport. These fixtures cannot transport more parts because of the use of multiple principles. For example, there are fixtures that transport 4 parts because they are in Principle 4, but according to the BSK flow engineers, they could transport 6 parts. In case Scania Production Zwolle chooses to use 1 principle, the BSK flow engineers should check per fixture how many parts can be placed at most on each fixture. In case a fixture can transport more parts, it would be transported less frequently which might lead to a decrease in the number of required trains. For our research, the number of parts per fixture is fixed as Section 1.6 explained.

2.4. Current performance of the BSK flow

The current performance of the BSK flow is based on the following Key Performance Indicators that show per train the productivity of the BSK flow: the physical fill rate and the time fill rate. The physical fill rate shows the percentage of used capacity, compared to the available capacity in a route. The time fill rate shows the percentage of used travel time in comparison to the available time, which is the logistical tact time of a route. For each train, the desired physical fill rate and time fill rate is 80%. Table 2.4 shows for each train the current performance. Based on this, the average physical fill rate is 71.7% and the average time fill rate is 72.6%. These KPIs show the productivity loss of the BSK flow.

Train	Name	Physical fill rate	Physical fill rate met?	Time fill rate	Time fill rate met?
Castor Train 1	AD1 Train	87.5%	YES	37.6%	NO
Castor Train 2	Sound caps Train	70.0%	NO	85.6%	YES
Castor Train 3	AL Train	88.5%	YES	55.1%	NO
Castor Train 4	*Not used*				
Castor Train 5	AB/headlights Train	68.8%	NO	73.1%	NO
Castor Train 6	Tank supports Train	80.3%	YES	59.6%	NO
Castor Train 7	*Not used*				
Castor Train 8	Specials Train	92.9%	YES	63.2%	NO
Castor Train 9	AD2 Train	55.9%	NO	52.2%	NO
Castor Train 10	Combination Train	90.6%	YES	98.7%	YES
Castor Train 11	Frontmodule/Airspring Train	46.6%	NO	74.1%	NO
Pollux Train 1	MZLLB Train	68.8%	NO	88.6%	YES
Pollux Train 2	Components Train	51.7%	NO	84.7%	YES
Pollux Train 3	LB2 Train	58.8%	NO	98.9%	YES
Pollux Train 4	*Not used*				

Table 2. 4. Current performance: KPIs of the BSK flow

2.5. Datasets of the BSK flow

Table 2.5 shows that the BSK flow has three datasets. The first dataset is from Scania Production Zwolle and is not complete. Dataset 2 is complete but there is uncertainty regarding the time periods of the added fixtures. Dataset 3 is an artificially generated dataset resembling the normal situation, which is based on the fixture overview and the individual train schemes from practice. This dataset is constructed, based on our knowledge about the BSK flow and with the help of the BSK flow engineers. Appendix F explains the construction of dataset 3. Analyses of the datasets of the BSK flow show that there are discrepancies in each train of the BSK flow, when we compare datasets 1 and 2 (real data from practice), with dataset 3. Appendix F also shows an example of these discrepancies for one train. As Section 5.1 explains, these discrepancies have an impact on the set-up for the solution evaluation.

Aspect of the dataset	Dataset 1	Dataset 2	Dataset 3
Name of the dataset	Scania - basic dataset	Scania - complete dataset	Artificially generated dataset resembling the normal situation
Number of fixtures in the dataset	85	117	117
Number of missing fixtures in the dataset	32	0	0
Origin of the data	Data from Scania	Data from Scania + addition of missing fixtures	Artificially generated dataset, based on train schemes from Scania
Reliability of the dataset	Reliable	Uncertainty w.r.t time periods of added fixtures	Artificially generated dataset
Number of complete trains	2	12	12
Percentage of complete trains	17%	100%	100%

Table 2. 5. General information about the three datasets of the BSK flow

Table 2.6 shows the input data of the first four fixtures of dataset 3 of Principle15minutes and type of trailer 1. Each dataset consists of the same columns. The fixture number is used to automatically fill the following columns: Logistical Tact time, Tact time Castor/Pollux; Principle; Fixture size; Trailer type; Castor/Pollux; Percentage. The Castor line and the Pollux line have a different tact time, as the column Tact Time Castor/Pollux shows. Moreover, not each fixture is in the same principle as the column Principle shows. As Section 1.4.1 explained, the logistical tact time of each fixture is calculated by: $Logistical\ tact\ time = tact\ time * principle$. The upper bound of the time period shows the time that the fixture needs to be at the assembly line, it resembles when the full fixture needs to be delivered. The lower bound is when the full fixture can be picked up. By subtracting the logistical tact time from the upper bound, the lower bound of the time period is calculated: $Lower\ Bound\ of\ the\ time\ period = Upper\ Bound -\ logistical\ tact\ time$.

Fixture number	Unique number	Index number	Logistical Tact Time	Tact Time Castor/Pollux	Lower Bound Time Period	Upper Bound Time Period	Principle	Fixture Size	Trailer Type(Name)	Castor/Pollux	Percentage
4	0	55	00:15:00	00:15:00	06:00:00	06:15:00	1	0.5	Rothar	P	1
8	1	96	00:15:00	00:15:00	06:00:00	06:15:00	1	1	Rothar	P	1
9	2	106	00:15:00	00:07:30	06:00:00	06:15:00	2	1	Rothar	C	1
10	3	0	00:15:00	00:07:30	06:00:00	06:15:00	2	1	Rothar	C	1

Table 2. 6. A part of dataset 3 for Principle15minutes and type of trailer 1

2.6. Requirements for the solution design of the BSK flow

Based on the core problem, the new routing method should be able to cope with the increased complexity of the BSK flow, it should be less labour intensive, it should be able to cope with changes in tact times, and it should be able to exploit the potential of the BSK flow. Moreover, the new routing method should result in an increase in productivity, which is measured through the average physical fill rate and the average time fill rate. To be of practical use, Scania Production Zwolle wants the new routing method to have a reasonable computational time. Another requirement of the new routing method is that it needs to be adaptable. This means that, when needed, extra aisles or roads can be uploaded into the new routing method. Furthermore, the new routing method needs to be able to make fixed and flexible routes, depending on the input data. Lastly, the new routing method needs to use realistic travel distance and travel time between locations.

2.7. Conclusion

At Scania Production Zwolle, the used supply methods are unit supply, batch picking, sequencing, and kitting. There is a warehouse for the unit supply parts, and the low-volume kits are stored at the High Bay warehouse, which are both outside the scope of this assignment. The bulk and the special BSK flow parts are stored at Platforms LB1 and LB2. The assembly lines consist of the Castor line and the Pollux line. In total, the production process consists of 8 function areas of which the most important production steps are: frame assembly (FA0); pipes and cables (FA1); axles (FA2); engine (FA3); cabin (FA4); tires (FA5); test & repair (FA6); Fit For Use (FA7). The production planning process consists of five steps: global planning assigns demand to production periods; planning program proposes production sequence; production sequence is approved after manual changes; mutation in production sequence; daily update of the production schedule.

The BSK flow consists of parts that are transported on fixtures from the on-site warehouses to the assembly lines by tugger trains on a regular tact. Those parts are first picked as batch, sequence, or kit, and are placed on fixtures in the warehouses. The BSK flow currently uses 12 trains and each train has 4 fixed routes. A train uses 4 trailers, and each trailer can transport one 1-euro size fixture or two ½-euro size fixtures. For each route of the BSK flow, the Total Route consists of the route inside the warehouse for the pickup of full fixtures, the route at the assembly line for the delivery of full fixtures and the pickup of empty fixtures, and the route inside the warehouse for the delivery of empty fixtures. All current train schemes of the BSK flow match with the partial LIFO, and some routes meet the strict LIFO policy. The BSK flow currently uses a manual routing method. This method results in the fixture overview, the individual train schemes, and the individual routing schemes.

One aspect of the core problem is the increased complexity of the BSK flow. An important notion is that the increased complexity of this flow consists of both the increased number of planning restrictions as well as the increase in the number of fixtures, the pickup and the delivery locations of this flow. The following planning restrictions are present: logistical tact time; train capacity; the pickup locations (warehouse locations); the delivery locations (line locations); 1:2:4 supply method; if possible, a separate delivery to the Castor line and the Pollux line; Regular and Special fixtures; used trailer (Rothar or Still); number of chassis per fixture. In the current manual routing method, the BSK flow uses 2 types of trailers, fixed warehouse locations and 5 principles. Regarding the planning restrictions, we observed the following possibilities to improve the BSK flow: use of 1 type of trailer, use of a marshalling area, and use of 1 principle. Moreover, we observed the possibility to adapt the partial LIFO from literature to the BSK flow, resulting in Adapted Partial LIFO. Adapted Partial LIFO entails that only the last pickup fixture is the first fixture that is delivered to the assembly line.

The current performance of the BSK flow is based on the following Key Performance Indicators that show per train the productivity of the BSK flow: the physical fill rate and the time fill rate. For the current train schemes, the average physical fill rate is 71.7% and the average time fill rate is 72.6%, which is lower than the target of 80%. There are three datasets of the BSK flow, and dataset 3 is the artificially generated dataset resembling the normal situation. The comparison of datasets 1 and 2 (real data from practice), with dataset 3 shows that there are discrepancies in each train of the BSK flow.

The requirements for the new routing method are the following: it should be able to cope with the increased complexity of the BSK flow, it should be less labour intensive, it should be able to cope with changes in tact times, and it should be able to exploit the potential of the BSK flow. Moreover, the new routing method should result in an increase in productivity, which is measured through the average physical fill rate and the average time fill rate. To be of practical use, Scania Production Zwolle wants the new routing method to have a reasonable computational time. Furthermore, the new routing method needs to be adaptable, so that when needed, extra aisles or roads can be uploaded. Furthermore, the new routing method needs to be able to make fixed and flexible routes, depending on the input data. Lastly, the new routing method needs to use realistic travel distance and travel time between locations.

3. Literature Review

In this chapter, we answer the second set of research questions, based on the conducted Systematic Literature Review (SLR). The SLR is about the Vehicle Routing Problem (VRP). Appendix G describes the SLR, based on the key theoretical concepts. This way, our theoretical support is evaluated systematically and is connected to our research questions. Based on the conducted SLR, our research questions are theoretically supported by relevant literature and theoretical principles.

RQ2: What concepts and methods described in the literature can be used to improve the routing of the BSK flow?

- What concepts and methods have been proposed in the literature for solving an internal logistics problem?
- What solution approach is suitable for the BSK flow of Scania Production Zwolle?
- What are the advantages and disadvantages of the considered solution approach?

The VRP is "concerned with the optimal design of routes to be used by a fleet of vehicles to serve a set of customers" (Baldacci et al., 2009). Therefore, the theory on the VRP is relevant for solving our internal logistics problem. Because of that, Section 3.1. explains relevant literature about the VRP. Afterwards, Section 3.2 describes popular VRP variants. Section 3.3 describes the combination of multiple VRP variants that are relevant for the BSK flow-VRP. Afterwards, Section 3.4 describes metaheuristics to solve VRPs and Section 3.5 explains heuristics to create an initial solution. Lastly, Section 3.6 concludes this chapter by answering the Research Questions.

3.1. The Vehicle Routing Problem

This section explains relevant literature about the Vehicle Routing Problem. First, Section 3.1.1. introduces the VRP. Afterwards, Section 3.1.2. gives the mathematical formulation of the VRP, while Section 3.1.3. focusses on possible solution approaches for solving the VRP.

3.1.1. Introduction to the Vehicle Routing Problem

The Vehicle Routing Problem is defined as "the problem of designing least-cost delivery routes from a depot to a set of geographically scattered customers, subject to side constraints" (Laporte, 2009). The VRP was introduced by Dantzig and Ramser in 1959 as the Truck Dispatching Problem, which is a generalisation of the Traveling Salesman Problem (TSP) (Dantzig & Ramser, 1959); (Laporte, 2009). The goal of the TSP is to find the shortest circuit or cycle, which passes through each of *n* points once and only once (Laporte & Nobert, 1987). If we assume only one vehicle of very large capacity, then the VRP reduces to the TSP (Kulkarni & Bhave, 1985); (Cordeau et al., 2007). Both the TSP and the VRP are combinatorial optimisation problems that are NP-hard (Caric & Gold, 2008); (Laporte & Nobert, 1987).

The VRP is a combinatorial optimisation problem that is concerned with the optimal design of routes to be used by a fleet of identical vehicles to serve a set of customers: given a set of customers, goods have to be delivered from a depot to a set of customers, by a fleet of identical vehicles at minimum route costs, taking into account all existing restrictions (Baldacci et al., 2008); (Caric & Gold, 2008); (Labadie et al., 2016). The solution of the classical VRP consists of a set of routes and each route begins and ends in the depot, while satisfying the constraints of the classical VRP (Caric & Gold, 2008). Furthermore, the usual objective of the VRP is to minimise the overall routing costs (Caric & Gold, 2008); (Elshaer & Awad, 2020). Besides that, some VRP variants focus on minimising the total travel distance, the number of vehicles, costs related to lateness, costs related to risks or hazards, travel time or a combination of these objectives (Braekers et al., 2016). Minimising the overall routing costs, is in practice often taken to be equivalent to either minimising the total travel distance, or to minimise the used number of vehicles and then minimise the total travel distance for the used number of vehicles (Baker & Ayechew, 2003).

Figure 3.1 shows an example of a single-depot VRP. The depot is the start and the end point of each route. The given set of customers are on the left. These customers also have a certain demand which is not visible in this figure. Solving this VRP, results in the right part of Figure 3.1, showing that 5 vehicles are needed to serve all customers.

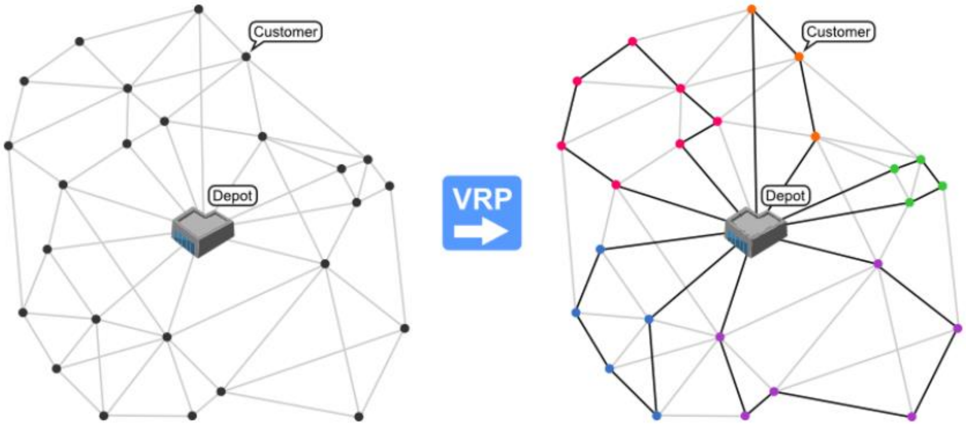

Figure 3. 1. Visualisation of a VRP example

Figure 3.1 represents the VRP by a graph. The classical VRP, in its undirected version, is defined on graph $G = (V, E)$ (Cordeau et al, 2005); (Baldacci et al., 2009). Here, $V = \{0, 1, \ldots., n\}$ is the set of vertices, E is the set of edges, vertex 0 represents the depot, and $V_c = \{1, 2, \ldots., n\}$ corresponds to the set of *n* customers (Baldacci et al., 2009); (Queiroga et al., 2021).

3.1.2. Mathematical model of the classical Vehicle Routing Problem

Kulkarni and Bhave (1985) have formulated the Capacitated Vehicle Routing Problem (CVRP), also referred to as the classical VRP or the basic VRP (Cordeau et al., 2007); (Elshaer & Awad, 2020). The mathematical model of the CVRP, formulated by Kulkarni and Bhave (1985), is as follows:

$$Minimize\ Z = \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{V} c_{ij}x_{ijk}$$

Subject to

$$\sum_{i=1}^{N}\sum_{k=1}^{V} x_{ijk} = 1 \qquad for\ j = 1,2, \ldots., N-1\ (1)$$

$$\sum_{j=1}^{N}\sum_{k=1}^{V} x_{ijk} = 1 \qquad for\ i = 1,2, \ldots., N-1\ (2)$$

$$\sum_{i=1}^{N} x_{ihk} - \sum_{j=1}^{N} x_{hjk} = 0 \quad for\ k = 1,2, \ldots, V, h = 1,2, \ldots., N\ (3)$$

$$\sum_{i=1}^{N} Q_i \sum_{j=1}^{N} x_{ijk} \leq P_k \quad for\ k = 1,2, \ldots, V\ \ (4)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{N} c_{ij}x_{ijk} \leq T_k\ for\ k = 1,2, \ldots, V\ \ (5)$$

$$\sum_{j=1}^{N-1} x_{Njk} \leq 1\ for\ k = 1,2, \ldots, V\ \ (6)$$

$$\sum_{i=1}^{N-1} x_{iNk} \leq 1 \; for \; k = 1,2, \dots., V \; (7)$$

$$x_{ijk} = 0 \; or \; 1 \;\; for \; all \; i, j, k \; (8)$$

$$y_i - y_j + Nx_{ijk} \leq N - 1 \;\; for \; 1 \leq i \neq j \leq N - 1, 1 \leq k \leq V \; (9)$$

Where
$V \; = \; Number \; of \; vehicles,$
$P_k \; = \; Capacity \; of \; vehicle \; k,$
$T_k \; = \; Maximum \; cost \; allowed \; for \; a \; route \; of \; vehicle \; k,$
$Q_i \; = \; Demand \; at \; node \; i, Q_N \; = \; 0$
$x_{ijk} = \; 1 \; if \; pair \; i, j \; is \; in \; route \; of \; vehicle \; k, 0 \; otherwise$
$c_{ij} \; = \; Costs \; of \; travelling \; from \; customer \; i \; to \; customer \; j,$
$N \; = \; Number \; of \; customers,$
$Z \; = \; Total \; costs \; of \; the \; solution$

Constraints 1 and 2 make sure that each customer is served by one and only one vehicle. Constraints 3 ensure route continuity, which means that if a vehicle visits a customer, it also must leave. Constraints 4 are about the vehicle capacity, ensuring that the vehicle capacity is not exceeded. Constraints 5 represent the total route constraints, ensuring that the maximum total route length is not exceeded. Constraints 6 and 7 are the vehicle availability constraints, ensuring that vehicle availability is not exceeded. Constraints 8 ensure that all i, j, k are either 0 or 1. Constraints 9 are the subtour elimination constraints (Kulkarni & Bhave, 1985).

3.1.3. Solving the Vehicle Routing Problem

Figure 3.2 shows the solution approaches for solving the Vehicle Routing Problem: VRPs can be solved exactly, via heuristics or metaheuristics (Konstantakopoulos et al., 2020). The VRP is a combinatorial optimisation problem that is NP-hard, which means that the calculation time needed to find an optimal solution may require exponential time (Bianchi et al., 2008). When a VRP is solved exactly, optimal solutions are obtained and optimality is guaranteed, which is an advantage of this solution approach (Talbi, 2009). However, the disadvantage of using an exact solution approach is that solving a VRP exactly can only be done for small problem instances, although this may already require too much computational time to be of practical use (Cordeau et al, 2005); (Konstantakopoulos et al., 2020).

Because exact methods require too much computational time to be of practical use, approximate algorithms have been developed, since they offer a better balance between solution quality and computational time (Konstantakopoulos et al., 2020); (Talbi, 2009). Heuristics and metaheuristics are approximate algorithms that find in a reasonable computational time a solution that is as good as possible, but this solution is not necessarily optimal (Caric & Gold, 2008); (Talbi, 2009).

It is an advantage that heuristics and metaheuristics have a better balance between solution quality and computational time, but the disadvantage is that optimality is not guaranteed. Another disadvantage of heuristics, according to the definition of classical heuristics by Laporte (2009), is that heuristics often get trapped in local optima, because they do not allow the intermediate solution to deteriorate during the process of finding better (optimal) solutions. Examples of classical heuristics are construction heuristics and improvements heuristics. On the other hand, metaheuristics like Tabu Search and Simulated Annealing (SA), include mechanisms that avoid getting trapped in local optima (Laporte, 2009); (Braekers et al., 2016).

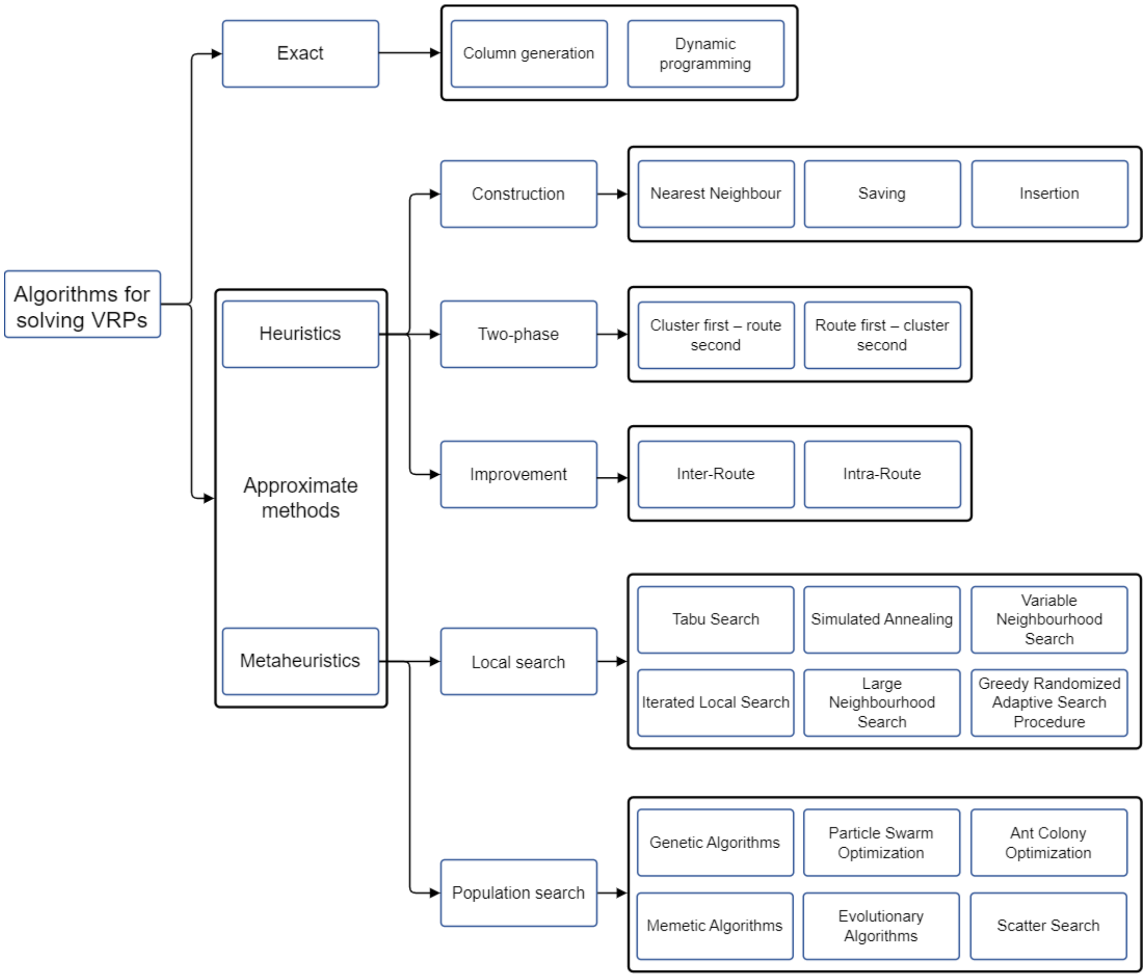

Figure 3. 2. Overview of algorithms for solving VRPs, extracted from Konstantakopoulos et al. (2020)

Besides the research on heuristics, the field of metaheuristics has emerged as the most promising direction for the field of VRP research (Caric & Gold, 2008). Since real-life VRP applications are considerably larger in scale, metaheuristics are often more suitable for practical use (Elshaer & Awad, 2020). An advantage of metaheuristics is the exploration of the solution space, which is much more thorough in comparison with heuristics: for example, moves that result in an inferior result can be accepted to escape from local optima (Cordeau et al., 2007).

Based on the preceding advantages and disadvantages of each solution approach, we have chosen metaheuristics as our solution approach for the BSK flow-VRP. The exact method is not chosen because even for small problem instances it may already require too much computational time to be of practical use for Scania Production Zwolle. Heuristics and metaheuristics are both approximate methods. Heuristics can get trapped in local optima, while metaheuristics can escape from local optima. Moreover, the field of metaheuristics has emerged as the most promising direction for the field of VRP research and metaheuristics are often more suitable for practical use.

3.2. Popular Vehicle Routing Problem variants

Besides the classical Vehicle Routing Problem, many VRP variants exist. Elshaer et al. (2020) describe 9 popular VRP variants. Based on their presence in literature, the following VRP variants are the four most popular variants: the VRP with Time Windows (VRPTW); The VRP with Pickup and Delivery (VRPPD); the Heterogeneous VRP (HVRP); the Multiple-depot VRP (MDVRP). An example of a less commonly used variant is the Multi-trip VRP (MT-VRP). Sections 3.2.1 to 3.2.5 explain these five variants. Afterwards, Section 3.2.6 explains the Adapted Partial LIFO and LIFO loading constraints.

3.2.1. The Vehicle Routing Problem with Time Windows

The Vehicle Routing Problem with Time Windows is one of the most widely studied variants of the VRP. In this VRP variant, the customer determines a time interval during which the order must be delivered. There are two types of time windows: soft and hard. In the case of hard time windows, a vehicle cannot arrive after the end of the time window. Moreover, in case the vehicle arrives before the start of the time window, it must wait until it opens. This means that hard time windows do not allow any delay. On the other hand, time windows can be violated in a VRP with soft time windows. However, violating time windows result in penalty costs (Elshaer & Awad, 2020); (Konstantakopoulos et al., 2020).

3.2.2. The Vehicle Routing Problem with Pickup and Delivery

The Vehicle Routing Problem with Pickup and Delivery is an extension of the VRP, by having goods transported from a depot to customers but also from customers to the depot (Eilam Tzoreff et al., 2002); (Wassan & Nagy, 2014). The VRPPD is a variant of the VRP, used if a number of items need to be moved from certain pickup points to other delivery points (Sitek & Wikarek, 2017). In the context of goods transportation, the Vehicle Routing Problem with Pickup and Delivery can be referred to as Pickup-and-Delivery Problem: the PDP (Toth & Vigo, 2014).

PDPs are Vehicle Routing Problems in which the transportation requests consist of the movement of goods or people between two particular locations: one location where someone or something is picked up, and a corresponding location for the delivery (Toth & Vigo, 2014). In the VRPPD, some customers expect deliveries from a depot, the delivery customers, while other customers have available supply to be picked up and transported to a depot, the pickup customers (Eilam Tzoreff et al., 2002). According to Toth and Vigo (2014), generally, neither of the locations in a PDP is a depot. Three types of PDPs exist: many-to-many, one-to-many-to-one, and one-to-one.

In one-to-one PDP, each commodity has a single origin and a single destination, and each customer request consists of transporting a load from the origin to the destination (Toth & Vigo, 2014). Because of that, the PDP with one-to-one is applicable to Scania Production Zwolle because fixtures need to be moved between their single origin (the warehouse location), to their single destination (the line location). Figure 3.3 shows an example of a one-to-one PDP, where the goods are loaded into a truck. In the remainder of this report, we use the term Vehicle Routing Problem with Pickup and Delivery that Wassan et al. (2014) and Eilam Tzoreff et al. (2002) use.

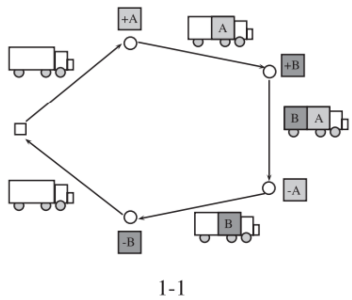

Figure 3. 3. One-to-one Pickup and Delivery Problem, extracted from Toth & Vigo (2014)

An important notion about the VRPPD for the BSK flow, is that routing a full fixture also implies routing the empty fixture afterwards. For example, we route for fixture number 4 the pickup of a full fixture in the warehouse and the delivery of that full fixture to the line location. By routing the full fixture number 4 (the pickup and the delivery), we will also route the pickup of the empty fixture number 4 from the line location and the delivery of the empty fixture number 4 to the warehouse location. The pickup of the empty fixture number 4 happens after the delivery of the full fixture number 4.

3.2.3. The Heterogeneous Vehicle Routing Problem

In the classical Vehicle Routing Problem, the fleet of vehicles is homogeneous. This means that all vehicles are identical and have the same capacity. On the other hand, when a heterogeneous fleet of vehicles is used, multiple types of vehicles exist. Each type of vehicle has a different capacity, fixed and variable costs. In practice, it is common to have different types of vehicles. For example, small size vehicles are mainly used to serve customers in city centres (last-mile distribution), while bigger vehicles are used to primarily serve customers at more considerable distances and with larger required volumes of orders (Elshaer & Awad, 2020); (Konstantakopoulos et al., 2020).

3.2.4. The Multiple-depot Vehicle Routing Problem

The theory about the Multiple-depot Vehicle Routing Problem is used when multiple depots are involved. When there are multiple depots, the distribution of vehicles along the depots needs to be determined. In the MDVRP, a customer will most commonly be assigned to the nearest depot. Because of that, the MDVRP can be seen as a series of multiple single-depot VRPs, which simplifies the initial MDVRP (Elshaer & Awad, 2020); (Konstantakopoulos et al., 2020). Another variant of VRP with multiple depots, is the Multi-Depot Cumulative Capacitated Vehicle Routing Problem (MDCCVRP), where several depots can be considered as starting points of routes and the goal is to minimise the sum of arrival times at customers (Lalla-Ruiz & Voß, 2020). The MDCCVRP is a variation of the Cumulative Capacitated Vehicle Routing Problem that is used when the goal is to minimise the sum of arrival times at customers instead of the total route distance (Lalla-Ruiz & Voß, 2020).

3.2.5. The Multi-trip Vehicle Routing Problem

In the Capacitated Vehicle Routing Problem, each vehicle is assumed to be only used once during the planning period. The planning period of the CVRP is usually a day. In case a vehicle makes more than one trip in the planning period, the CVRP is unrepresentative. This is the case in many practical situations, where a vehicle makes more than one trip in the planning period, which results in the Multi-trip VRP (Brandão & Mercer, 1998).

3.2.6. Adapted Partial LIFO and LIFO loading constraints

Section 2.2.4 introduced the Partial LIFO and the Strict LIFO loading constraints that are present in the current routes of the BSK flow. Moreover, that section explained that we observed the possibility to adapt the Partial LIFO to the BSK flow. The Partial LIFO adapted to the BSK flow, shortened to Adapted Partial LIFO, entails that only the last pickup fixture is the first fixture that is delivered. Based on the preceding, we incorporate the following loading policies into our solution approach: No Policy, Adapted Partial LIFO, and Strict LIFO. By incorporating different loading policies in our solution approach, we can experiment what the impact is on the performance of the BSK flow.

LIFO loading constraints means that, “considering all shipments that are currently on board a vehicle, one must deliver the shipment that is most recently picked” (Toth & Vigo, 2014). Figure 3.4 shows two paths where 0 illustrates the depot, i^+ the pickup points, and i^- are the delivery points associated with request i (Cherkesly et al., 2015). The path in (a) respects the LIFO policy since we deliver first the item that is picked up most recently. Moreover, (b) shows that the LIFO policy is not respected, because the item picked up at 1^+ cannot be delivered to 1^- without first removing the item picked up at 2^+.

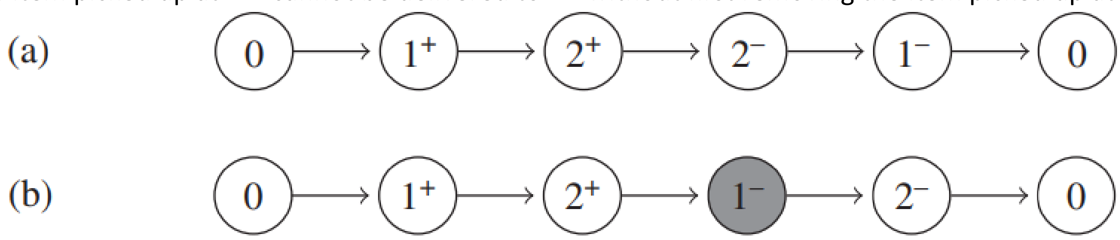

Figure 3. 4. Example of LIFO loading constraints, extracted from Cherkesly et al. (2015)

3.3. Combination of multiple Vehicle Routing Problem variants for the BSK flow-VRP

We use the theory on the Vehicle Routing Problem to improve the routing of the BSK flow. We need to tailor the VRP to the BSK flow, by combining multiple VRP variants that represent the BSK flow. Therefore, Section 3.3.1 gives an overview of the BSK flow characteristics that are present in VRP variants. Section 3.3.2 explains the separation of time periods, principles, and types of trailers into separate instances. Next, Section 3.3.3 summarises the relevant VRP variants for the BSK flow-VRP.

3.3.1. Characteristics of the BSK flow-VRP

As introduced in Section 1.2.2, the BSK flow consists of parts that are transported on fixtures from the on-site warehouses to the assembly lines by trains on a regular tact. For each route of the BSK flow, the Total Route consists of the route inside the warehouse for the pickup of full fixtures (Route_WH), the route at the assembly line for the delivery of full fixtures and the pickup of empty fixtures (Route_LL), and the route inside the warehouse for the delivery of empty fixtures (Route_WHBack). Fixtures are transported multiple times a day and are switched in Platform LB1 or Platform LB2, and the trains have a capacity of 4 trailers. The BSK flow uses two types of trains, each with a fixed type of trailer as Section 2.2.1 explained. In the fixture overview from Scania Production Zwolle, the type of trailer is mentioned. Therefore, we use the type of trailer as the heterogeneous aspect instead of the type of trains. We incorporate multiple loading constraints in our solution approach.

To summarise, the characteristics of the BSK flow are: transportation of fixtures, regular tact, heterogeneous trains, loading constraints, pickup and delivery, on-site warehouses, and multiple trips per day. Not all characteristics of the BSK flow need to be incorporated into our solution approach. This is because our solution approach solves one instance at a time. For our solution approach to be able to solve one instance at a time of the BSK flow, the following VRP variants need to be incorporated into the BSK flow-VRP:

- <u>Transportation of fixtures</u>: fixtures need to be transported by trains that have a certain capacity. The basic VRP, also known as the Capacitated VRP, is the relevant VRP variant for this characteristic.
- <u>Pickup and delivery</u>: a full fixture is picked up at the warehouse and is delivered to the assembly line. Assigning the full fixture implies that after the full fixture is delivered, that the empty fixture is picked up at the assembly line and is afterwards delivered to the warehouse. The Vehicle Routing Problem with Pickup and Delivery is the relevant VRP variant for this characteristic.
- <u>Loading constraints</u>: we incorporate multiple loading constraints into our solution approach. This way we can analyse which type of loading constraints improves the BSK flow performance.

3.3.2. Solving separate instances

The BSK flow-VRP solves one instance at a time. An instance is a combination of a time period, a principle, and a type of trailer. For each fixture in the dataset, we know the instance it belongs to: the time period, the principle, and the type of trailer. Based on that, we create sub datasets which are based on the principle and the type of trailer. This results in having the following sub datasets:

- Principle15minutes_Type1: fixtures in Principle 1 (Pollux) and Principle 2 (Castor) that use a Rothar trailer, sorted on their time period;
- Principle15minutes_Type2: fixtures in Principle 1 (Pollux) and Principle 2 (Castor) that use a Still trailer, sorted on their time period;
- Principle3_Type1: fixtures in Principle 3 that use a Rothar trailer, sorted on their time period;
- Principle3_Type2: fixtures in Principle 3 that use a Still trailer, sorted on their time period;
- Principle4_Type2: fixtures in Principle 4 that use a Still trailer, sorted on their time period;
- Principle6_Type1: fixtures in Principle 6 that use a Rothar trailer, sorted on their time period.

The preceding results in having sub datasets with all fixtures per principle and type of trailer, which are sorted on their time period. Table 3.1 shows an example of the fixtures that need to be routed in the first 4 instances of sub dataset Principle15minutes_Type1: fixtures in time periods 0, 1, 2, and 3 with Principle15minutes and type of trailer 1. By using sub datasets, the BSK flow-VRP solves one time period after another of the same sub dataset. This way, the BSK flow-VRP solves instances separately. In the remainder of this report, we shorten Principle4_Type2 and Principle6_Type1 to Principle 4 and Principle 6. This is because these principles only use one type of trailer.

Instance	Time Period	Principle	Type of trailer	# of fixtures	Fixtures to be routed
0	Time Period 0	Principle15minutes	Type1	14	[4, 8, 9, 10, 11, 14, 87, 88, 91, 105, 107, 118, 122, 123]
1	Time Period 1	Principle15minutes	Type1	18	[3, 12, 18, 64, 64, 65, 89, 90, 92, 94, 95, 96, 98, 99, 109, 111, 120, 123]
2	Time Period 2	Principle15minutes	Type1	12	[2, 5, 13, 15, 21, 38, 39, 42, 56, 93, 105, 107]
3	Time Period 3	Principle15minutes	Type1	17	[18, 19, 34, 44, 45, 49, 64, 64, 65, 89, 90, 92, 94, 95, 98, 99, 135]

Table 3. 1. Overview of first 4 instances of sub dataset Principle15minutes_Type1

By solving one instance at a time, the following characteristics of the BSK flow and thus VRP variants, become redundant for the BSK flow-VRP:

- Heterogeneous trains: by separating the instances per principle and type of trailer, we can run the BSK flow-VRP for each instance separately. This way, it becomes redundant to incorporate the Heterogeneous VRP into the BSK flow-VRP.
- On-site warehouses: switching an empty fixture for a full fixture is done in Platform LB1 and Platform LB2. However, we incorporate Platforms LB1 and LB2 into the BSK flow-VRP as one fictive warehouse, with the real travel distances and the real travel times between the warehouse and the line locations. This makes it redundant for the BSK flow-VRP to incorporate the Multiple-depot VRP.
- Multiple trips per day and regular tact: fixtures are transported multiple times a day on a regular tact. Due to the logistical tact time, vehicles will have to be back on time for the start of the next logistical tact time. Therefore, the next tact can be seen as independent from the previous one. Because of that, the fixtures will be planned for all logistical tact times, making it redundant to incorporate the Multi-trip VRP and the VRP with Time Windows into the BSK flow-VRP.

3.3.3. Relevant Vehicle Routing Problem variants for the BSK flow-VRP

By solving one instance at a time, we only have to model the Capacitated Vehicle Routing Problem, the Vehicle Routing Problem with Pickup and Delivery, and the loading constraints for the BSK flow-VRP. Based on the preceding, the BSK flow-VRP is the Vehicle Routing Problem with Pickup and Delivery and loading constraints for internal logistics. Regarding the loading constraints, we incorporate the following strategies into our solution approach: No Policy, Adapted Partial LIFO, and Strict LIFO.

3.4. Metaheuristics for solving the VRPPD and LIFO loading constraints

Appendix G.5 shows the Systematic Literature Review for using metaheuristics to solve the VRP with Pickup and Delivery and LIFO loading constrains. That appendix also shows that Tabu Search (Section 3.4.1) is the most used local search metaheuristic for solving a VRPPD. Moreover, the Variable Neighbourhood Search (Section 3.4.2) and Simulated Annealing (Section 3.4.3) are the second and third most used local search metaheuristic for solving a VRPPD. Section 3.4.4 explains the use of neighbourhood operators for local search. Regarding the population search, Genetic Algorithms (Section 3.4.5) is the most used method to solve the VRPPD. Moreover, Ant Colony Optimisation (Section 3.4.6) is a popular population search to solve the VRPPD.

3.4.1. Tabu Search

Tabu Search is a memory-based local search metaheuristic that was introduced by Glover and is widely used for solving Vehicle Routing Problems (Gmira et al., 2021); (Glover et al., 2021). Tabu Search is described in literature as being a successful procedure which is widely used for solving a variety of VRPs, yielding good solutions with reasonable computational time (Ceschia et al., 2010); (Laporte et al., 2000). Tabu Search is an iterative method, starting with an initial solution and it applies local modifications (moves) to improve the solution (Gmira et al., 2021); (Prescott-Gagnon et al., 2012). Section 3.4.4 explains the neighbourhood operators that Tabu Search uses.

The first step of Tabu Search is that a simple heuristic generates the initial solution, and it becomes the current solution S. Then the algorithm creates a candidate list of neighbours to the current solution at each iteration. At each iteration, the best solution S' in the neighbourhood of the current solution is selected, even if it is worse than the current solution, and becomes the new current solution. This process is repeated until a stopping criterion is satisfied. When the stopping criterion is satisfied, the best solution during the search is returned (Gmira et al., 2021); (Prescott-Gagnon et al., 2012).

The current solution of Tabu Search may deteriorate from one iteration to the next, which is not possible in classical descent methods. These new, poorer solutions are only accepted to avoid paths already investigated, which ensures that new regions of a problem's solution space will be investigated. The goal of this is to avoid local minima and ultimately find the desired solution (Bräysy & Gendreau, 2005). While executing Tabu Search, a Tabu List is made and continuously updated (Caric & Gold, 2008). This Tabu List is kept to avoid cycling, which forbids to perform certain moves that could lead back to a previously visited solution. Moreover, the Tabu List is also used to drive the search towards regions of the solution space that were not yet explored, which have high potential of containing good solutions (Brandão, 2011). The Tabu status can be overridden by the aspiration criterion. The classical aspiration criterion is that the Tabu status of an exchange is overridden if it leads to a neighbourhood solution that is better than the best-known solution (Gmira et al., 2021).

3.4.2. Variable Neighbourhood Search

Variable Neighbourhood Search (VNS) is a metaheuristic that is developed in 2001 and the idea of VNS is similar to that of Simulated Annealing. Contrary to SA, VNS does not use a single neighbourhood structure but instead it uses a hierarchy of more narrow as well as of broader neighbourhood definitions. VNS starts with an "incumbent" solution x. From this solution x, "the procedure jumps to a random neighbour solution x' contained in one of these neighbourhoods (a step called shaking), improves the solution x' by local search according to the smallest pre-defined neighbourhood, which yields a solution x", and accepts or rejects x" depending on whether it is better than x or not. In the case of rejection, the current neighbourhood size for the shaking step is increased by one; in the case of acceptance, it is re-set to the smallest value" (Bianchi et al., 2008).

3.4.3. Simulated Annealing

The term Simulated Annealing comes from simulating the physical annealing process, where particles of a solid arrange themselves into a thermal equilibrium. A start solution is initialised from the solution space. In every iteration, a neighbour solution y is generated by a small change in the current solution x. If the objective value of y is better than or equal to the objective value of x, neighbour solution y is accepted. If the neighbour solution y has a worse objective function value than x, the solution y is only accepted with a certain probability. This probability is initially high but decreases after a lot of iterations. The method stops when a better solution is not found after a predetermined number of iterations (Bianchi et al., 2008).

3.4.4. Neighbourhood Operators

Local search methods use neighbourhood operators, since a neighbour is a solution that differs from the current solution by only one move (Ceschia et al., 2010); (Prescott-Gagnon et al., 2012). Local search operators for the Vehicle Routing Problem are divided into Intra-route operators and Inter-route operators. Intra-route refers to the application of the operator on a single route: operators move one or more customers from one position in the route to another position in the same route. Intra-route operators are used to reduce the overall distance. Figure 3.5 shows that Intra-route operators consist of Relocate, Exchange, 2-Opt, and Or-Opt (Caric & Gold, 2008); (Paraskevopoulos et al., 2007).

The first Intra-route operator is Relocate, which shows that customer a1 is relocated to a new position in the route. Intra-route operator Exchange swaps the position of two customers and is in other articles therefore referred to as the Swap operator. The intersection of arcs is transformed by the Intra-route 2-Opt operator, if savings exist after the direction of arcs are changed and the appropriate arcs have been deleted and added. The Or-Opt transforms the intersection of arcs with reordering customers on a route if savings exist. For each operator holds that the operator is only executed if it leads to reducing the overall distance of the route (Caric & Gold, 2008); (Paraskevopoulos et al., 2007).

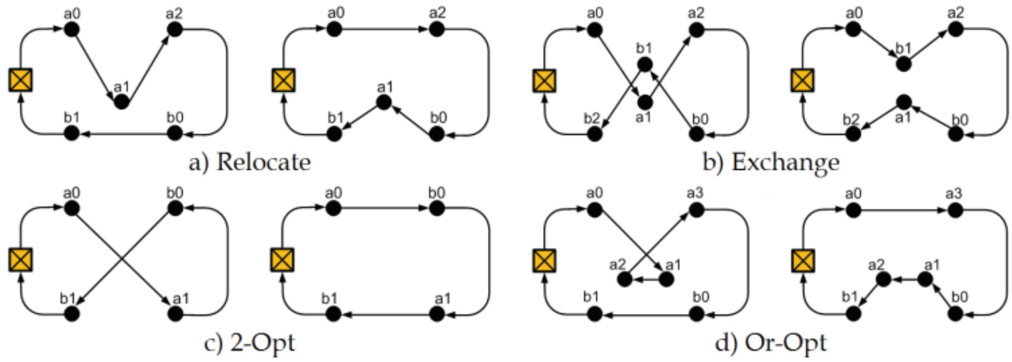

Figure 3. 5. Intra-route operators, extracted from Caric & Gold (2008)

Inter-route operators work with two routes. Besides reducing the overall distance, they can sometimes reduce the number of vehicles as well. Figure 3.6 shows that the Inter-route operators consist of Relocate, Exchange, Cross-Exchange, and Icross-Exchange. The first Inter-route operator is Relocate, which moves customer a1 from one route to another. The Exchange operator swaps two customers: customers a1 and b1, both from different routes, are swapped. Two groups of customers from one route to another are swapped by the Cross-Exchange operator. The Icross-Exchange swaps customers the same way as the Cross-Exchange, but the customers are placed in reverse order in both groups. For each operator holds that the operator is only executed if it leads to reducing the overall distance of the route (Caric & Gold, 2008); (Paraskevopoulos et al., 2007).

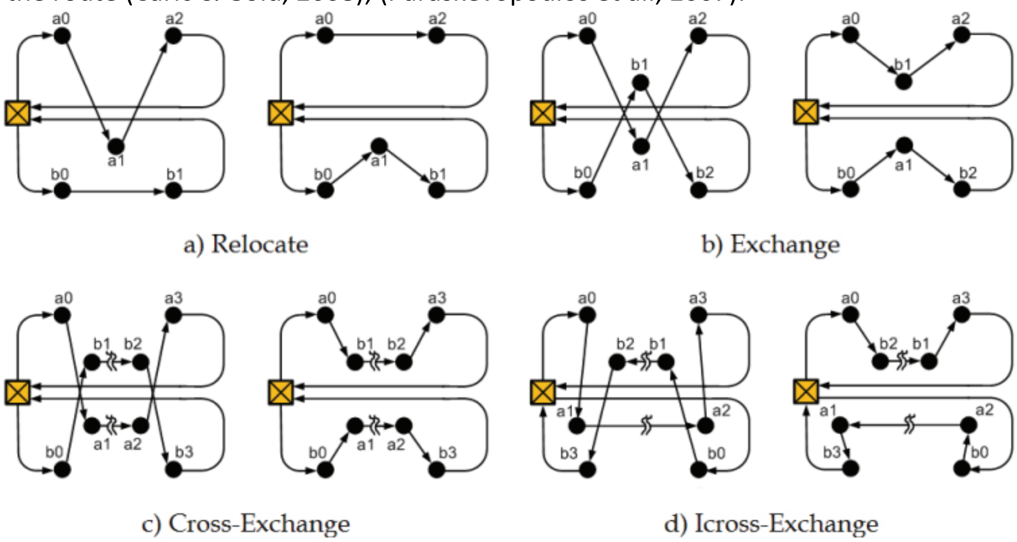

Figure 3. 6. Inter-route operators, extracted from Caric & Gold (2008)

For the BSK flow-VRP, we use the following neighbourhood operators: Inter-route Relocate, Inter-route Exchange, Intra-route Relocate, and Intra-route Exchange. We have chosen Inter-route and Intra-route neighbourhood operators so that we can improve all instances of the BSK flow-VRP. We use Inter-route operators because they can reduce the number of vehicles, besides reducing the overall distance. Using fewer trains results in a cost reduction which is the economic advantage Scania

Production Zwolle wants. Furthermore, we use the Intra-route operators so that the instances that use only one train can also be improved via Tabu Search. In the remainder of this report, Relocate is referred to as move and Exchange is referred to as swap.

3.4.5. Genetic Algorithms

Genetic Algorithms (GA's) are a metaheuristic that are based on the principles of biological evolution, natural selection, gene recombination, and survival of the fittest in living nature systems to study artificial systems. An initial population (parents) of solutions, known as chromosomes, is randomly generated. Besides random generation, local search methods can be used to generate the initial population (parents) of solutions. In each iteration the following steps are conducted: evaluating the fitness of chromosomes, selecting two parents, and recombining parents while ensuring diversity. First, by a fitness function, the quality of chromosomes is evaluated in each iteration. Next, a selection of two parents is conducted, based on the fitness of each chromosome. Those parents are recombined using crossover to provide the offspring (children). Diversity of the population is ensured by applying the mutation procedure. The best solutions are then selected to be used as parents in the next iteration. These steps are conducted until a stopping criterion is reached. GA's work in conjunction with local search: usually the offspring is improved through local search (Konstantakopoulos et al., 2020); (Rabbouch et al., 2019). An advanced version of GA's is Memetic Algorithms (MA's), where for each child a local improvement method is applied. GA's and MA's both belong to the greater category of Evolutionary Algorithms (Konstantakopoulos et al., 2020); (Labadie et al., 2016).

3.4.6. Ant Colony Optimisation

Ant Colony Optimisation is a nature-inspired metaheuristic, which links optimisation with biological ants. This metaheuristic is based on the foraging behaviour of ants: when ants walk from their nest to a source of food, it seems that ants do not simply find a random route but a quite 'good' route in terms of shortness or travel times. In other words, because of their behaviour they are able to solve an optimisation problem. Their success is based on how they communicate and how they decide where to go: when ants are walking, they deposit the chemical pheromone on the ground and ants are tended to choose routes that are marked by strong pheromone concentrations. Starting with two unexplored routes between the nest and the source of food, a short one and a long one, ants randomly choose the first time one of these routes. By chance, some ants have chosen the shorter route and those ants are the first to reach the food and start their walk home. Because of that, pheromone starts to accumulate faster on the short route than on the longer route. Since ants tend to choose routes that are marked by strong pheromone concentrations, ants subsequently tend to follow the shorter route because it has more pheromone, which results in depositing more pheromone and making it even more attracting for other ants to follow this route (Bianchi et al., 2008); (Labadie et al., 2016).

3.5. Using heuristics to create an initial solution

Section 3.5.1 describes the Nearest Neighbour Heuristic (NNH), and Section 3.5.2 describes the Saving heuristic, both are construction heuristics. Afterwards, Section 3.5.3 explains the two-phase heuristics.

3.5.1. Nearest Neighbour Heuristic

The goal of the Nearest Neighbour Heuristic for the Capacitated Vehicle Routing Problem variant is to generate an initial feasible solution, by adding the Nearest Neighbour of the last added customer in the route. In the CVRP, each customer is added by the criterion of the Nearest Neighbour from the last added customer until the maximum capacity is reached (Caric & Gold, 2008); (Lima et al., 2018). The NNH starts from the depot, which is the CurrentNode. The customer with the smallest distance from the depot is determined*, Node n*, and that customer is added to the first vehicle. Now, the added customer becomes the new CurrentNode, and the next customer with the closest distance from the new CurrentNode is determined. The determination of the customer with the closest distance from the CurrentNode is repeated, until the capacity of the vehicle is insufficient. When capacity is reached, a new vehicle is started from the depot, where the depot starts as the CurrentNode. The process ends when all customers are assigned to a vehicle (Caric & Gold, 2008); (Yu et al., 2016). The NNH is easy to implement and it is quickly executed, but sometimes it can miss shorter routes due to the greedy nature of this algorithm (Lima et al., 2018); (Yücenur & Demirel, 2011). Thus, improving the solution of the NNH is needed. Previous research indicates that combining the NNH with Tabu Search improves the quality of the initial solution (Masudin et al., 2019); (Sun et al., 2018).

3.5.2. Saving heuristic

The saving heuristic is sometimes referred to as the Clark and Wright heuristic (Caric & Gold, 2008). For the Capacitated Vehicle Routing Problem, this heuristic starts from an initial solution. This initial solution consists of each route having only one customer and a corresponding vehicle. So, the number of vehicles is at the beginning equal to the number of customers. Each new iteration looks at the maximum saving when unifying two routes. The saving can consist of a reduction in overall distance or travel time (Cordeau et al., 2007).

3.5.3. Two-phase heuristics

Two-phase heuristics are based on dividing the Vehicle Routing Problem solution process into two separate subproblems: clustering and routing. Clustering consists of organising customers into feasible clusters. This way subsets are determined, each corresponding to a route. Routing consists of determining the sequence of customers on each route. Cluster-first, route-second means that first the feasible clusters of customers are determined, and afterwards a vehicle route is constructed for each of them. The other way around, route-first, cluster-second, the tour is first build based on all customers. In the second phase, the route is segmented into feasible vehicle routes (Caric & Gold, 2008); (Cordeau et al., 2007).

3.6. Conclusion

We use the theory on the Vehicle Routing Problem to improve the routing of the BSK flow at Scania Production Zwolle. The VRP is "concerned with the optimal design of routes to be used by a fleet of vehicles to serve a set of customers" (Baldacci et al., 2009). Therefore, theory on the VRP is relevant for solving our internal logistics problem. Based on the executed Systematic Literature Review, the BSK flow-VRP is the Vehicle Routing Problem with Pickup and Delivery and loading constraints for internal logistics. Regarding the loading constraints, we incorporate the following strategies into our solution approach: No Policy, Adapted Partial LIFO, and Strict LIFO.

Vehicle Routing Problems can be solved exactly, via heuristics or via metaheuristics. Based on the advantages and disadvantages of those solution approaches, we have chosen metaheuristics as the solution approach for the BSK flow-VRP. The advantages of metaheuristics are that metaheuristics can escape from local optima, the field of metaheuristics has emerged as the most promising direction for the field of VRP research, and metaheuristics are often more suitable for practical use. Furthermore, metaheuristics have a better balance between solution quality and computational time, but the disadvantage is that optimality is not guaranteed. We described the following metaheuristics that can be used to solve the BSK flow-VRP: Tabu Search; Simulated Annealing; Variable Neighbourhood Search; Genetic Algorithms; Ant Colony Optimisation. From the metaheuristics we have chosen Tabu Search since this is the best fitting choice for solving the BSK flow-VRP: Tabu Search is described in literature as being a successful procedure which is widely used for solving a variety of VRPs, yielding good solutions with reasonable computational time. To be of practical use for SPZ, the solution approach needs to be able to find good solutions within reasonable computational time. Furthermore, we have chosen for Tabu Search since it is the most used metaheuristic to solve a VRPPD. We incorporate the Inter-route swap, the Inter-route move, the Intra-route swap, and the Intra-route move in Tabu Search. We have chosen the Nearest Neighbour Heuristic to generate the initial solution of Tabu Search.

4. Solution design

Chapter 3 identified the BSK flow-VRP as a Vehicle Routing Problem with Pickup and Delivery and loading constraints for internal logistics. We incorporate multiple loading constraints into our solution approach. This chapter focusses on the proposed solution design, and addresses Research Question 3:

RQ3: How does the proposed solution design for routing the BSK flow look like?

- How can the concepts and methods from the literature be tailored to our problem?
- How does the mathematical model of the solution design look like?
- How does the flowchart of the solution design look like?

Section 4.1 gives the formulation of the BSK flow-VRP. Afterwards, we explain the adaption of the following algorithms that we use to solve the BSK flow-VRP: the Nearest Neighbour Heuristic (Section 4.2) and Tabu Search (Section 4.3). In Section 4.4, we describe the solution approach of the BSK flow-VRP. Next, we elaborate on the verification and the validation of our solution approach. Finally, Section 4.6 concludes this chapter by answering Research Question 3.

4.1. Formulation of the BSK flow-VRP

This section formulates the BSK flow-VRP, which consists of describing the model requirements (Section 4.1.1), the problem description (Section 4.1.2), the simplifications and assumptions (Section 4.1.3), and the mathematical model of the BSK flow-VRP (Section 4.1.4).

4.1.1. Model requirements

Our model should focus on minimising the total travel distance, which might result in a reduction in the required number of trains used by the BSK flow. When fewer trains are needed, this results in a cost reduction which is the economic advantage Scania Production Zwolle wants. Besides this general requirement, our model should also meet the following requirements:

- To be of practical use for SPZ, solving our model should be finished within a reasonable computational time;
- To be able to use our model in the future, our model needs to be adaptable. This means that, when needed, extra aisles or roads can be uploaded into the model. Moreover, the model needs to be able to deal with changes in tact times;
- Every fixture that is present in the dataset, needs to be assigned to a train;
- The model should be able to make fixed and flexible routes, depending on the input data;
- Realistic travel distance and travel time between locations must be used.

4.1.2. Problem description

We adapt the mathematical model from Cherkesly et al. (2015) to the BSK flow-VRP. This mathematical model was found in the SLR for the Vehicle Routing Problem with Pickup and Delivery and LIFO loading constraints, the VRPPDL. The mathematical model from this article includes time window constraints. Because of that, we leave out the time window constraints, because the BSK flow-VRP does not incorporate time windows. Moreover, our problem description incorporates the use of routes inside the warehouse, resulting also in a Total Route that starts and ends with the route inside the warehouse. This way, our model can be used for internal logistics.

In the BSK flow-VRP, the network at Scania Production Zwolle is defined as a directed weighted graph, to pick up and deliver the fixtures from the BSK flow. Let n denote the number of requests per instance, for the Vehicle Routing Problem with Pickup and Delivery and LIFO loading constraints. The VRPPDL can be defined on a directed graph $G = (N, A)$, where $N = \{ 1, \dots, 2n \}$ is the set of nodes and A is the set of arcs. The sets of the pickup and the delivery nodes are the subsets $P = \{1, \dots, n\}$ and $D = \{\mathrm{n} +$

$1, \ldots, 2n\}$ respectively. Subset P is the set of the pickup nodes inside the warehouse, which are the same nodes where the empty fixtures are delivered to.

For each node $i \in \mathrm{N}$, the load picked up or delivered at this node is represented by q_i, with $q_i = ½ \; or \; 1$ if $i \in \mathrm{P}$, and $q_i = -q_{i-n}$ if $i \in \mathrm{D}$. The load q_i corresponds to the size of the fixtures, which are ½-euro sized or 1-euro sized fixtures. An unrestricted set K of identical vehicles with capacity Q is available. Let s_i be the service duration at node i, which is the required time for changing the fixture at the warehouse location or at the line location. A nonnegative travel distance d_{ij} and nonnegative travel time t_{ij} are associated with every arc $(i, j) \in \mathrm{A}$. Moreover, T^k is the maximum route duration, which requires that for each vehicle, the total travel time of the used arcs $(i, j) \in \mathrm{A}$ and the total service duration at the pickup and the delivery nodes i $(i \in P, n + i \in D)$, are less than or equal to T^k. The objective function of the BSK flow-VRP is to minimise the total travel distance.

Each request i is associated with a pickup node $i \in \mathrm{P}$ and a delivery node $n + i \in \mathrm{D}$, denoted as i^+ and i^-. For the BSK flow-VRP, the pickup node is a full fixture that needs to be picked up at the warehouse and delivered to the line location. After delivering the full fixture, the empty fixture with the same fixture number, needs to be brought back to their warehouse location. The Total Route of the BSK flow consists of 3 stages: the pickup of full fixtures; the delivery of full fixtures and the pickup of empty fixtures; the delivery of empty fixtures. Therefore, the total route of the BSK flow consists of the following parts:

- The route inside the warehouse to pick up the full fixtures;
- The route at the assembly line to deliver the full fixtures and to pick up the empty fixtures;
- The route inside the warehouse to deliver the empty fixtures.

So, for every fixture, we need to pick up the full fixture at their warehouse location, deliver it to the assembly line where we pick up the empty fixture, and afterwards deliver the empty fixture to their warehouse location.

All in all, the Total Route of vehicle k of the BSK flow-VRP consists of the route inside the warehouse to pick up the full fixtures ($Route\_WH\_full^k$), the route at the assembly line to deliver the full fixtures to their line locations and to pick up the empty fixtures at the same line location ($Route\_LL^k$), and the route inside the warehouse to deliver the empty fixtures ($Route\_WH\_empty^k$). This results in the $TotalRoute$ for vehicle k: $TotalRoute^k = Route\_WH\_full^k + Route\_LL^k + Route\_WH\_empty^k$. The route at the assembly line ($Route\_LL^k$) consists of a sequence of requests i. The route inside the warehouse ($Route\_WH\_full^k$ and $Route\_WH\_empty^k$) consists of the same requests i, the same fixtures, but the sequence depends on the used loading constraints. Based on the preceding, the set of arcs can be described by the following 5 types of arcs (i, j):

- Route inside the warehouse (the pickup of full fixtures): from the first pickup node ($i_{n=1} \in P$) inside the warehouse to the last pickup node($j_m \in P$) inside the warehouse;
- Warehouse to the assembly line: from the last warehouse node ($i_m \in P$) to the first node at the assembly line ($j_{n=1} \in D$)
- Route at the assembly line (the delivery of full fixtures and the pickup of empty fixtures): from the first delivery node at the assembly line ($i_{n=1} \in D$) to the last delivery node at the assembly line ($j_m \in D$). At each line location at the assembly line, delivering a full fixture implies the pickup of the empty fixture at the same line location.
- From the assembly line to the warehouse: from the last delivery node at the assembly line ($i_m \in D$), back to the first warehouse location ($i_{n=1} \in P$)
- Route inside the warehouse (the delivery of empty fixtures): from the first delivery node of the empty fixture inside the warehouse ($i_{n=1} \in P$), to the last delivery node of the empty fixture inside the warehouse ($j_m \in P$). The delivery of the empty fixtures takes place inside the warehouse, which corresponds to the set of pickup nodes.

4.1.3. Model simplifications and assumptions

Section 2.2.1 explained that regarding the trailers, different frame types exist. However, in consultation with the BSK flow engineers, we decided to assume that our model uses one frame type that is accessible on both sides. This means that we assume that we use one frame type for the Rothar trailer, and one frame type for the Still trailer, and that the used frame types are accessible on both sides. Assuming the use of one frame type for both the Still and the Rothar trailers is a simplification because in practice Scania Production Zwolle does not use one frame type. The network of SPZ incorporates the special crossings. In case an arc has a special crossing, extra time is added to the travel time of that arc. This results in a simplification: in reality, a train must sometimes wait for a special crossing, while in our model, a train always receives the extra time for the special crossing. Because of that, we use a different extra time for the special crossings.

Furthermore, we assume a normal production day, which means that we assume that there are no line stops. However, SPZ experiences sometimes line stops. Moreover, we assume that the train has no acceleration time. Another assumption is that we use 8 km/h for the travel speed, which is the maximum speed inside the factory. However, the speed in practice will sometimes be lower. Nevertheless, we assume that the speed of the trains is always 8 km/h. This is the same speed that the BSK flow engineers use for their manual creation of routes. Moreover, we assume that each train has 4 trailers behind it, resulting in a capacity of 4.0 per train.

4.1.4. Mathematical model of the BSK flow-VRP

The Vehicle Routing Problem with Pickup and Delivery and loading constraints for the BSK flow-VRP can be formulated as a three-index model. For each arc $(i,j) \in \mathrm{A}$ and each vehicle $k \in \mathrm{K}$, let x_{ij}^k be a binary variable equal to 1, if and only if vehicle k uses arc (i,j). For each node $i \in \mathrm{N}$ and each vehicle $k \in \mathrm{K}$, let Q_i^k be the load of vehicle k upon leaving node i, and let T^k be the maximum route duration of vehicle k. The mathematical model is used to find the best routes at the assembly lines. The route inside the warehouse to pick up the full fixtures ($Route\_WH\_full^k$) and the route to deliver the empty fixtures ($Route\_WH\_empty^k$) result from the route at the assembly line, and depends on the used type of loading constraints. In case of the Strict LIFO policy, the route inside the warehouse to pick up the full fixtures ($Route\_WH\_full^k$) is the reverse of the route at the assembly line ($Route\_LL^k$). The Adapted Partial LIFO entails that only the fixture that is picked up last ($Route\_WH\_full^k$), is delivered first at the assembly line ($Route\_LL^k$). The VRPPD and loading constraints, extracted from Cherkesly et al. (2015), and adapted to the BSK flow-VRP can then be formulated as:

$$minimise \sum_{k\in K}\sum_{(i,j)\in A} d_{ij}x_{ij}^k \tag{1}$$

$$subject\ to \sum_{k\in K}\sum_{j\in N} x_{ij}^k = 1, \forall\ i \in \mathrm{P}, \tag{2}$$

$$\sum_{j\in N} x_{ij}^k - \sum_{j\in N} x_{n+i,j}^k = 0, \forall\ i \in \mathrm{P}, k \in K, \tag{3}$$

$$\sum_{j\in N} x_{ij}^k = 1, \qquad \forall\ k \in \mathrm{K}, \quad \forall\ i = i_1 \in \mathrm{P}, \tag{4}$$

$$\sum_{j\in N} x_{ji}^k - \sum_{j\in N} x_{ij}^k \ = 0, \forall\ i \in \mathrm{P}\ \cup \mathrm{D}\,, \qquad k \in \mathrm{K}, \tag{5}$$

$$\sum_{i\in N} x_{ij}^k = 1,\ \ \forall k \in \mathrm{K},\ \ \forall j = j_m \in \mathrm{P}\,, \tag{6}$$

$$Q_j^k \geq (Q_i^k + q_j)x_{ij}^k, \forall (i,j) \in A, k \in K, \tag{7}$$

$$\max\{0, q_i\} \leq Q_i^k \leq \min\{Q, Q + q_i\}, \forall i \in N, k \in K, \tag{8}$$

$$\sum_{(i,j)\in A} t_{ij}x_{ij}^k + \sum_{i\in P} s_i + \sum_{n+i\in D} s_i \leq T^k, \qquad \forall k \in \mathrm{K} \tag{9}$$

$$x_{ij}^k \in \{0,1\}, \forall (i,j) \in A, k \in K. \tag{10}$$

The objective function minimises the total travel distance (1). Constraints 2 and 3 ensure that each pickup node is visited exactly once, and that for every request the pickup and the delivery node are visited by the same vehicle. Constraints 4, 5, and 6 define a path structure for every vehicle: constraints 4 and 6 ensure that each route starts at the first warehouse location($i_1 \in \mathrm{P}$) and ends at the last warehouse location ($j_m \in \mathrm{P}$), and constraints 5 are flow conservation constraints for each node $i \in P \cup D$. Constraints 7 and 8 compute the load variables according to the arcs used in the solution and ensure that the vehicle capacity is respected. Constraints 9 are the route duration constraints, ensuring that the total travel time and the required changing time of each vehicle does not exceed the maximum travel time T^k. Constraints 10 ensure that all x_{ij}^k are either 0 or 1.

4.2. Explanation of adapting the Nearest Neighbour Heuristic to the BSK flow-VRP

We use an adapted version of the Nearest Neighbour Heuristic to solve the BSK flow-VRP. The adapted NNH solves one instance at a time. This section explains how we adapt the NNH to the BSK flow-VRP. The goal of the NNH is to assign fixtures to a train (k) for a specific instance, based on adding the fixture that is the Nearest Neighbour. We keep assigning fixtures until all fixtures are assigned. Fixtures are assigned to a train until the maximum travel time or the maximum capacity of that train has reached.

Figure 4.1 on Page 43 shows the flowchart with the steps of the NNH. The choices of the NNH described in this section, are substantiated in Chapter 5 with experimental results. In Figure 4.1, the total travel distance is shortened to total distance. The first step is to import the instance data, which consists of the time information and the fixture information of that instance. At the beginning of the NNH, this data also shows the list of unassigned fixtures. The second step is to set train k to 0, which is the first train. Next, at step 3 we initialise the empty train k, through initialising the empty routes: Route_WH, Route_LL, Route_WHBack, and the Total Route. At step 3, we also set the CurrentNode to 0, which means that the empty train starts from the warehouse. We also set the used capacity, the total travel distance, and the total travel time to 0 since it is an empty train (step 3).

The Nearest Neighbour is the fixture that, when added after the CurrentNode of Route_LL on train k, results in the lowest total travel distance of the new Total Route. To find the Nearest Neighbour, we construct at step 4 a table that calculates the total travel distance, the total travel time, and the used capacity for the new Total Route. These calculations are only executed for the unassigned fixtures and are based on the new Total Route when fixture n is added to train k. Fixture n is added after the CurrentNode of Route_LL on train k. For train k, the Total Route consists of the route inside the warehouse to pick up the full fixtures (Route_WH), the route at the assembly line to deliver the full fixtures and to pick up the empty fixtures (Route_LL), and the route inside the warehouse to deliver the empty fixtures (Route_WHBack). At step 4, the total travel distance is calculated for the new Total Route for each of the unassigned fixtures. In case the train is empty, the total travel distance is only the travel distance between the warehouse location and the line location of that fixture, instead of the total travel distance from the new Total Route. The routes inside the warehouse (Route_WH and Route_WHBack) depend on the used loading constraints. When we use No Policy, the shortest route inside the warehouse is determined. Besides that, we apply Adapted Partial LIFO or Strict LIFO from the warehouse (the pickup of full fixtures) to the assembly line (the delivery of full fixtures and the pickup of empty fixtures).

Step 4 calculates per unassigned fixture the total travel distance, the total travel time and the used capacity for the new Total Route. This might result in new Total Routes that violate the maximum travel time or the maximum capacity. Therefore, we delete fixtures that are not feasible because of violating the maximum travel time or the maximum capacity (step 5). Afterwards, we check if there are feasible fixtures left (step 6). If this is not the case, we set train k to k+1. This way, the next empty train (k+1) is initialised (step 3) and the NNH continues with step 4.

In case there are feasible fixtures left (step 6), we add fixture n with the lowest total travel distance, which is the Nearest Neighbour, to train k (step 7). This means that fixture n is added after the CurrentNode in Route_LL of train k. After the Route_LL is updated (step 7), we also update the other routes, which consists of updating Route_WH, Route_WHBack, and the Total Route of train k (step 8). Moreover, we also update the total travel distance, the total travel time, and the used capacity of train k (step 8). Afterwards, we check if all fixtures are assigned (step 9). If this is not the case, we delete fixture n from the list of unassigned fixtures and we set CurrentNode to fixture n (step 10). Next, the NNH goes back to step 4, where a new table is constructed to determine the next Nearest Neighbour. We keep assigning fixtures until all fixtures are assigned and when all fixtures are assigned, the NNH stops.

The preceding describes how we tailor the standard Nearest Neighbour Heuristic, described in Section 3.5.1, to the BSK flow-VRP. The standard NNH starts and ends at the depot, while the routes of the BSK flow start and end inside the warehouse. Therefore, we tailor the NNH to the BSK flow-VRP: the NNH constructs the Total Route, which consists of the route to pick up full fixtures inside the warehouse (Route_WH), the route to deliver full fixtures at the assembly line and to pick up empty fixtures at the same line location (Route_LL), and the route to deliver empty fixtures to the warehouse (Route_WHBack). To summarise, the NNH constructs for each train the Total Route: Total Route = Route_WH + Route_LL + Route_WHBack.

4.3. Explanation of adapting Tabu Search to the BSK flow-VRP

We use an adapted version of Tabu Search to solve the BSK flow-VRP. Section 4.3.1 explains via a flowchart how we adapt Tabu Search to the BSK flow-VRP. Afterwards, Section 4.3.2 explains how we dynamically set the maximum computational time, so that we use the maximum computational time of 2 hours for Tabu Search in the best possible way.

4.3.1. Flowchart of adapting Tabu Search to the BSK flow-VRP

Figure 4.2 on Page 43 shows the flowchart of Tabu Search that is adapted to the BSK flow-VRP. Tabu Search starts with the solution from the Nearest Neighbour Heuristic, which is the Initial Solution S_0. Tabu Search, like the NNH, solves the BSK flow-VRP one instance at a time. Moreover, since Tabu Search is executed after the NNH, the same data about the instance is available. The first step of Tabu Search is the initialisation of the Initial Solution S_0 and the Tabu List.

Next, we set the Best Solution S* and the Current Solution S equal to the Initial Solution S_0 (step 2). At step 3, we create a candidate table of neighbours to the Current Solution S, by executing the neighbourhood operators. The candidate table contains the admissible neighbourhood solutions, based on the Inter-route swap, the Inter-route move, the Intra-route swap, and the Intra-route move. The candidate table contains for each candidate the new Total Routes after a swap or move is executed, as well as the trains and the unique fixture numbers that are involved. Furthermore, the candidate table contains the total travel distance, which is the total travel distance of all Total Routes in the instance. Moreover, the candidate table contains for each candidate their individual travel time and the used capacity. This way, admissibility of the neighbourhood solution is checked: a neighbour is only in the candidate table if the maximum travel time and the maximum capacity constraints are not violated. Moreover, a neighbour obeys the used loading constraints. So, in case the LIFO loading constraints are used, this means that the route inside the warehouse (Route_WH) is the reverse from the route at the assembly line (Route_LL).

The next step, step 4, is to select the best Solution S’ from the candidate table. The selection of the best Solution S’ is based on the objective function, which is to minimise the total travel distance. Therefore, we select the Solution S’ from the candidate table that has the lowest total travel distance. Afterwards, step 5, we check if Solution S’ is in the Tabu List. In case Solution S’ is not Tabu, we check if Solution S’ is better than the Best Solution S* (step 8). If Solution S’ is in the Tabu List, we check if the Tabu status can be overridden (step 6). The Tabu status can be overridden by the aspiration criterion. We use the classical aspiration criterion, which is that the Tabu status of an exchange is overridden if it leads to a neighbourhood solution that is better than the best-known solution. So, if a Solution S’ is Tabu but the total travel distance of that solution is lower than the total travel distance of the Best Solution S*, the Tabu Solution S’ is better than the best-known solution, and the Tabu status will therefore be overridden. In case Solution S’ is in the Tabu List and the Tabu status can be overridden (steps 5 and 6), we check if Solution S’ is better than the Best Solution S* (step 8). If the Tabu status of Solution S’ cannot be overridden, Solution S’ is deleted from the candidate table (step 7) and Tabu Search goes back to step 4.

At step 8 we check if Solution S’ is better than the Best Solution S*. If this is the case, we update the Best Solution S*: Best Solution S* = Solution S’ (step 9). Afterwards, we update the Tabu List, and we update the Current Solution S, by setting it equal to Solution S’ (step 10). In case Solution S’ is not better than the Best Solution S* (step 8), only the Tabu List and the Current Solution are updated (step 10). This way, step 9, the update of the Best Solution S* is skipped when Solution S’ is not better than the Best Solution S*. At step 11, we check if the stopping criterion or the time criterion is satisfied. If this is not the case, a next iteration is started and the candidate table of neighbours to the Current Solution is created. In case the stopping criterion or the time criterion is satisfied, Tabu Search ends. When the stopping or the time criterion is satisfied, the best solution during the search is returned. Appendix H.3 shows an example of neighbours to the initial solution and a part of the candidate table, which is part of the process of Tabu Search.

Section 4.2 explained how we tailor the NNH to the BSK flow-VRP by incorporating the Route_WH, the Route_LL, and the Route_WHBack, into the NNH. This incorporation results for each train in the Total Route: Total Route = Route_WH + Route_LL + Route_WHBack. Similarly, the new route of each candidate after executing a swap or move during Tabu Search, also consists of the preceding Total Route. This way, we also tailor Tabu Search to the BSK flow-VRP.

4.3.2. Dynamic computational time: use of Tabu List Length and Extra Length

To be of practical use for Scania Production Zwolle, the maximum computational time of executing Tabu Search for a whole production day is 2 hours. The dataset of the whole production day consists of 1965 fixtures and Table 4.1 shows the 6 available sub datasets. Tabu Search solves one instance at a time: one time period of 1 principle with 1 type of trailer. When we import a sub dataset that contains all time periods, Tabu Search solves one time period of the sub dataset at a time. For example, Principle 6 consists of 23 time periods. For this sub dataset, Tabu Search starts with solving time period 0 and once that time period is finished, it goes to the next time period. Solving the next time period is initialised until all time periods of the sub dataset are solved.

Available subdatasets	Number of time periods	Number of fixtures per sub dataset	Maximum computational time per sub dataset	Maximum computational time per time period of each sub dataset
Principle15minutes_Type1	69	944	00:57:39	00:00:50
Principle15minutes_Type2	69	399	00:24:22	00:00:21
Principle3_Type1	46	119	00:07:16	00:00:09
Principle3_Type2	46	332	00:20:16	00:00:26
Principle4	34	76	00:04:38	00:00:08
Principle6	23	95	00:05:48	00:00:15

Table 4. 1. Overview of maximum computational time per sub dataset

One way of executing Tabu Search is to use a static computational time. If we use a static way, we calculate the maximum computational time per sub dataset as: $\frac{number\ of\ fixtures\ in\ sub\ dataset}{total\ number\ of\ fixtures} * 7200$. The 7200 in the formula is the total seconds available when the maximum computational time is 2 hours. For Principle 6, the static computational time is 5 minutes and 48 seconds. Since this sub dataset consists of 23 time periods, the static maximum computational time per time period is 15 seconds. Using the static computational time results in executing each time period for the same length, while there is a possibility that the solution has not been improved for several iterations.

To make sure that we use the maximum computational time in the best possible way, we set the computational time dynamically. At the beginning of running a sub dataset, we calculate the maximum computational time of that sub dataset and the maximum computational time per time period. During each time period, we keep track of the calculation time that Tabu Search spends. We also keep track of the number of executed iterations per time period via an iteration counter. Tabu Search ends in time period t, if the stopping criterion or the time criterion is satisfied. This means that Tabu Search ends in time period t if the maximum computational time is reached, or because of the stopping criterion. Once Tabu Search ends in time period t, Tabu Search starts on the next time period (t+1). At the beginning of the next time period, we recalculate the available computational time for the sub dataset as $new\ computational\ time\ of\ subdataset = computational\ time\ of\ sub\ dataset - time\ spent$. Next, we recalculate the computational time of the time period: $new\ computational\ time\ of\ time\ period = \frac{new\ computational\ time\ of\ sub\ dataset}{time\ periods\ left}$. This way, we dynamically set the calculation time per time period, based on the actual time spent in the previous time period(s). Because of that, it becomes possible to execute more iterations in an instance that improves, in comparison to when we would use a static running time. This is substantiated by Table J.6 in Appendix J. This table shows that executing Tabu Search for Principle 6 requires only 4 minutes and 43 seconds, while using a static computational time would require 5 minutes and 48 seconds. An important notice is that we run the following sub datasets first: Principle15minutes_Type2, Principle3_Type1, Principle3_Type2, Principle 4, Principle 6. This way, we know the total computational time of Tabu Search of those sub datasets, and the remainder of the 7200 seconds can be used to execute the largest sub dataset: Principle15minutes_Type1.

Before we can execute Tabu Search, we have to determine the length of the Tabu List: the Tabu List Length. Using the stopping criterion is based on the total of the Tabu List Length and the Extra Length. Section 5.5 substantiates the choice for the best Tabu List Length and the best Extra Length. We use the Tabu List Length and the Extra Length to prevent Tabu Search from executing iterations in a time period that has not found improvements for the previous *x* iterations, where *x* is equal to the total of the Tabu List Length and the Extra Length. In case there are no improvements in the total travel distance for the previous *x* iterations, the iteration counter is set to the stopping criterion. The stopping criterion is a large number. Because of that, the stopping criterion is satisfied, and Tabu Search stops for that time period (t), and Tabu Search starts executing the next time period (t+1).

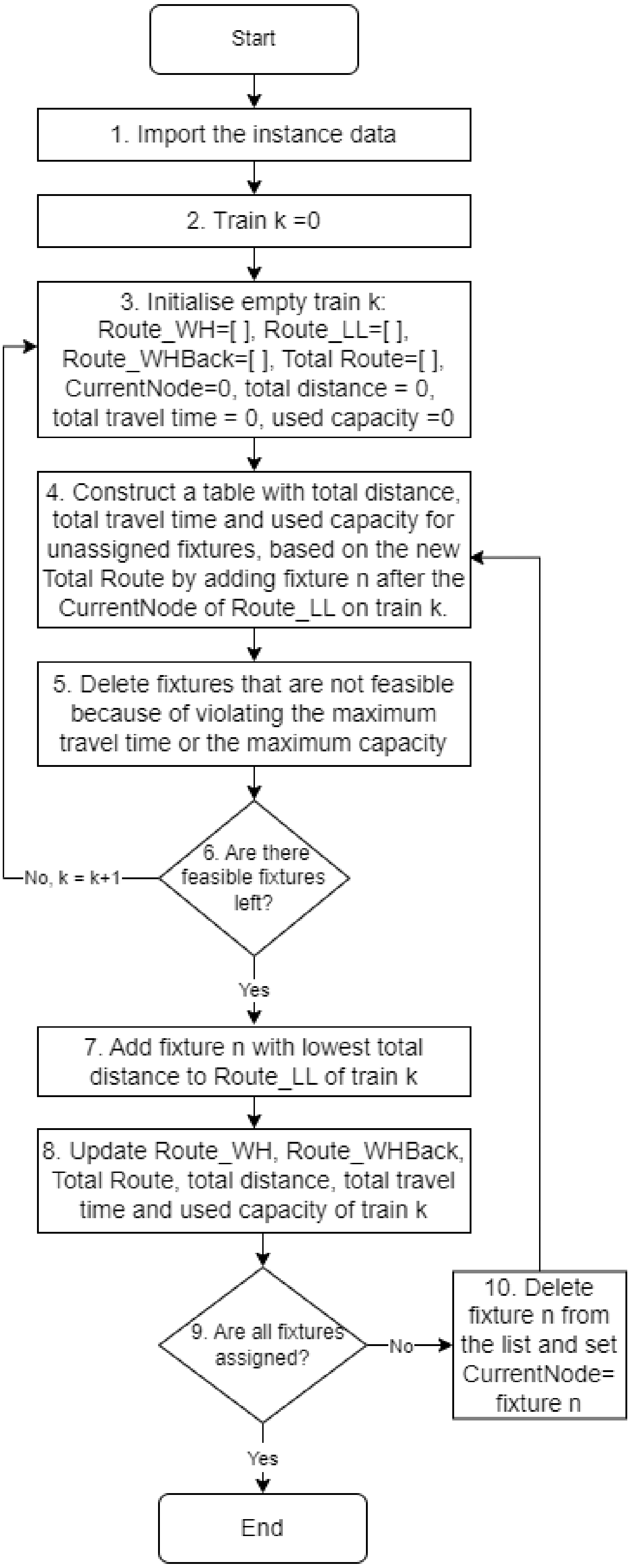

Figure 4. 1. Flowchart of the Nearest Neighbour Heuristic that is adapted to the BSK flow-VRP

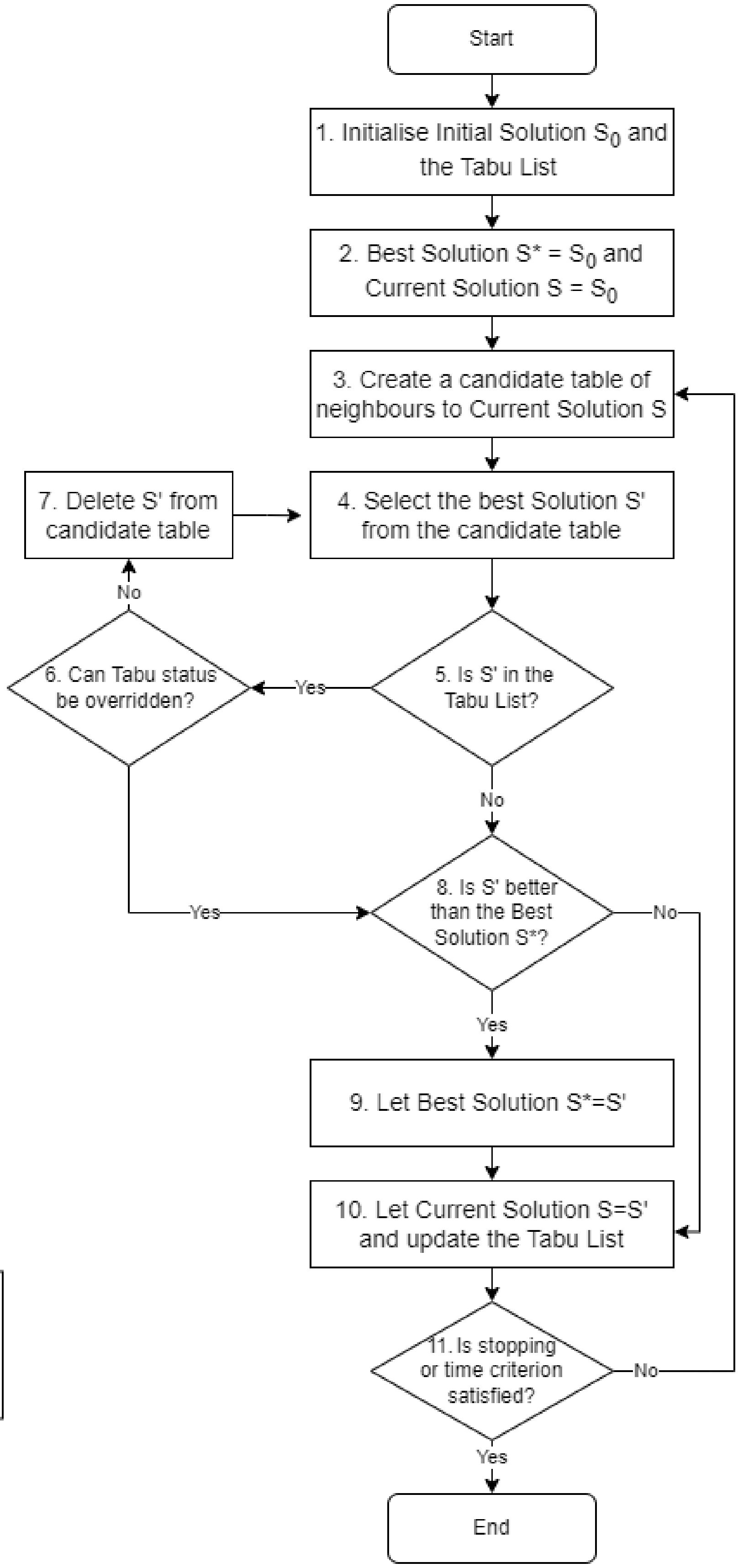

Figure 4. 2. Flowchart of Tabu Search that is adapted to the BSK flow-VRP

4.4. Description of the solution approach for the BSK flow-VRP

Section 4.1 focussed on formulating the model of the BSK flow-VRP. To solve the BSK flow-VRP, we use the Nearest Neighbour Heuristic (Section 4.2) and Tabu Search (Section 4.3). An important notion is that both algorithms are adapted to the BSK flow-VRP. Section 4.4.1 describes the important parts of the solution approach for the BSK flow-VRP. Next, Section 4.4.2 gives an example of a solution from the NNH and explains the used Key Performance Indicators.

4.4.1. Important parts of the solution approach for the BSK flow-VRP

The solution approach for the BSK flow-VRP consists of importing data, executing the Nearest Neighbour Heuristic and Tabu Search, and generating output. Both the NNH and Tabu Search are adapted to the BSK flow-VRP. Figure 4.3 gives a schematic overview of the inputs, processes, and outputs of the solution approach for the BSK flow-VRP. To be of practical use for Scania Production Zwolle, executing Tabu Search for one complete day of input data, has to be finished within 2 hours.

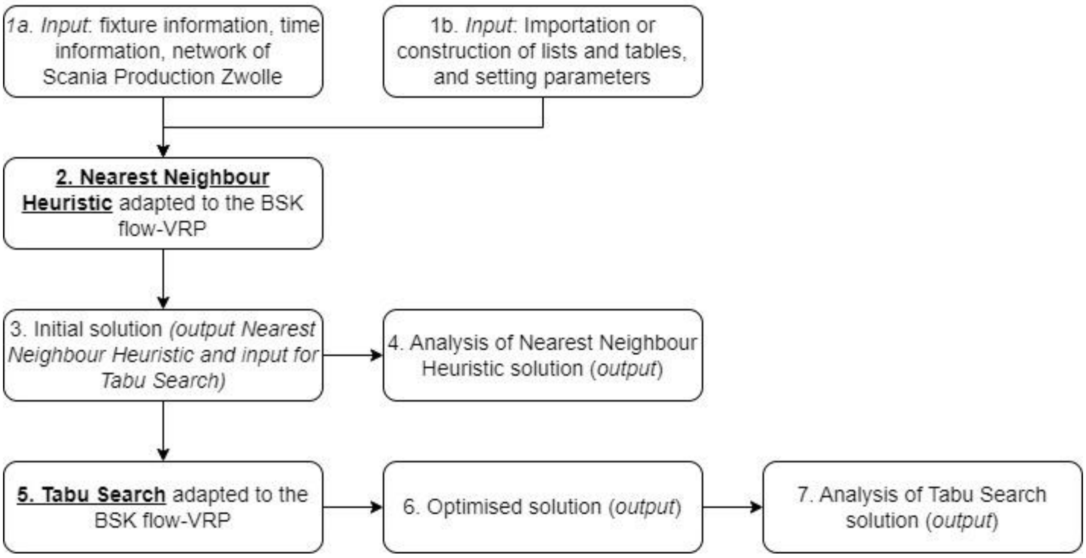

Figure 4. 3. Flowchart of the solution approach for the BSK flow-VRP

The first step of the solution approach is the input step, which consists of steps 1a and 1b. Step 1a consists of importing the following input data into the solution approach: the fixture information, the time information, and the network of SPZ. Importation or construction of lists and tables, and setting parameters is also part of the input step (step 1b). Afterwards, the Nearest Neighbour Heuristic is executed (step 2). Executing the NNH results in output: the initial solution (step 3), which we analyse (step 4). Both the initial solution as well as the analysed solution of the NNH, are output of the solution approach for the BSK flow-VRP. After the NNH is executed, we execute Tabu Search. Tabu Search starts with the initial solution from the NNH. Executing Tabu Search (step 5), results in the optimised solution (step 6), which is also analysed (step 7). The optimised solution and the analysed solution from Tabu Search are also output of the solution approach for the BSK flow-VRP. Appendix I explains more detailed the inputs and the outputs of the solution approach for the BSK flow-VRP.

4.4.2. Route example of the solution approach for the BSK flow-VRP

Our solution approach creates individual train routes that are generated automatically and saved individually per figure. Figure 4.4 shows the route of train 0 after the Nearest Neighbour Heuristic is executed for time period 0, Principle15minutes with trailer type 2. This figure shows the total travel distance (CurrentDistance), the total travel time (CurrentTime), the used capacity (CurrentCapacity), the used trailer (CurrentTrailer), the physical fill rate (FillRateCapacity), and the time fill rate (FillRateTime). For readability, the plot only shows the warehouse nodes so the Route_WH and the Route_WHBack are the same in this plot. Our output tables show the following Key Performance

Indicators: the total travel distance (km), the total travel time (decimal), the average physical fill rate, the average time fill rate, and the average Just-In-Time percentage. Furthermore, our output tables show the maximum, the minimum, and the average number of trains needed as well as the computational time of executing the NNH and Tabu Search.

Our solution approach calculates for each fixture the expected time it is delivered at the assembly line. Moreover, we know for each fixture the lower bound of their time period and their logistical tact time. Based on this information, we calculate the JIT percentage: $JIT\ percentage = \frac{expexted\ time\ of\ delivery - lower\ bound\ of\ time\ period}{logistical\ tact\ time} * 100$. The JIT percentage shows per fixture the percentage of logistical tact time that is needed to deliver the fixture at the assembly line. Based on the JIT percentages of all fixtures, the average JIT percentage is calculated. The average JIT percentage of the current train schemes is 37.7%, which we compare with the outcome of our experiments.

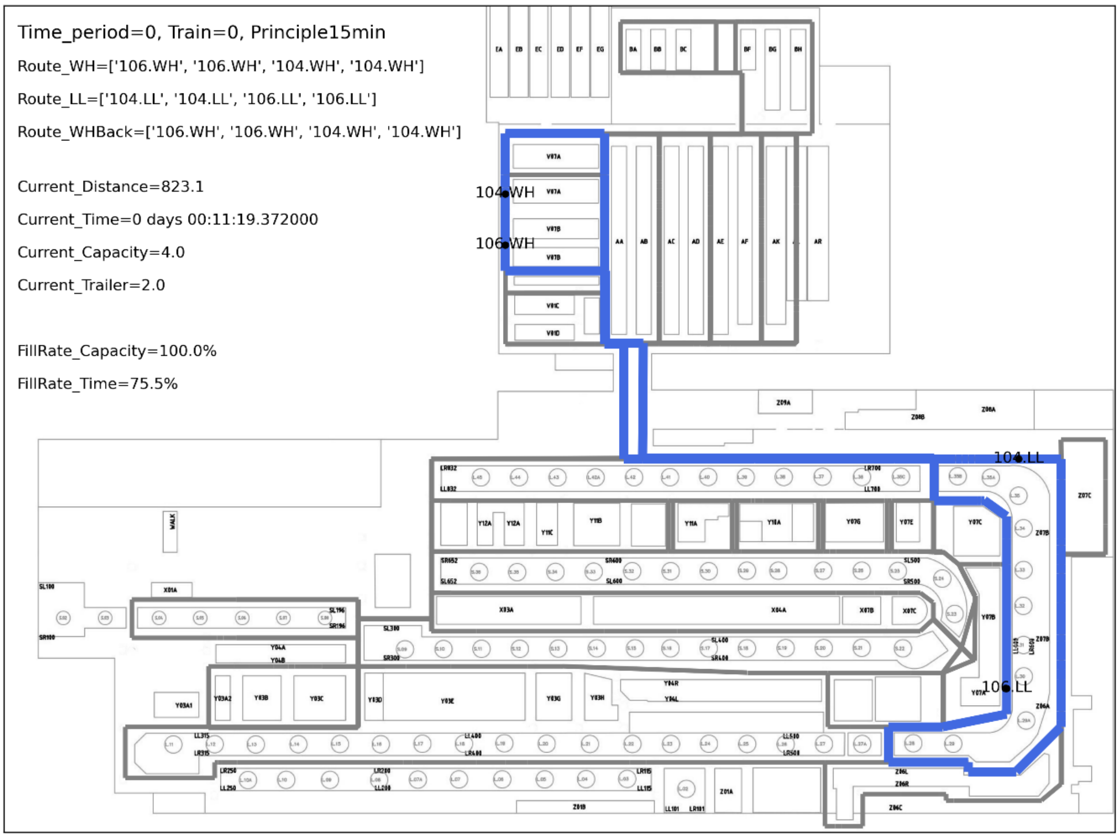

Figure 4. 4. Solution example of No Policy loading constraints for time period 0, Principle15minutes with trailer type 2

4.5. Verification and validation of our solution approach

Verification means that the conceptual model has been transformed into a computer model satisfactorily (Robinson, 2014). Moreover, validation means that the model is sufficiently accurate for the purpose at hand (Robinson, 2014). We use algorithms to solve the BSK flow-VRP: the Nearest Neighbour Heuristic and Tabu Search, and both are adapted to the BSK flow-VRP. Our solution approach consists of importing the data, executing the algorithms, and generating the output. This way, we have transformed the BSK flow-VRP model into a solution approach that we execute in Python. Therefore, this section explains the verification and the validation of our solution approach.

4.5.1. Verification

To make sure that the conceptual model has been transformed into a computer model satisfactorily, we have used the following verification methods: debugging, visualisation of output, and meetings with the stakeholders of Scania Production Zwolle.

The first verification method is debugging. Debugging in Python is possible by placing breakpoints in the code. By placing breakpoints, we can step through the code and check if the code works as we expect. Moreover, by visualising output of the solution approach, we can also check if the solution approach works properly. Examples of output visualisations are the Fixtures plots, the Possible Fixtures plots, and the Route plots. Section 4.4.2 shows an example from our solution approach, which shows the individual train scheme and the used KPIs. Moreover, Appendix H.1 explains the construction of a route via the NNH, which includes the output visualisations of our solution approach.

Lastly, we have used meetings with the stakeholders of SPZ to verify that our solution approach works satisfactorily. We had meetings with the BSK flow engineers, the company supervisors, the team leaders, and the supervisors of the Platforms LB1 and LB2. The first meetings were about the network of SPZ. Afterwards, we had meetings about the NNH. Furthermore, we also had meetings about Tabu Search to show that it optimises the NNH outcomes. During those meetings we received feedback that we incorporated into the solution approach.

4.5.2. Validation

The meetings with the stakeholders of the BSK flow were used to verify our solution approach, but it was also a way to validate our solution approach. The stakeholders of the BSK flow have a lot of knowledge about the BSK flow. Therefore, we showed the results of the solution approach to check if the outcomes are sufficiently accurate, which is confirmed by the stakeholders.

Another way of validating our solution approach is that we used the current train schemes, which are manually created. We used those train schemes as input for our solution approach to substantiate the choice for the fixture changing time and the extra time for the special crossings. In reality, a BSK flow train must sometimes wait for the special crossings. However, in our solution approach, the train always receives extra time for using the special crossings: the special crossing time. Because of that, we use a different extra time for the special crossings. We analysed the current train schemes with different special crossing times, while starting out with 90 seconds as the fixture changing time. The BSK flow engineers use 90 seconds as the fixture changing time. We varied the extra time for the special crossings between 0 and 20 seconds.

We used our solution approach to construct the routes of the current train schemes. This way, we constructed for each train from the current train schemes, the manually created routes. This results in output that shows the total travel time of each route that also incorporates the 90 seconds changing time per fixture. For each route, we checked if the total travel time was lower than or equal to the maximum travel time. Table 4.2 shows that using 90 seconds as the fixture changing time results in route violations, even when we use a low special crossing time. Route violations are routes that require more travel time than the available logistical tact time of that route. Therefore, we calculated per special crossing time the maximum fixture changing time that results in 0 route violations.

Special Crossing Time (seconds)	Overview of maximum fixture changing time that has 0 route violations		Overview of the largest travel time of an individual fixture (fixture number 90)		
	Number of route violations with 90 seconds as the fixture changing time	Maximum fixture changing time that has 0 route violations (seconds)	Largest travel time of an individual fixture	Additional fixture changing time (4 fixtures)	Total Travel Time
0	5	77.9	00:09:03	00:05:12	00:14:15
2.5	5	73.5	00:09:21	00:04:54	00:14:15
5	5	69.2	00:09:38	00:04:37	00:14:15
10	8	60.4	00:10:13	00:04:02	00:14:15
15	11	51.7	00:10:48	00:03:27	00:14:15
20	11	42.9	00:11:23	00:02:52	00:14:15

Table 4. 2. For different special crossing times: overview of maximum fixture changing time that has 0 route violations, and overview of the largest travel time of an individual fixture (fixture 90)

During one of the meetings with the BSK flow stakeholders, we showed these results and in consultation with the BSK flow engineers, we have chosen for the setting 2.5 seconds special crossing time and 73.5 seconds as the fixture changing time. This way, we have the highest fixture changing time, while also having a special crossing time. Another important notion is that, during this analysis, we already saw improvements to the current train schemes. Our solution approach created routes that had a lower total travel distance than the manually created routes. Therefore, we had to manually change these routes in our solution approach in order to recreate the manually created routes.

After the analysis of the current train schemes, we also analysed the individual fixture routes. Fixture number 90 turns out to have the largest travel time of the individual fixtures. Figure 4.5 shows the plot of fixture number 90, showing the travel time is 561.01 seconds, which corresponds to 00:09:21. The total travel time, after adding the additional fixture changing time of 4 fixtures, is 00:14:15 as Table 4.2 shows. In other words, there are 45 seconds travel time left, when we consider the smallest logistical tact time of 15 minutes, from Principle 1 (Pollux) and Principle 2 (Castor). The analysis of the individual fixture routes shows that the largest route can be accomplished within 15 minutes. Because of that, we can execute an experiment that uses 1 principle: Principle 1 for Pollux and Principle 2 for Castor, resulting in 15 minutes as the logistical tact time. When using 1 principle, the upper bound of the time period remains the same, but the lower bound changes. The lower bound, which is the time a fixture can be picked up at the warehouse, becomes the upper bound minus 15 minutes.

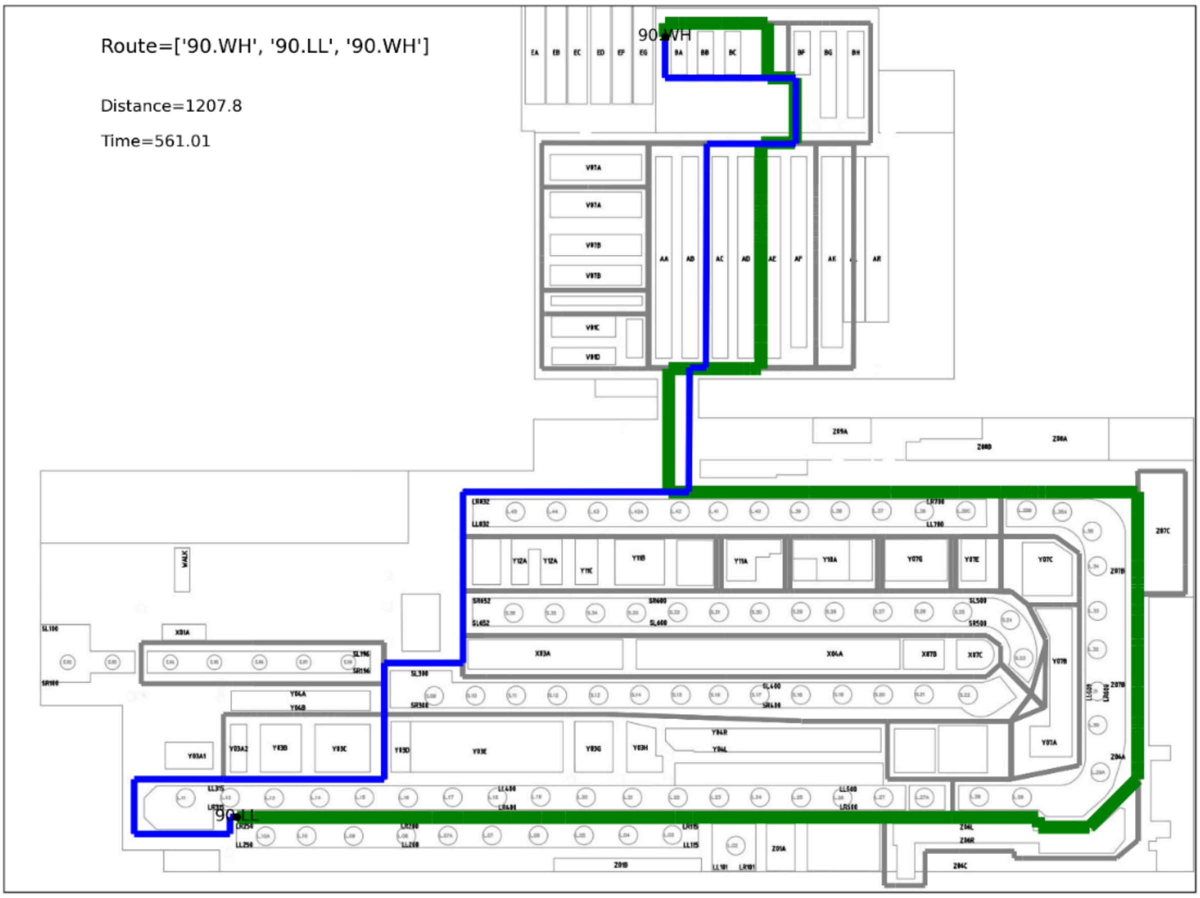

Figure 4. 5. Plot of fixture 90: individual route

4.6. Conclusion

This chapter described the formulation of the BSK flow-VRP model, which is the Vehicle Routing Problem with Pickup and Delivery and loading constraints for internal logistics. Regarding the loading constraints, we incorporate the following strategies: No Policy, Adapted Partial LIFO, and Strict LIFO. Our model focusses on minimising the total travel distance of the BSK flow, which might result in a reduction in the required number of trains used by the BSK flow. When fewer trains are needed, this results in a cost reduction which is the economic advantage Scania Production Zwolle wants. The model should be able to solve within a reasonable computational time. To be able to use our model in the future, our model needs to be adaptable. Moreover, the model needs to be able to deal with changes in tact times. Every fixture that is present in the dataset that we run, needs to be assigned to a train. The model should be able to make fixed and flexible routes, depending on the input data. Furthermore, our model should incorporate realistic travel distance and travel time between locations.

To solve the BSK flow-VRP, we use the Nearest Neighbour Heuristic and Tabu Search. Via flowcharts, we explained the NNH and Tabu Search. An important notion is that we tailored the NNH and Tabu Search to the BSK flow-VRP. Our solution approach to solve the BSK flow-VRP, consists of importing data, executing the NNH and Tabu Search, and generating the output. The standard NNH starts and ends at the depot, while the routes of the BSK flow start and end inside the warehouse. Therefore, we tailor the NNH to the BSK flow-VRP by constructing for each train the Total Route: Total Route = Route_WH + Route_LL + Route_WHBack. Similarly, the new route of each candidate after executing a swap or move during Tabu Search, also consists of the preceding Total Route. This way, we also tailor Tabu Search to the BSK flow-VRP. Based on the preceding, we tailored the concepts and methods from literature to our problem.

Our solution approach should be able to solve the BSK flow-VRP in a reasonable computational time. This requirement is especially relevant for optimising the results via Tabu Search. To be of practical use for SPZ, Tabu Search should be finished within 2 hours. We verified our solution approach through debugging, visualisation of output, and meetings with the stakeholders of SPZ. Moreover, the meetings with the stakeholders also contributed to the validation of our solution approach. Furthermore, we also used the current train schemes that were created manually, to validate our solution approach.

5. Evaluation of the solution design

This chapter focusses on the solution evaluation by answering Research Question 4.

RQ4: How does the solution approach perform for different experiments?

- What are the different experiments that we evaluate?
- How does the solution approach perform for each experiment?

First, Section 5.1 describes the data instances that we use in our experiments. Next, we describe in Section 5.2 the experimental design. Sections 5.3 to 5.6 describe the results of experiments 1 to 4 that we use to substantiate the settings of our solution approach. Afterwards, Section 5.7 explains the results of experiments 5 to 12. Lastly, Section 5.8 concludes this chapter by answering RQ 4.

5.1. Data instances

Section 2.5 explained that there are discrepancies between datasets 1 and 2, in comparison with dataset 3. Because of the many discrepancies, we use dataset 3 for the evaluation of our solution design. Dataset 3 is an artificially generated dataset resembling the normal situation, which is based on the fixture overview and the individual train schemes from practice. We have the following sub datasets: Principle15minutes_Type1; Principle15minutes_Type2; Principle3_Type1; Principle3_Type2; Principle 4; Principle 6. By using these sub datasets, our solution approach solves one time period after another of the same sub dataset. This way, our solution approach solves instances separately.

There are two collections of data available from dataset 3: dataset 3.1 and dataset 3.2. Dataset 3.1 is a small dataset with data of 4 time periods of each principle and both types of trailers. Dataset 3.1 contains in total 172 fixtures that need to be routed. We use dataset 3.1 to substantiate the settings of our solution approach. Dataset 3.2 is a large dataset of a full production day, which contains data from all time periods per principle and both types of trailers. The dataset of a full production day consists of 1965 fixtures. We use dataset 3.2 to generate results for experiments 5 to 12.

5.2. Experimental design

We perform all experiments on a computer with an i7-10700 processor of 2.90 GHz and 16.0 GB RAM, which is representative for the laptops used by the BSK flow engineers. Table 5.1 shows an overview of all experiments. The first four experiments are executed to substantiate choices of our solution approach. Experiments 5 to 12 are used to evaluate our solution approach. For experiments 6 to 12, we change the used planning restrictions. Based on the analysis of the results of experiments 5 to 12, we advise Scania Production Zwolle on how to improve the routing of the BSK flow. In the tables with the results of the experiments, we shorten total travel distance (km) to total distance (km). Furthermore, we shorten in the tables Tabu Search to TS.

#	Experiment name	Used planning restrictions (Changes in planning restrictions in bold)		
#1	Experiments 1.1, 1.2, and 1.3 substantiate choices of the Nearest Neighbour Heuristic	5 principles	Fixed pick-up/delivery locations (warehouse)	2 type of trailers
#2	Determination of the location of Adapted Partial LIFO and Strict LIFO	5 principles	Fixed pick-up/delivery locations (warehouse)	2 type of trailers
#3	Determination of the Tabu List Length and the Extra Length	5 principles	Fixed pick-up/delivery locations (warehouse)	2 type of trailers
#4	Random policy	5 principles	Fixed pick-up/delivery locations (warehouse)	2 type of trailers
#5	Current settings of the BSK flow	5 principles	Fixed pick-up/delivery locations (warehouse)	2 type of trailers
#6	Use of 1 type of trailer	5 principles	Fixed pick-up/delivery locations (warehouse)	**1 type of trailer**
#7	Use of a marshalling area	5 principles	**Marshalling area**	2 type of trailers
#8	Use of 1 principle	**1 principle**	Fixed pick-up/delivery locations (warehouse)	2 type of trailers
#9	Use of a marshalling area and 1 type of trailer	5 principles	**Marshalling area**	**1 type of trailer**
#10	Use of a marshalling area and 1 principle	**1 principle**	**Marshalling area**	2 type of trailers
#11	Use of 1 principle and 1 type of trailer	**1 principle**	Fixed pick-up/delivery locations (warehouse)	**1 type of trailer**
#12	Use of a marshalling area, 1 principle and 1 type of trailer	**1 principle**	**Marshalling area**	**1 type of trailer**

Table 5. 1. Overview of all experiments

5.3. Experiment 1: substantiation of choices of the Nearest Neighbour Heuristic

Experiment 1 consists of experiments 1.1 (Section 5.3.1), 1.2 (Section 5.3.2), and 1.3 (Section 5.3.3). These experiments are used to substantiate choices of the Nearest Neighbour Heuristic. For each experiment we describe the purpose, the results, and the insights.

5.3.1. Experiment 1.1: substantiation for the choice of the first fixture

The purpose of experiment 1.1 is to substantiate which fixture is assigned to train k as the first fixture during the Nearest Neighbour Heuristic. Table 5.2 shows the results of experiment 1.1. This table shows that using only the travel distance from the warehouse to the line location for assigning the first fixture, yields better results than when using the total travel distance to assign the first fixture. Table 5.2 shows that this is the case for all three loading constraints. Therefore, we incorporate in our solution approach that assigning the first fixture is based on only the travel distance from the warehouse location to the line location.

Experiment	First Fixture: Total Travel Distance versus Warehouse to Line Travel Distance	Used loading constraints	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Average Just-In-Time percentage	Computational Time
E1.1.	Only Warehouse to Line Travel Distance	No Policy	662.9	5.24	12	6	10.64	74.97%	68.83%	36.05%	00:04:48
	Total Travel Distance	No Policy	712.1	5.51	13	6	10.80	73.90%	71.78%	37.28%	00:04:45
	Only Warehouse to Line Travel Distance	Adapted Partial LIFO	699.3	5.43	12	7	10.94	78.83%	75.17%	40.57%	00:03:48
	Total Travel Distance	Adapted Partial LIFO	740.4	5.66	13	7	11.16	71.26%	70.72%	37.18%	00:03:32
	Only Warehouse to Line Travel Distance	Strict LIFO	693.4	5.40	12	7	10.94	74.14%	69.95%	38.66%	00:03:30
	Total Travel Distance	Strict LIFO	742.8	5.67	14	6	11.06	71.82%	72.32%	39.14%	00:03:24

Table 5. 2. Results of experiment 1.1: assigning the first fixture

5.3.2. Experiment 1.2: substantiation for the choice of the Nearest Neighbour

After the first fixture is assigned to train k, we have to substantiate which fixture is assigned to train k as the Nearest Neighbour. Therefore, the purpose of experiment 1.2 is to substantiate this choice. Section 4.2 explained that the Nearest Neighbour Heuristic constructs the Total Route. The Total Route consists of the route to pick up full fixtures inside the warehouse (Route_WH), the route to deliver full fixtures at the assembly line and to pick up empty fixtures at the same line location (Route_LL), and the route to deliver empty fixtures to the warehouse (Route_WHBack). Based on this, we can assign a fixture as the Nearest Neighbour in the following ways:

- Route_LL: the fixture that has the lowest travel distance from the CurrentNode to their line location at the assembly line;
- Route_WH: the fixture that has the lowest travel distance from the CurrentNode to their warehouse location;
- Route_WHBack: the fixture that has the lowest travel distance from the CurrentNode to their warehouse back location;
- Total Route: the fixture that, when added after the CurrentNode of Route_LL on train k, results in the lowest total travel distance of the new Total Route.

Table 5.3 shows the results of experiment 1.2. This table shows that using the Total Route to determine the Nearest Neighbour yields the best results. Furthermore, using the Total Route to determine which fixture is the Nearest Neighbour also results in the lowest maximum number of trains and the lowest average number of trains. To conclude, the use of the Total Route to determine the Nearest Neighbour yields the best results for all three loading constraints. Therefore, we incorporate in our solution approach that determining the Nearest Neighbour is based on the Total Route.

Experiment	Nearest Neighbour	Used loading constraints	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Average Just-In-Time percentage	Computational Time
E1.2.	Total Route	No Policy	659.8	5.22	12	6	10.64	74.97%	68.61%	35.93%	00:04:43
	Route_LL	No Policy	666.4	5.24	13	6	10.67	74.62%	69.71%	36.91%	00:04:45
	Route_WHBack	No Policy	733.5	5.63	13	6	11.13	71.26%	70.93%	37.31%	00:04:22
	Route_WH	No Policy	727.8	5.60	13	6	11.03	71.94%	71.23%	37.52%	00:06:41
	Total Route	Adapted Partial LIFO	688.3	5.37	12	6	10.81	73.74%	69.14%	37.29%	00:03:37
	Route_LL	Adapted Partial LIFO	702.7	5.29	13	6	10.70	74.39%	70.14%	38.10%	00:03:45
	Route_WHBack	Adapted Partial LIFO	765.1	5.79	13	6	11.13	71.26%	73.04%	39.34%	00:03:46
	Route_WH	Adapted Partial LIFO	750.5	5.71	13	7	11.28	75.87%	76.82%	41.33%	00:03:39
	Total Route	Strict LIFO	693.4	5.40	12	6	10.75	74.14%	69.95%	38.66%	00:03:30
	Route_LL	Strict LIFO	712.3	5.49	13	6	10.91	72.75%	71.02%	39.74%	00:03:38
	Route_WHBack	Strict LIFO	750.7	5.71	13	7	11.28	75.87%	76.83%	41.14%	00:03:37
	Route_WH	Strict LIFO	800.9	5.98	13	6	11.35	69.91%	73.43%	40.10%	00:03:30

Table 5. 3. Results of experiment 1.2: substantiation of which fixture is the Nearest Neighbour

5.3.3. Experiment 1.3: substantiation of the objective function

The purpose of experiment 1.3 is to substantiate if we should minimise the total travel distance or the total travel time as the objective function. Table 5.4 shows the results of experiment 1.3. This table shows that using the minimum total travel distance as the objective function of the Nearest Neighbour Heuristic yields better results. When we use the NNH with the minimum total travel time as the objective function, there are differences in which fixture is the Nearest Neighbour in comparison with when we use the total travel distance as the objective function. This difference is because of the special crossings that add extra travel time. Because the special crossings add extra travel time, the fixture with the lowest travel distance is not automatically the fixture that has the lowest travel time. Therefore, there are differences in the choices of the Nearest Neighbour when we use the minimum total travel time instead of the minimum total travel distance as the objective function.

Experiment	Objective function: Minimise Total Travel Distance versus Total Travel Time	Used loading constraints	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Average Just-In-Time percentage	Computational Time
E1.3.	Minimise Total Travel Distance	No Policy	662.9	5.24	12	6	10.64	74.97%	68.83%	36.05%	00:04:48
	Minimise Total Travel Time	No Policy	693.5	5.41	14	6	11.05	72.11%	69.71%	37.23%	00:04:39
	Minimise Total Travel Distance	Adapted Partial LIFO	699.3	5.43	12	7	10.94	78.83%	75.17%	40.57%	00:03:48
	Minimise Total Travel Time	Adapted Partial LIFO	734.7	5.63	14	7	11.28	70.35%	70.46%	37.95%	00:03:39
	Minimise Total Travel Distance	Strict LIFO	693.4	5.40	12	7	10.94	74.14%	69.95%	38.66%	00:03:30
	Minimise Total Travel Time	Strict LIFO	742.7	5.67	14	7	11.29	70.26%	70.81%	39.07%	00:03:23

Table 5. 4. Results of experiment 1.3: substantiation of objective function

The preceding results in different routes which impact the number of trains that are required. At first glance, the result that minimising the total travel time leads to a higher total travel time seems counterintuitive. However, looking at the number of trains that are required on average as well as the maximum number of trains needed, show that minimising the total travel time results in the use of more trains in comparison to minimising the total travel distance. Because more trains are needed when we minimise the total travel time, the total travel distance and the total travel time is higher in comparison to when we minimise the total travel distance. Because of the preceding results, the objective function of the solution approach is to minimise the total travel distance.

5.4. Experiment 2: incorporation of Adapted Partial LIFO and Strict LIFO

The purpose of experiment 2 is to determine where we apply Adapted Partial LIFO and Strict LIFO in the routes of the BSK flow. The Total Route of the BSK flow consists of the following 3 parts: Route_WH, Route_LL, and Route_WHBack. Based on this, we can apply Adapted Partial LIFO and Strict LIFO:

1. from the route inside the warehouse (Route_WH) to the route at the assembly line (Route_LL), shortened to Warehouse to Line;
2. from the route at the assembly line (Route_LL) to the route inside the warehouse (Route_WHBack), shortened to Line to Warehouse Back;
3. apply at both 1 and 2, shortened to Both.

Table 5.5 shows the results of experiment 2. This table only shows the results of Adapted Partial LIFO and Strict LIFO because we only need to determine for those 2 strategies how to apply them in our solution approach. In case we use the No Policy strategy, we do not need to incorporate (Adapted Partial) LIFO into the solution approach. Table 5.5 shows that applying Adapted Partial LIFO and Strict LIFO from the Warehouse to the Line yields the best results, in comparison with applying Adapted Partial LIFO and Strict LIFO from the Line to the Warehouse Back or both. Because of that, our solution approach incorporates Adapted Partial LIFO and Strict LIFO strategies this way.

Experiment	Application of Adapted Partial LIFO and Strict LIFO	Used loading constraints	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Average Just-In-Time percentage	Computational Time
E2.	Warehouse to Line	Adapted Partial LIFO	699.3	5.43	12	7	10.94	78.83%	75.17%	40.57%	00:03:48
	Line to Warehouse Back	Adapted Partial LIFO	767.4	5.80	14	7	11.57	68.62%	70.34%	34.78%	00:03:36
	Both	Adapted Partial LIFO	783.3	5.99	14	8	11.80	67.37%	70.90%	36.33%	00:02:59
	Warehouse to Line	Strict LIFO	693.4	5.40	12	6	10.75	74.14%	69.95%	38.66%	00:03:30
	Line to Warehouse Back	Strict LIFO	798.8	5.96	14	7	11.72	67.99%	71.11%	34.26%	00:03:21
	Both	Strict LIFO	798.8	5.96	14	7	11.72	67.99%	71.11%	34.26%	00:03:21

Table 5. 5. Results of experiment 2: incorporation of Adapted Partial LIFO and Strict LIFO

5.5. Experiment 3: determination of Tabu List Length and Extra Length

Experiment 3 consists of 2 experiments: experiment 3.1 and experiment 3.2. The purpose of experiment 3.1 is to determine the length of the Tabu List. After we determined the best Tabu List Length, the purpose of experiment 3.2 is to determine the best Extra Length. We use the Tabu List Length and the Extra Length to prevent Tabu Search from executing iterations in a time period that has not found improvements for the previous x iterations, where x is equal to the total of the Tabu List Length and the Extra Length. In case there are no improvements in the total travel distance for the previous x iterations, the iteration counter is set to the stopping criterion. This way, we set a limit to the number of iterations without any improvement.

To determine the best Tabu List Length, we executed a long run for 4 time periods. A long run is when we execute our solution approach for a longer period of time. Table 5.6 shows the results of this experiment. This table shows that the Tabu List Length 6 has the lowest computational time for the best results in terms of total travel distance and total travel time. Because of that, Tabu List Length 6 is the best setting for the No Policy strategy of the current settings of the BSK flow.

Experiment	Tabu List Length	Extra Length	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E3.1. Tabu List Length	0 (NNH Total)	0 (NNH Total)	54.10	0.44	12	11	11.50	83.91%	72.24%	00:00:23
	3	0	42.43	0.38	12	11	11.50	83.91%	63.14%	00:39:53
	4		42.40	0.38	12	11	11.50	83.91%	63.14%	00:40:08
	5		42.40	0.38	12	11	11.50	83.91%	63.15%	00:40:11
	6		42.28	0.37	12	11	11.50	83.91%	62.95%	00:39:59
	7		42.28	0.37	12	11	11.50	83.91%	62.95%	00:40:03
	8		42.28	0.37	12	11	11.50	83.91%	62.95%	00:40:02

Table 5. 6. Experiment 3.1: overview of results per Tabu List Length for the current settings of the BSK flow

To determine the best Extra Length, we executed a long run for 4 time periods, while using the Tabu List Length 6. Using the Tabu List Length 6, we executed runs with different Extra Lengths between 0 and 7. Table 5.7 shows the results of these runs. This table shows that Extra Length 2 yields an improvement in comparison to Extra Lengths 0 and 1, while the Tabu List Length is 6.

Experiment	Tabu List Length	Extra Length	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E3.2. Extra Length	0 (NNH Total)	0 (NNH Total)	54.10	0.44	12	11	11.50	83.91%	72.24%	00:00:24
	6	0	45.80	0.39	12	11	11.50	83.91%	65.56%	00:06:54
		1	45.80	0.39	12	11	11.50	83.91%	65.56%	00:07:10
		2	44.20	0.38	12	11	11.50	83.91%	65.01%	00:07:47
		3	44.20	0.38	12	11	11.50	83.91%	64.99%	00:07:55
		4	44.20	0.38	12	11	11.50	83.91%	64.99%	00:08:04
		5	44.20	0.38	12	11	11.50	83.91%	64.99%	00:08:12
		6	44.20	0.38	12	11	11.50	83.91%	65.01%	00:08:27
		7	44.20	0.38	12	11	11.50	83.91%	64.99%	00:08:35

Table 5. 7. Experiment 3.2: overview of results per Extra Length for the current settings of the BSK flow

Table 5.8 shows per principle the results of the Nearest Neighbour Heuristic, and the results of Tabu Search when we use Extra Length 0 and Extra Length 2, while the Tabu List Length is 6. This table shows that the improvement of Extra Length 2 is traced back to Principle 6. Therefore, Extra Length 2 is the best setting for Principle 6. For the other principles, using Extra Length 2 while the Tabu List Length is 6, does not improve the solution further in comparison to using Extra Length 0 and Tabu List Length 6. Since using Extra Length 2 requires more computational time than Extra Length 0, while not further improving the results, we set the Extra Length for the other principles to 0.

Experiment	Used setting	Principle	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E3.2. Extra Length	NNH	Principle15minutes_Type1	19.10	0.15	5	4	4.50	76.39%	82.55%	00:00:11
		Principle15minutes_Type2	7.90	0.07	2	2	2.00	93.75%	81.85%	00:00:02
		Principle3_Type1	4.90	0.04	1	1	1.00	100.00%	64.28%	00:00:01
		Principle3_Type2	11.00	0.09	2	2	2.00	84.38%	68.24%	00:00:07
		Principle4	5.60	0.04	1	1	1.00	81.25%	53.10%	00:00:01
		Principle6	5.60	0.05	1	1	1.00	87.50%	36.60%	00:00:01
		Total	54.10	0.44	12	11	11.50	83.91%	72.24%	00:00:24
	Tabu List Length = 6, and Extra Length = 0	Principle15minutes_Type1	17.40	0.15	5	4	4.50	76.39%	77.61%	00:03:27
		Principle15minutes_Type2	7.50	0.07	2	2	2.00	93.75%	79.65%	00:00:43
		Principle3_Type1	4.20	0.04	1	1	1.00	100.00%	57.55%	00:00:14
		Principle3_Type2	7.10	0.06	2	2	2.00	84.38%	51.30%	00:01:33
		Principle4	4.00	0.04	1	1	1.00	81.25%	42.62%	00:00:30
		Principle6	5.60	0.05	1	1	1.00	87.50%	36.60%	00:00:26
		Total	45.80	0.39	12	11	11.50	83.91%	65.56%	00:06:54
	Tabu List Length = 6, and Extra Length = 2	Principle15minutes_Type1	17.40	0.15	5	4	4.50	76.39%	77.66%	00:03:29
		Principle15minutes_Type2	7.50	0.07	2	2	2.00	93.75%	79.65%	00:00:55
		Principle3_Type1	4.20	0.04	1	1	1.00	100.00%	57.55%	00:00:17
		Principle3_Type2	7.10	0.06	2	2	2.00	84.38%	51.30%	00:01:47
		Principle4	4.00	0.04	1	1	1.00	81.25%	42.62%	00:00:29
		Principle6	4.00	0.04	1	1	1.00	87.50%	29.75%	00:00:50
		Total	44.20	0.38	12	11	11.50	83.91%	65.01%	00:07:47

Table 5. 8. Experiment 3.2: overview per principle for Extra Length 0 and 2, while Tabu List Length is 6

This experiment gives insights in the procedure that we use to identify the best Tabu List Length and the best Extra Length for the No Policy strategy of experiment 5: the experiment with the current settings of the BSK flow. The same procedure is used to identify the best Tabu List Length and the best Extra Length for experiments 6 to 12. To conclude, the best Tabu Search settings for experiment 5 are:

- Principle 6: Tabu List Length is 6 and Extra Length is 2;
- Other principles: Tabu List Length is 6 and Extra Length is 0.

5.6. Experiment 4: random policy

First, Section 5.6.1 describes the purpose of the experiments with random policy. The random policy experiments consists of experiments 4.1, 4.2, 4.3, and 4.4. Based on the results in Section 5.6.2, Section 5.6.3 provides insights of the random policy experiments.

5.6.1. Purpose of the experiments with random policy

For experiment 4 we use two versions of the Nearest Neighbour Heuristic, and both versions are adapted to the BSK flow-VRP, which we shorten to the NNH. The purpose of experiment 4 is to get a reference point between executing the NNH without a smart way of adding the Nearest Neighbour (the random NNH), in comparison to when we add the Nearest Neighbour in a structured way (the standard NNH). Experiment 4 uses a random policy to construct the initial solution during the NNH. This means that we randomly assign fixtures as the Nearest Neighbour. The random initial solution is afterwards optimised via Tabu Search. Sections 5.6.2 shows for each experiment the results of the random policy, which consists of running each instance 5 times. This results in the minimum, the maximum, and the average results per Key Performance Indicator. For each experiment, we compare the results of the random policy with the results of the standard NNH and Tabu Search.

5.6.2. Results of the experiments with random policy: experiments 4.1, 4.2, 4.3, and 4.4

Table 5.9 shows the results for experiments 4.1, 4.2, 4.3, and 4.4 when using No Policy. The tables in Appendix J also show the Adapted Partial LIFO and the Strict LIFO results of these experiments.

Experiment 4.1 executes 4 time periods of all principles and both types of trailers. The results of experiment 4.1 show that the Tabu Search results after the random Nearest Neighbour Heuristic are worse, in comparison to the results of Tabu Search after the standard NNH. This is traced back to the larger principles (Principle15min_Type1 and Principle15min_Type2), which yields worse Tabu Search results in comparison to the results of Tabu Search after the standard NNH.

Experiment 4.2 executes 4 time periods of all small principles: Principle3_Type1, Principle3_Type2, Principle 4, and Principle 6. Table 5.9 shows that for 4 time periods, the random Tabu Search results of the small principles are better in comparison to the results of Tabu Search after the standard NNH.

Experiment 4.3 executes all time periods of the small principles. Table 5.9 only shows the results of Principle3_Type1 and Principle 4. This is because the random Tabu Search results of Principle3_Type1 and Principle 4 are comparable with the results of Tabu Search after the standard NNH, although the random runs require more computational time.

Experiment 4.4 executes a long run of all time periods of Principle3_Type2 and Principle 6. Table 5.9 shows that for Principle3_Type2 and Principle 6, the random Tabu Search results are comparable with the results of Tabu Search after the standard NNH, although the random runs require more computational time.

Experiment	Principle	Experiment name		Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E4.1. Random 4 time periods: all principles and types of trailers	All principles	No Randomness	NNH	53.30	0.43	12	11	11.50	87.21%	63.66%	00:00:54
		No Randomness	TS	47.20	0.40	12	11	11.50	87.21%	58.62%	00:09:05
		Random: minimum	NNH	72.50	0.54	15	12	13.25	78.43%	67.98%	00:00:25
		Random: minimum	TS	48.50	0.41	14	12	12.75	79.69%	53.71%	00:08:11
E4.2. Random 4 time periods: Small Principles	Small Principles	No Randomness	NNH	26.60	0.21	5	5	5.00	88.28%	54.66%	00:00:31
		No Randomness	TS	22.40	0.19	5	5	5.00	88.28%	48.68%	00:04:10
		Random: minimum	NNH	32.40	0.24	5	5	5.00	88.28%	60.97%	00:00:10
		Random: minimum	TS	19.20	0.17	5	5	5.00	88.28%	45.07%	00:03:35
		Random: maximum	NNH	35.70	0.26	5	5	5.00	88.28%	65.85%	00:00:21
		Random: maximum	TS	21.70	0.19	5	5	5.00	88.28%	47.91%	00:04:12
		Random: average	NNH	33.54	0.25	5	5	5.00	88.28%	62.81%	00:00:14
		Random: average	TS	20.72	0.18	5	5	5.00	88.28%	46.93%	00:03:52
E4.3. Random: all time periods of Principle 3 Type1 and Principle 4	Principle 3 Type 1	No Randomness	NNH	42.10	0.33	1	1	0.93	69.19%	48.74%	00:00:08
		No Randomness	TS	38.80	0.31	1	1	0.93	69.19%	46.03%	00:01:50
		Random: average	NNH	50.10	0.37	1	1	0.93	69.19%	55.28%	00:00:08
		Random: average	TS	38.84	0.31	1	1	0.93	69.19%	46.06%	00:01:54
	Principle 4	No Randomness	NNH	35.00	0.25	1	1	0.88	55.83%	40.72%	00:00:06
		No Randomness	TS	28.20	0.22	1	1	0.88	55.83%	34.74%	00:02:06
		Random: average	NNH	33.86	0.25	1	1	0.88	55.83%	39.67%	00:00:11
		Random: average	TS	28.38	0.22	1	1	0.88	55.83%	34.86%	00:03:03
E4.4. Long random run: all time periods of Principle 3 Type 2 and Principle 6	Principle 3 Type 2	No Randomness	NNH	116.40	0.91	2	2	1.87	84.01%	67.42%	00:01:15
		No Randomness	TS	75.50	0.69	2	2	1.87	84.01%	51.08%	00:16:55
		Random: minimum	NNH	141.00	1.04	2	2	1.87	83.05%	76.44%	00:00:41
		Random: minimum	TS	75.40	0.69	2	2	1.87	84.01%	51.04%	00:46:10
		Random: average	NNH	147.18	1.07	2.6	2	1.88	83.43%	79.25%	00:00:41
		Random: average	TS	75.62	0.69	2	2	1.87	84.01%	51.17%	00:49:33
	Principle 6	No Randomness	NNH	29.90	0.24	1	1	0.91	88.10%	36.99%	00:00:06
		No Randomness	TS	21.20	0.20	1	1	0.91	88.10%	29.81%	00:04:43
		Random: average	NNH	51.64	0.36	1	1	0.91	88.10%	55.12%	00:00:06
		Random: average	TS	21.20	0.20	1	1	0.91	88.10%	29.81%	00:13:34

Table 5. 9. Experiment 4: results of experiments 4.1, 4.2, 4.3, and 4.4.

5.6.3. Insights of the experiments with random policy

Overall, randomly running 4 time periods of the small principles (experiment 4.2), showed that Tabu Search yields better results in comparison to the Tabu Search results after the standard Nearest Neighbour Heuristic. The manual routing method results in fixed routes, and each train has 4 routes. So, if Scania Production Zwolle uses our solution approach for fixed routes, 4 time periods are executed. Therefore, if SPZ uses our solution approach to generate fixed routes, we advise SPZ to use the random policy of the NNH for the smaller principles, and the standard NNH for the larger principles. This is because for the larger principles (Principle15minutes_Type1 and Principle15minutes_Type2), the random starting solution yields worse Tabu Search results (experiment 4.1). Furthermore, running all time periods randomly of Principle3_Type1 and Principle 4, requires more computational time for comparable results (experiment 4.3). Similarly, executing all time periods randomly of Principle3_Type2 and Principle 6 for a longer time (experiment 4.4), requires more computational time for comparable results. To conclude, this experiment shows that executing all time periods of the NNH in a structured way (the standard NNH), yields better results in comparison to the random NNH. Experiments 5 to 12 execute all time periods. Therefore, for experiments 5 to 12, we use the standard NNH that is adapted to the BSK flow-VRP to generate the initial solution for Tabu Search.

5.7. Evaluation of our solution approach: experiments 5 to 12

To evaluate our solution approach, this section describes the results of experiments 5 to 12. Table 5.10 on Page 59 shows the results of experiments 5 to 12. For experiment 5, we show the Nearest Neighbour Heuristic results as well as the Tabu Search results. For experiments 6 to 12, we only show the improved results from Tabu Search. For experiment 5, our expectation is that our solution approach improves the routes of the BSK flow, which can be observed via a lower total travel distance, and this might result in a reduction in the required number of trains. Furthermore, our expectation for experiments 6 to 12 is that the change(s) in used planning restrictions also leads to improved routes.

5.7.1. Results of experiment 5: comparison of solution approach to current train schemes

The purpose of experiment 5 is to evaluate the results from our solution approach for the current settings of the BSK flow. This way, we compare the results of our solution approach with the Key Performance Indicators of the current train schemes.

Experiment 5 resembles the current settings of the BSK flow: the use of 2 types of trailers, fixed warehouse locations, and the use of 5 principles. The average number of trains needed after the Nearest Neighbour Heuristic varies between 10.64 and 10.81, which is lower than the 12 trains that the current train schemes need. Furthermore, after Tabu Search the average number of trains needed varies between 10.30 and 10.75. The average Just-In-Time percentage varies between 35.93% and 38.66%, which is comparable with the average JIT percentage of 37.7% of the current train schemes. Compared to the current train schemes, the average time fill rate decreases. This is traced back to the lower average number of trains and the lower total travel time of our solution approach. The average physical fill rate after the NNH is better than the average physical fill rate of 71.7% of the current train schemes. Furthermore, after Tabu Search the average physical fill rate improves further. The improvement in average physical fill rate is because the same number of fixtures are transported by fewer trains on average, which yields a higher average physical fill rate. The used computational time for Tabu Search is less than 2 hours and varies for the used loading constraints. Because of the use of the stopping criterion that Section 4.3.2 described, the used computational time is lower than the available time.

Based on the results of experiment 5, we conclude that our solution approach improves the performance of the BSK flow in comparison with the current train schemes. The improvements of our solution approach are visible for all three types of loading constraints. Furthermore, Sections 5.7.2 to 5.7.4 show that the performance of the BSK flow can be further improved by incorporating changes in the used planning restrictions, and we execute these experiments for all loading constraints.

5.7.2. Results of experiments 6 to 8: 1 change in the used planning restrictions

The purpose of experiments 6 to 8 is to evaluate our solution approach while we change one of the used planning restrictions. This way, we compare the outcome of our solution approach when one of the used planning restrictions has changed with the results of experiment 5.

Compared to the results of experiment 5, experiments 6 to 8 show further improvements in the total travel distance, the total travel time, and the average number of trains. The changes in planning restrictions of these experiments do not yield a reduction in the maximum number of trains. The average physical fill rate increases further, since the same number of fixtures are transported by fewer trains on average. Regarding the average time fill rates, we observe a significant decrease in experiment 7. The used marshalling area in experiment 7 is closer to the assembly line, which results in a lower total travel time. The lower total travel time contributes to the lower average time fill rate. The average time fill rate for experiment 8 increases, which is traced back to the use of 1 principle. In the current train schemes, the trains with a logistical tact time of 15 minutes have the highest average time fill rates, while the other principles have the lowest average time fill rates. This means that the routes of Principle 3 (Type 1 and Type 2), Principle 4, and Principle 6 are shorter than their available logistical tact time. By using 1 principle, the routes improve, and the available logistical tact time is 15 minutes for each train. The better routes in combination with a logistical tact time of 15 minutes results in an increase of the average time fill rate. The Tabu Search results of experiment 7 yields a decrease of 45.6% in terms of total travel distance in comparison with the NNH results of experiment 5. Furthermore, for the Strict LIFO strategy, Tabu Search of experiment 7 is executed in 58 minutes. The No Policy and the Adapted Partial LIFO strategy require slightly less than 2 hours computational time. Although the Strict LIFO strategy requires only 58 minutes, the Tabu Search results of the Strict LIFO strategy (377.3 km) are only slightly worse than the No Policy strategy (375.1 km) or the Adapted Partial LIFO strategy (371.9 km).

5.7.3. Results of experiments 9 to 11: 2 changes in the used planning restrictions

The purpose of experiments 9 to 11 is to evaluate our solution approach while we change two of the used planning restrictions. This way, we compare the outcome of our solution approach when two of the used planning restrictions are changed with the results of experiment 5.

Compared to the results of experiment 5, experiments 9 to 11 show further improvements in the total travel distance, the total travel time, and the average number of trains. For experiments 9 and 10, the Strict LIFO strategy yields a lower total travel distance than the No Policy or Adapted Partial LIFO strategy: the total travel distance of experiment 9 decreases with 48.9% in comparison to the Nearest Neighbour Heuristic results of experiment 5, and the reduction of experiment 10 is 47.2%. Experiment 11 does not yield a reduction in the maximum number of trains. Experiments 9 and 10 do yield a reduction in the maximum number of trains: experiment 9 results in 11 trains while experiment 10 results in 10 trains. For all three experiments, the average physical fill rate increases further, since the same number of fixtures are transported by fewer trains on average. Regarding the average time fill rates, we observe a significant decrease in experiment 9, which is traced back to the use of the marshalling area. The average time fill rates for experiments 10 and 11 increase, which is traced back to the use of 1 principle. Figure 5.1 shows the maximum number of trains needed per time period after Tabu Search for experiments 9 and 10 (No Policy strategy). For experiment 10, the required number of trains per time period shows fluctuations throughout the day. In time periods 32, 33, and 34, zero trains are needed because of the break between the morning and the afternoon shift.

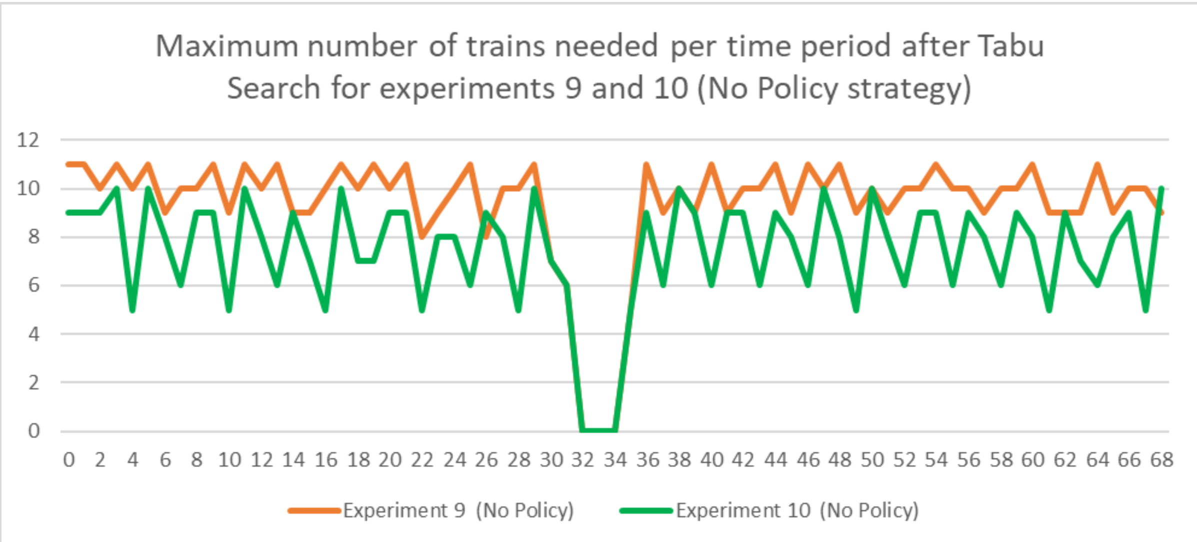

Figure 5. 1. Overview of maximum number of trains needed per time period after Tabu Search for experiments 9 and 10

5.7.4. Results of experiment 12: 3 changes in the used planning restrictions

The purpose of experiment 12 is to evaluate our solution approach while we change all the used planning restrictions. This way, we compare the outcome of our solution approach when all used planning restrictions are changed with the results of experiment 5.

Compared to the Nearest Neighbour Heuristic results of experiment 5, changing the 3 used planning restrictions yields a reduction of 46,8% (No Policy), 49.5% (Adapted Partial LIFO) or 50.2% (Strict LIFO) in total travel distance. The total travel time also decreases in this experiment. This experiment, like experiment 10, results in a maximum number of 10 trains instead of the 12 trains in the current train schemes. The average number of trains is also lower for experiment 12. The average physical fill rate is at 92.35% the highest of experiments 5 to 12, which is traced back to the lowest average number of trains in experiment 12. Furthermore, the average time fill rate increases, which is traced back to the use of 1 principle. For experiment 12, the Strict LIFO strategy yields the lowest total travel distance and the lowest total travel time, while the average time fill rate is slightly lower. Figure 5.2 shows the maximum number of trains needed per time period after Tabu Search for experiment 12 in comparison with experiment 5. For experiment 12, the required number of trains per time period shows fluctuations throughout the day, which does not occur in experiment 5.

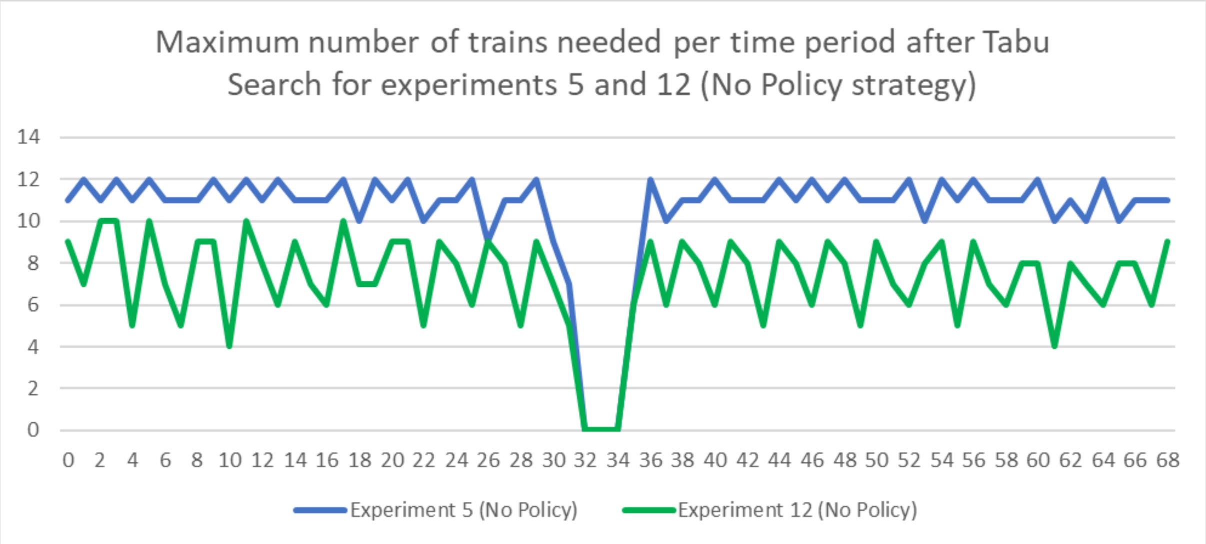

Figure 5. 2. Overview of maximum number of trains needed per time period after Tabu Search for experiments 5 and 12

5.7.5. Required investments for changing the used planning restrictions

For experiments 6 to 12, we change the used planning restrictions. Based on the results of these experiments, we calculate for the experiments that yield a reduction in the required number of trains the Return on Investment (ROI). We use the ROI in our advice to Scania Production Zwolle. In case SPZ needs one train less, SPZ would need 2 train operators less. This is because 2 employees (FTEs) operate one train: one employee in the morning shift and one in the afternoon shift. The saving of 2 FTEs is set to 100. The costs of each investment are scaled, based on the value of 100 for saving 2 FTEs. Each change in the used planning restrictions requires an investment. We have estimated the required investments, which the BSK flow engineers agreed on, for each change in the used planning restrictions. The investments are estimated on the following:

- Use of 1 type of trailer: 81.8, the estimated costs to switch to only the Still trailer;
- Marshalling area: 227.3, the estimated costs to set up the marshalling area, with a rented construction to cover the marshalling area, and creating the required entrance and exit;
- Use of 1 principle: 18.2, the estimated costs for advanced navigation systems and a workshop for the operators.

5.7.6. Overview of Return on Investment

Experiments 9, 10, and 12, result in the following Return on Investment:

- Experiment 9: the investments are estimated on 81.8 (use of 1 type of trailer) and 227.3 (marshalling area), while saving 100 by needing 1 train less. Based on this, the ROI of experiment 9 is 3.09 years.
- Experiment 10: the investments are estimated on 18.2 (use of 1 principle) and 227.3 (marshalling area), while saving 200 by needing 2 trains less. Based on this, the ROI of experiment 10 is 1.23 years.
- Experiment 12: the investments are estimated on 18.2 (use of 1 principle), 227.3 (marshalling area), and 81.8 (1 type of trailer), while saving 200 by needing 2 trains less. Based on this, the ROI of experiment 12 is 1.64 years.

Experiment	Experiment Name	Used loading constraints	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Average Just-In-Time percentage	Computational Time
E5. NNH	Current settings of the BSK flow	No Policy	659.8	5.22	12	6	10.64	74.97%	68.61%	35.93%	00:04:43
		Adapted Partial LIFO	688.3	5.37	12	6	10.81	73.74%	69.14%	37.29%	00:03:37
		Strict LIFO	693.4	5.40	12	6	10.75	74.14%	69.95%	38.66%	00:03:30
E5. TS	Current settings of the BSK flow	No Policy	549.7	4.63	12	6	10.54	75.74%	61.63%	35.93%	01:53:08
		Adapted Partial LIFO	586	4.82	12	5	10.30	77.64%	66.06%	37.29%	01:38:48
		Strict LIFO	619.5	5.00	12	6	10.75	74.14%	64.77%	38.66%	01:57:13
E6. TS	Use of 1 type of trailer	No Policy	535.7	4.56	12	6	9.87	81.18%	65.37%	36.65%	01:58:38
		Adapted Partial LIFO	578.2	4.78	12	6	10.12	79.12%	66.39%	37.59%	01:59:15
		Strict LIFO	606.9	4.93	12	5	10.00	80.06%	69.44%	39.13%	01:54:02
E7. TS	Use of a marshalling area	No Policy	375.1	3.72	12	5	9.88	81.74%	53.92%	27.70%	01:59:17
		Adapted Partial LIFO	371.9	3.70	12	5	9.88	81.74%	53.62%	27.70%	01:58:16
		Strict LIFO	377.3	3.73	12	5	9.88	81.74%	54.11%	27.70%	00:58:20
E8. TS	Use of 1 principle	No Policy	552.2	4.64	12	5	8.45	83.24%	82.73%	45.20%	01:58:48
		Adapted Partial LIFO	597.8	4.89	13	5	8.68	76.11%	79.63%	43.35%	01:59:23
		Strict LIFO	623.9	5.02	13	6	8.83	79.21%	85.26%	48.04%	01:57:48
E9. TS	Use of a marshalling area and 1 type of trailer	No Policy	359.9	3.63	11	5	9.38	85.52%	54.40%	28.45%	01:59:07
		Adapted Partial LIFO	357.3	3.62	11	5	9.38	85.52%	54.20%	28.45%	01:49:28
		Strict LIFO	354.1	3.60	11	5	9.38	85.52%	53.94%	28.45%	01:50:13
E10. TS	Use of a marshalling area and 1 principle	No Policy	371.3	3.70	10	5	7.39	96.53%	76.57%	38.26%	01:59:16
		Adapted Partial LIFO	368.7	3.68	10	5	7.39	96.53%	76.29%	38.26%	01:59:44
		Strict LIFO	366.1	3.67	10	5	7.39	96.53%	76.02%	38.26%	01:58:41
E11. TS	Use of 1 principle and 1 type of trailer	No Policy	559.7	4.68	12	5	8.04	80.70%	81.01%	42.81%	01:59:29
		Adapted Partial LIFO	561.1	4.69	12	5	8.26	80.84%	81.29%	42.83%	01:59:21
		Strict LIFO	620.9	5.00	12	5	8.33	77.89%	83.55%	45.10%	01:59:46
E12. TS	Use of a marshalling area, 1 principle and 1 type of trailer	No Policy	350.9	3.58	10	4	7.03	92.35%	70.95%	34.77%	01:59:41
		Adapted Partial LIFO	347.9	3.57	10	4	7.03	92.35%	70.63%	34.77%	01:59:57
		Strict LIFO	345.2	3.55	10	4	7.03	92.35%	70.34%	34.77%	01:59:33

Table 5. 10. Results of experiment 5 (NNH and Tabu Search results), and the Tabu Search results of experiments 6 to 12

5.8. Conclusion

The BSK flow has three datasets, but we have only used dataset 3 to evaluate our solution approach. This is because of the discrepancies in each train of the BSK flow, when we compare datasets 1 and 2 (real data from practice), with dataset 3. Dataset 3 is the artificially generated dataset resembling the normal situation. We executed 4 groups of experiments to substantiate choices of our solution approach. The substantiated choices of experiments 1.1, 1.2, and 1.3 are the same for the No Policy, Adapted Partial LIFO, and Strict LIFO strategy. Experiment 1.1 substantiates that we use only the travel distance from the warehouse to the line location for assigning the first fixture to train k. The results of experiment 1.2 substantiates the choice for the Nearest Neighbour: the Nearest Neighbour is the fixture that, when added after the CurrentNode of Route_LL on train k, results in the lowest total travel distance of the new Total Route. Experiment 1.3 substantiates that the objective function of the solution approach is to minimise the total travel distance. Experiment 2 shows that applying Adapted Partial LIFO and Strict LIFO from the Warehouse to the Line yields the best results. Experiment 3 showed for the No Policy strategy the used methodology to determine the best Tabu List Length and the best Extra Length for experiment 5. The same procedure is used to identify the best Tabu List Length and the best Extra Length for experiments 6 to 12. Experiment 4 is the experiment where we randomly assigned the Nearest Neighbour. Randomly running 4 time periods of the small principles (Principle3_Type1, Principle3_Type2, Principle 4 and Principle 6), showed that Tabu Search yields better results in comparison to the Tabu Search results after the standard Nearest Neighbour Heuristic. The manual routing method results in fixed routes, and each train has 4 routes. So, if Scania Production Zwolle uses our solution approach for fixed routes, 4 time periods are executed. Therefore, if SPZ uses our solution approach to generate fixed routes, we advise SPZ to use the random policy of the NNH for the small principles, and the standard NNH for the larger principles. This is because for the larger principles (Principle15minutes_Type1 and Principle15minutes_Type2), the random starting solution does not yield better Tabu Search results. Furthermore, this experiment showed that executing all time periods of the NNH in a structured way (the standard NNH), yields better results in comparison to the random NNH. Experiments 5 to 12 execute all time periods. Therefore, for experiments 5 to 12, we use the standard NNH that is adapted to the BSK flow-VRP to generate the initial solution for Tabu Search.

Experiment 5 compared the results of our solution approach with the Key Performance Indicators of the current train schemes. Based on those results, we conclude that our solution approach improves the performance of the BSK flow in comparison with the current train schemes. The following improvements in performance are observed in experiment 5: lower average number of trains; increase in average physical fill rate; decrease in total travel distance and total travel time. The improvements of our solution approach are visible for all three loading constraints. Experiments 6 to 12 show that the performance of the BSK flow is further improved by incorporating changes in the used planning restrictions. The most important improvement occurs in experiments 9, 10, and 12, which showed a decrease in the maximum number of trains: experiment 9 results in 11 trains, and experiments 10 and 12 result in 10 trains. For experiments 10 and 12, the required number of trains per time period shows fluctuations throughout the day, which does not occur in experiment 9. Based on the required investments, we calculated the Return on Investment for these experiments: the ROI of experiment 9 is 3.09 years; the ROI of experiment 10 is 1.23 years; the ROI of experiment 12 is 1.64 years. In comparison with the NNH results of experiment 5, we observed for experiments 6 to 12 the following improvements: lower average number of trains; increase in average physical fill rate; decrease in total travel distance and total travel time. Experiments 8, 10, 11, and 12 use 1 principle. The results of these experiments showed an increase in the average time fill rate, while the experiments that use 5 principles showed a decrease in the average time fill rate. Moreover, experiment 7 yields a decrease of 45.6% in terms of total travel distance in comparison with the NNH results of experiment 5. Furthermore, for the Strict LIFO strategy, Tabu Search of experiment 7 is executed in only 58 minutes.

6. Conclusions and recommendations

In this chapter, we present the conclusions (Section 6.1) and the recommendations (Section 6.2) from our research conducted at Scania Production Zwolle on the BSK flow. Furthermore, we describe in Section 6.1.1 how our solution approach solves the core problem of the BSK flow. Moreover, we reflect in Section 6.1.2 on our research by providing the practical and the theoretical contributions of our research. Lastly, we provide a discussion where we describe the research limitations (Section 6.2.1) and the possibilities for future research (Section 6.2.2).

6.1. Conclusions

We started with introducing our research, by stating the core problem, the research objective, and the main research question. Using a problem cluster, we found out that the manual routing method of the BSK flow that Scania Production Zwolle uses, is not efficient because of the increased complexity of this flow and the labour intensity of this method, affecting the ability to cope with changes in tact times and the ability to exploit its potential, which results in a productivity loss of the BSK flow. Our research objective is to advise SPZ on how to improve the routing of the BSK flow, based on our solution approach. We translated the research goal into the main research question:

How can the routing of the BSK flow be optimised, to increase the productivity of the BSK flow?

After the introduction of our research, we presented the outcomes of the analysis of the current situation of the BSK flow. The BSK flow consists of parts that are transported on fixtures from the on-site warehouses to the assembly lines by trains on a regular tact. Those parts are first picked as batch, sequence, or kit, and are placed on fixtures in the warehouses. SPZ currently uses 12 trains for the BSK flow, and each train has 4 fixed routes. A train uses 4 trailers, and each trailer can transport one 1-euro size fixture or two ½-euro size fixtures. The BSK flow currently uses a manual routing method, which results in the fixture overview, the individual train schemes, and the individual routing schemes. Furthermore, the BSK flow currently uses the following planning restrictions: 2 types of trailers, fixed warehouse locations, and 5 principles. Regarding the planning restrictions, we observed the following possibilities to improve the BSK flow: use of 1 type of trailer, use of a marshalling area, and use of 1 principle. For each route of the BSK flow, the Total Route consists of the route inside the warehouse for the pickup of full fixtures, the route at the assembly line for the delivery of full fixtures and the pickup of empty fixtures, and the route inside the warehouse for the delivery of empty fixtures. The current routing method of the BSK flow is manual, which results in a productivity loss of the BSK flow. The productivity loss of the BSK flow is observed via their Key Performance Indicators: the average physical fill rate (71.7%) and the average time fill rate (72.6%) are below their target of 80%. The physical fill rate shows the percentage of used capacity, compared to the available capacity in a route. The time fill rate shows the percentage of used travel time in comparison to the logistical tact time of a route.

Using a Systematic Literature Review, we identified the problem faced at SPZ as a Vehicle Routing Problem: the BSK flow-VRP is the Vehicle Routing Problem with Pickup and Delivery and loading constraints for internal logistics. Regarding the objective of the BSK flow-VRP, the objective is to minimise the total travel distance, which might result in a reduction in the number of trains. This is because using fewer trains results in a cost reduction which is the economic advantage SPZ wants. Moreover, the maximum route duration keeps track of the travel time instead of the travel distance. For each route of the BSK flow we observed that either the Partial LIFO or the Strict LIFO loading constraints are present in the current routes. Regarding Partial LIFO, we observed the possibility to adapt partial LIFO to the BSK flow, resulting in the Adapted Partial LIFO strategy. Based on the preceding, we incorporated No Policy, Adapted Partial LIFO, and Strict LIFO as the loading constraints in our solution approach. Adapted Partial LIFO entails that only the last pickup fixture is the first fixture that is delivered to the assembly line, whereas Strict LIFO entails that the route at the assembly line is the reverse of the route inside the warehouse to pick up the full fixtures. The SLR showed that VRPs can be solved exactly, via heuristics or via metaheuristics. Based on the advantages and disadvantages of the possible solution approaches, metaheuristics is the best option. Therefore, we have chosen metaheuristics as the solution approach for the BSK flow-VRP. From the metaheuristics we have chosen Tabu Search since this is the best fitting choice for solving the BSK flow-VRP: Tabu Search is described in literature as being a successful procedure which is widely used for solving a variety of VRPs, yielding good solutions with reasonable computational time. To be of practical use for SPZ, Tabu Search should be finished within 2 hours. We have chosen the Nearest Neighbour Heuristic to generate the initial solution for Tabu Search. Based on the SLR, our research contributes to theory as Section 6.1.2 elaborates on this.

We incorporated the NNH and Tabu Search into our solution approach to solve the BSK flow-VRP. Based on this, our solution approach consists of: importing the required BSK flow data; executing the NNH and Tabu Search; generating the output. An important notion is that both the NNH and Tabu Search are adapted to the BSK flow-VRP. This adaption is needed because the standard NNH starts and ends at the depot, while the routes of the BSK flow start and end inside the warehouse. Therefore, we tailor the NNH to the BSK flow-VRP by constructing for each train the Total Route: Total Route = Route_WH + Route_LL + Route_WHBack. Similarly, the new route of each candidate after executing a swap or move during Tabu Search, also consists of the preceding Total Route. This way, we also tailor Tabu Search to the BSK flow-VRP. Based on the preceding, we tailored the concepts and methods from literature to our problem. We verified our solution approach in the following ways: debugging, visualisation of output, and meetings with the stakeholders of SPZ. We also used the meetings with the stakeholders for the validation of our solution approach. Furthermore, we also used the current train schemes that were created manually, to validate our solution approach.

There are three datasets of the BSK flow, but we have only used dataset 3 for the evaluation of the solution approach. This is because there are discrepancies in each train of the BSK flow, when we compare datasets 1 and 2 (real data from practice) with dataset 3, which is the artificially generated dataset resembling the normal situation. We substantiated the choices of our solution approach based on the experimental results of experiments 1 to 4: the substantiation of the NNH (experiment 1); the substantiation of applying Adapted Partial LIFO and Strict LIFO (experiment 2); the substantiation of the Tabu List Length and the Extra Length (experiment 3); the substantiation for using the standard NNH that is adapted to the BSK flow-VRP instead of incorporating a random policy into the NNH (experiment 4). After we incorporated these choices into our solution approach, we evaluated our solution approach by running experiments 5 to 12, which shows that our solution approach solves the core problem. The purpose of experiment 5 is to evaluate the results from our solution approach for the current settings of the BSK flow. This way, we compare the outcome of our solution approach with the Key Performance Indicators of the current train schemes. Furthermore, the purpose of experiments 6 to 12 is to evaluate our solution approach while changing the used planning restrictions. For experiment 5, our expectation is that our solution approach improves the routes of the BSK flow, which can be observed via a lower total travel distance, and this might result in a reduction in the required number of trains. Furthermore, our expectation for experiments 6 to 12 is that the change(s) in the used planning restrictions also leads to improved routes. Below are the most important findings of experiments 5 to 12.

- <u>Experiment 5</u>: current settings of the BSK flow. Based on the results of experiment 5, we conclude that our solution approach improves the performance of the BSK flow in comparison with the current train schemes. After Tabu Search, the average number of trains varies between 10.64 and 10.81, which is lower than the 12 trains that the current train schemes need. After Tabu Search, the average physical fill rate varies between 74.14% and 77.64%, which is higher than the average physical fill rate of 71.7% of the current trains schemes. Compared to the current train schemes, the average time fill rate decreases. This is traced back to the lower average number of trains and the lower total travel time of our solution approach.

Furthermore, Tabu Search results in a decrease in the total travel distance and the total travel time.

- <u>Experiments 6, 7, and 8</u>: 1 change in the used planning restrictions. Compared to the NNH results of experiment 5, the results of these experiments show a decrease in the total travel distance and the total travel time, a lower average number of trains, and an increase in the average physical fill rate. The average time fill rate of experiments 6 and 7 decreases, due to the lower average number of trains and the lower total travel time. After Tabu Search of experiment 8, the average time fill rate varies between 79.63% and 85.26%, which is higher than the average time fill rate of 72.6% of the current trains schemes. This increase in average time fill rate is traced back to the use of 1 principle.
- <u>Experiments 9, 10, and 11</u>: 2 changes in the used planning restrictions. The results of experiments 9 and 10 show a decrease in the required number of trains: after Tabu Search, experiment 9 needs at most 11 trains and experiment 10 needs at most 10 trains. Furthermore, compared to the NNH results of experiment 5, the results of experiments 9, 10, and 11 show a decrease in the total travel distance and the total travel time, a lower average number of trains, and an increase in the average physical fill rate. The average time fill rate of experiment 9 decreases, due to the lower average number of trains and the lower total travel time. The average time fill rate of experiments 10 and 11 increases, which is traced back to the use of 1 principle.
- <u>Experiment 12</u>: 3 changes in the used planning restrictions. The results of experiment 12 show a decrease in the required number of trains: after Tabu Search, experiment 12 needs at most 10 trains. Furthermore, compared to the NNH results of experiment 5, the results of experiment 12 show a decrease in the total travel distance and the total travel time, a lower average number of trains, an increase in the average physical fill rate, and an increase in the average time fill rate.

Table 6.1 shows the NNH results of experiment 5, and the Tabu Search results of experiments 9, 10, and 12.

Experiment	Experiment Name	Used loading constraints	Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Average Just-In-Time percentage	Computational Time
E5. NNH	Current settings of the BSK flow	No Policy	659.8	5.22	12	6	10.64	74.97%	68.61%	35.93%	00:04:43
		Adapted Partial LIFO	688.3	5.37	12	6	10.81	73.74%	69.14%	37.29%	00:03:37
		Strict LIFO	693.4	5.40	12	6	10.75	74.14%	69.95%	38.66%	00:03:30
E9. TS	Use of a marshalling area and 1 type of trailer	No Policy	359.9	3.63	11	5	9.38	85.52%	54.40%	28.45%	01:59:07
		Adapted Partial LIFO	357.3	3.62	11	5	9.38	85.52%	54.20%	28.45%	01:49:28
		Strict LIFO	354.1	3.60	11	5	9.38	85.52%	53.94%	28.45%	01:50:13
E10. TS	Use of a marshalling area and 1 principle	No Policy	371.3	3.70	10	5	7.39	96.53%	76.57%	38.26%	01:59:16
		Adapted Partial LIFO	368.7	3.68	10	5	7.39	96.53%	76.29%	38.26%	01:59:44
		Strict LIFO	366.1	3.67	10	5	7.39	96.53%	76.02%	38.26%	01:58:41
E12. TS	Use of a marshalling area, 1 principle and 1 type of trailer	No Policy	350.9	3.58	10	4	7.03	92.35%	70.95%	34.77%	01:59:41
		Adapted Partial LIFO	347.9	3.57	10	4	7.03	92.35%	70.63%	34.77%	01:59:57
		Strict LIFO	345.2	3.55	10	4	7.03	92.35%	70.34%	34.77%	01:59:33

Table 6. 1. Results of experiment 5 (NNH), and the Tabu Search results of experiments 9, 10, and 12

6.1.1. Solving the core problem

Overall, our research shows that our solution approach solves the core problem of the BSK flow in the following ways:

- <u>the increased complexity of this flow</u>: our solution approach can cope with the increased complexity of this flow, since the Nearest Neighbour Heuristic with the current settings takes about 5 minutes to solve one production day of the whole BSK flow. Afterwards, Tabu Search requires additional computational time of less than 2 hours. Moreover, our solution approach can cope with the current planning restrictions (experiment 5), but it can also deal with changes in the used planning restrictions as the results of experiments 6 to 12 show.
- <u>the labour intensity of this method</u>: the use of our solution approach is less labour intensive since our solution approach solves the BSK flow-VRP and automatically generates the desired outputs.

- <u>affecting the ability to cope with changes in tact times</u>: by changing the logistical tact time in the input data and changing the maximum travel time in the solution approach, our solution approach copes with changes in tact times.
- <u>the ability to exploit its potential</u>: Tabu Search optimises the initial solution from the NNH, which shows that our solution approach is able to exploit the potential of the BSK flow. Moreover, experiments 9, 10, and 12 also showed a reduction in the maximum number of trains.
- <u>Productivity</u>: the average physical fill rate of experiments 5 to 12 increased in comparison to the average physical fill rate of the current train schemes. Furthermore, the experiments that use 1 principle also show an increase in the average time fill rate. The increased average physical fill rates and the increased average time fill rates resemble the desired increase in productivity.

6.1.2. Contribution to theory and practice

Our research contributes to theory in the following ways: the adaption of the Nearest Neighbour Heuristic and Tabu Search to the BSK flow-VRP; use of multiple loading constraints in our solution approach. Furthermore, our research contributes to practice in the following ways: the use of decomposing the big problem into smaller instances; solving the core problem.

Our research contributes to theory in the following ways:

- The adaption of the Nearest Neighbour Heuristic and Tabu Search to the BSK flow-VRP

The BSK flow-VRP is the Vehicle Routing Problem with Pickup and Delivery and loading constraints for internal logistics. An important difference between available VRP literature and the BSK flow-VRP is that the routes of the BSK flow-VRP starts and ends inside the warehouse. Therefore, we tailored the NNH and Tabu Search to the BSK flow-VRP by incorporating for each train the Total Route: Total Route = Route_WH + Route_LL + Route_WHBack. Based on the preceding, we tailored the concepts and methods from literature to our problem.

- Use of multiple loading constraints in our solution approach

Regarding the loading constraints, we incorporated No Policy, Adapted Partial LIFO, and Strict LIFO. Our research conducts experiments to find out what the impact is on the performance of the BSK flow if we use No Policy, Adapted Partial LIFO, or the Strict LIFO loading constraints. Previous research uses only one type of loading constraints, while we evaluate the impact of the loading constraints on the performance of the BSK flow. This way, using multiple loading constraints is a contribution to theory.

Our research contributes to practice in the following ways:

- The use of decomposing the big problem into smaller instances

The BSK flow-VRP decomposes the "big problem" into smaller instances. The big problem is the dataset for one full production day, which consists of all fixtures that need to be routed for all time periods, principles, and types of trailers. An instance consists of a time period, a principle, and a type of trailer. By solving the smaller instances separately and adding the solutions together, the BSK flow-VRP solves the "big problem". The use of decomposing the big problem into smaller instances is of practical use, since the use of separate instances makes it possible to first solve the smaller instances. This way, we can use the remaining computational time for executing the largest principle (Principle15min_Type1).

- Solving the core problem

Our research shows that our solution approach solves the core problem, which is a contribution to practice. Our solution approach can cope with the increased complexity of the BSK flow, it is less labour intensive, it can cope with changes in tact times, and it has the ability to exploit the potential of the BSK flow. Furthermore, our solution approach results in an increase in the productivity of the BSK flow.

6.2. Recommendations

Our first recommendation for Scania Production Zwolle is to use our solution approach for the route creation of the BSK flow instead of the manual route creation. Our second recommendation for SPZ is to look for other internal logistics flows that could use our solution approach in an adapted form. Our solution approach minimises the total travel distance for the BSK flow. However, the solution approach does not take the safety into account. It is possible that a route of the solution approach is not desired due to safety or congestion inside the factory, even though the result of our solution approach is better. Therefore, we advise SPZ to check this before the solution is implemented. Furthermore, we advise SPZ to gather more data about the BSK flow. While gathering the data, it is important that the data is accurate to prevent the discrepancies that our analysis of the current datasets showed: our analysis showed many discrepancies between datasets 1 and 2, in comparison with dataset 3.

Based on the evaluation of our solution approach, we have also recommendations that are based on the three planning levels: operational (short-term), tactical (mid-term), and strategic (long-term).

- On the operational level, we recommend SPZ to use our solution approach for creating the fixed routes. By using input data of only 4 time periods, the solution approach will make those 4 fixed routes. For the smaller principles, we advise the use of the NNH with the random policy.
- For the tactical level, we advise SPZ to start testing the use of the flexible routes that the solution evaluation of experiments 5 to 12 generated. Regarding the use of flexible routes, experiments 9, 10, and 12 showed the best results when using the Strict LIFO loading constraints. To get a return on their investment, SPZ can choose between experiments 9, 10, and 12. The executed changes in planning restrictions in these 3 experiments yielded a decrease in the required number of trains. SPZ needs to make a trade-off between experiments 9, 10, and 12: experiment 9 needs one train less and has no large fluctuations of needed trains during the day; experiments 10 and 12 both yielded a decrease of 2 trains, but they have fluctuations in the number of trains needed during the day. Moreover, experiment 9 yields an average physical fill rate of 85.52%, while experiment 10 results in 96.53%, and experiment 12 results in 92.35%. Similarly, experiment 10 yields the best average time fill rate: 76,02% (experiment 10) versus 53.94% (experiment 9), and 70.34% (experiment 12). Furthermore, the ROI of experiment 10 (1.23 years) is lower than the ROI of experiments 9 (3.09 years), and of experiment 12 (1.64 years).
- In the long-term, SPZ needs to decide on the implementation of one of the used planning restrictions from experiments 5 to 12. We also advice SPZ in the long-term to use an advanced navigation system that can show the flexible routes instead of using the printed fixed routes.

6.2.1. Research limitations

Scania Production Zwolle wanted the maximum computational time of Tabu Search to be 2 hours. When we set the time criterion for an experiment to 3 hours, the longer run showed a better result compared to the shorter run. Since there were many discrepancies between datasets 1 and 2 in comparison with dataset 3, we only used dataset 3 for the solution evaluation.

6.2.2. Future research

For our research we assumed the layout of the warehouse to be fixed. Therefore, a possibility for future research is to incorporate different layouts of the warehouse. Another possibility for future research is to experiment with the number of chassis that can be placed on one fixture. We have assumed the number of chassis per fixture as fixed. However, when there are more chassis placed on one fixture, it needs to be less often delivered to the assembly line. Another possibility for future research is to incorporate the different frame types from practice. We generated the initial solution via the Nearest Neighbour Heuristic. Future research could use another heuristic to generate the initial solution, for example the Saving Heuristic, which might result in a better initial solution. Another possibility for future research is to incorporate the extra time from the special crossings in a different way.

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Appendix A. Scania Production System

Scania wants to be the leader in sustainable transport, which creates a world of mobility that is better for business, society, and the environment. Scania uses the Scania Production System to achieve this vision. The SPS is based on Lean Production, which was inspired by the Toyota Production System (Scania Production Zwolle, 2022). Lean Production or Lean Manufacturing is characterised "as a traditional approach to eliminate waste in the value stream and ensure the efficiency of the production processes" (Valamede & Akkari, 2020). Most of the time, Lean Production is limited to one factory. However, Lean Production is applied in the whole supply chain of Scania, which results in a lean supply network. The Lean Production of Scania is resembled by the Scania Production System in Figure A.1.

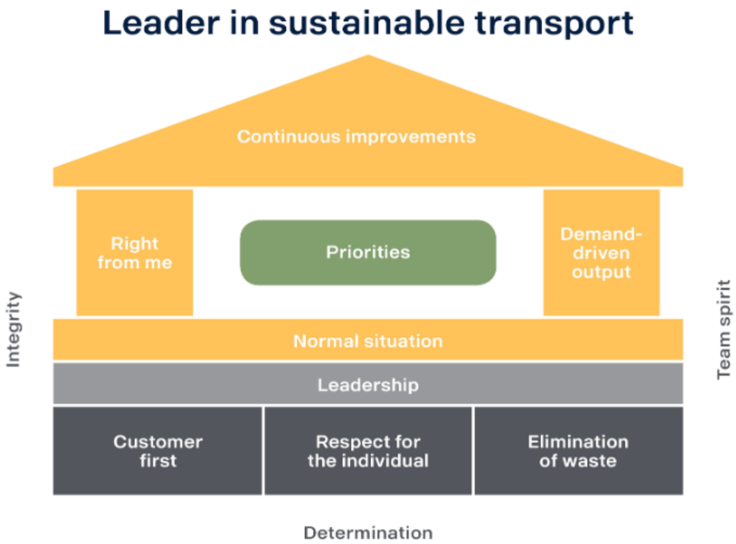

Figure A. 1. The Scania Production System

Three of the six core values form the foundations of the house. These core values are customer first, respect for the individual, and the elimination of waste. A core concept of Lean Production is the elimination of waste, which is translated in the Just-In-Time delivery of parts. This way, a waste of money and stock can be prevented. The other three core values of Scania are determination, team spirit, and integrity. Next is the leadership mission, to make sure the right strategy is implemented, an efficient operation is run, and teams as well as individuals are continuously developed within Scania. Besides the core values, Scania uses the following four main principles: normal situation, "right from me", demand-driven output, and continuous improvements. These main principles are important, because together they form a continuous work process and mindset. The goal of this is to add customer value and eliminate waste, which resembles the lean production view. An example of continuous improvements can be found in the Kaizen sessions. For Scania, the normal situation consists of standardisation, the tact time, levelled flow, balanced flow, visualisation, and real-time management. The tact time is the available time per workstation of the assembly lines. The principle "right from me" means that we pass our work on without mistakes. Inside the house are the four priorities of Scania: safety, health, and environment; quality; delivery reliability; costs (Scania Production Zwolle, 2022).

The core values of customer first and elimination of waste can be retraced to the production process. This is because the production is based on actual placed customer orders: Scania has a demand-driven output. The customer has many options to choose from regarding the cabin, motor, gearboxes, shafts, frames, and the appearance of the truck. These options are possible because of the modular design, the logistical systems, and flexibility of Scania's employees (Scania Production Zwolle, 2022).

Appendix B. Background information about the function areas

There are 8 different function areas at the assembly lines. FA-area stands for "funktionsområde" and that is Swedish for function area. The function areas are depicted for the Castor line in Figure B.1. Moreover, the assembled parts per function area are summarised in Table B.1. In each FA, there is a subdivision into specific workstations. The mechanics perform the standardised tasks at those workstations. At each workstation, the standardised tasks can be found in the work instructions. Because of the modular design, not all trucks will have the same configuration. Therefore, the required tasks are different for the trucks. At each workstation there are a specific number of mechanics to finish the required tasks. Moreover, there is a team leader at each workstation to support the mechanics where needed to make sure that the required tasks are finished within the available time.

Function area	Part(s) assembled
FA0	Frame assembly
FA1	Pipes and cables
FA2	Axles
FA3	Engine
FA4	Cabin
FA5	Tires
FA6	Test & Repair
FA7	Fit for Use

Table B. 1. Overview of assembled parts per function area

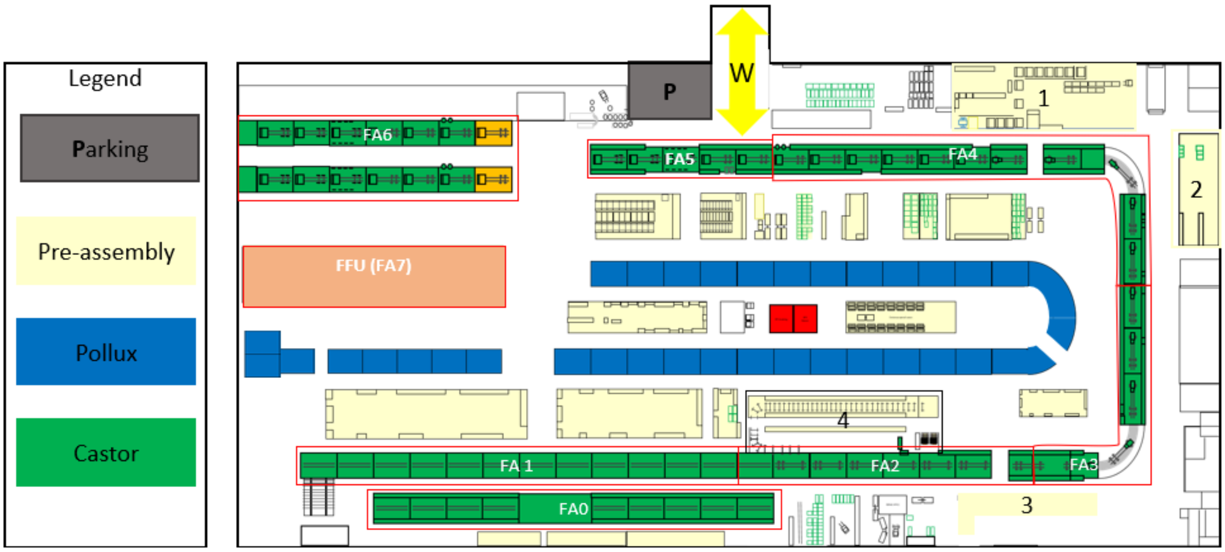

Figure B.1. Overview of function areas

Figure B.2 shows FA0 on the left and FA1 on the right. The first area, FA0, is the frame assembly department. The Castor line and the Pollux line have a separate frame construction area. When the frame parts are separate, it is called a frame. After the separate frame parts are assembled for one truck, it is called a chassis. At FA1 the pipes and cables are, among other things, assembled.

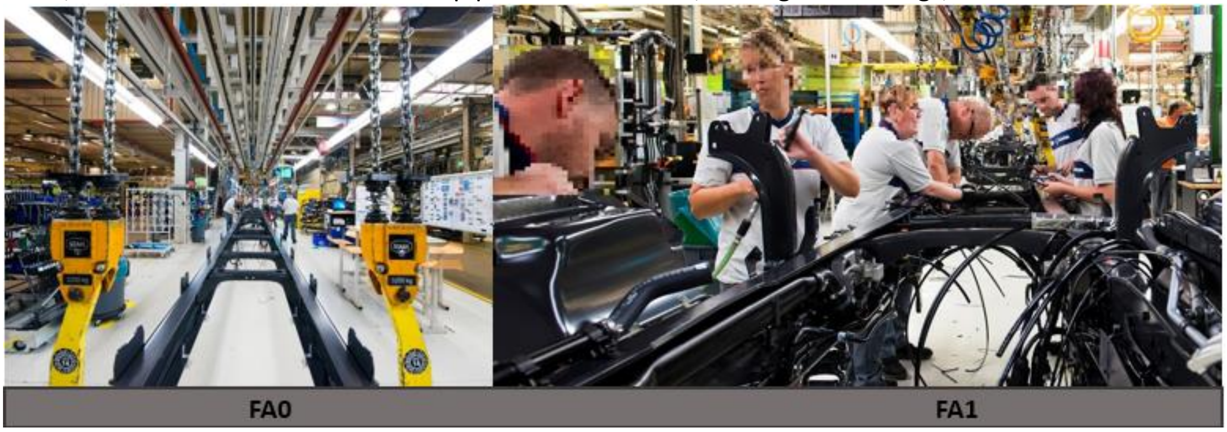

Figure B.2. Function areas 0 and 1

At the beginning of FA2, the chassis is placed on a carrier. Afterwards, the axle substructures are assembled at FA2. The next area, FA3, is the engine drop, where the assembled engine and gearbox is dropped as a unit into the chassis. Figure B.3 shows on the left part the assembly of an axle and the right part of this figure shows the engine drop.

Figure B.3. Function areas 2 and 3

At FA4 the cabin is, among other things, assembled. For the assembly of the cabin, the eagle is used as can be seen in Figure B.4. FA5 resembles the end of the assembly line where, among others, the tires are assembled.

Figure B.4. Function areas 4 and 5

Figure B.5 shows FA6 on the left and FA7 on the right. FA6 consists of test & repair of finished trucks. FA7 consists of the Fit For Use area, where special additional requests from customers are added that could not be included in the normal specifications. An example of Fit For Use is the special military equipment that is required for the Gryphus by the Dutch military.

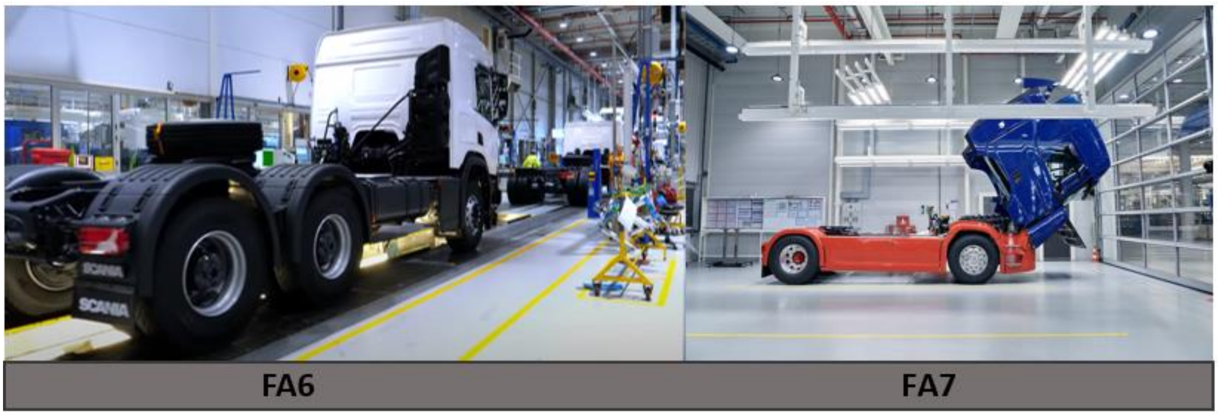

Figure B.5. Function areas 6 and 7

Appendix C. Special crossings in the production process

Special crossings make the routing of the BSK flow more complex because of possible waiting times. In Figure C.1, the 14 special crossings are added in red to the layout of the factory. Number 1 shows the cabin crossing, where the cabin is transported over the road to the assembly line by the eagle. Figure B.4 shows how a cabin is crossed over the road by the eagle. Number 2 is the carrier crossing of the Castor line. Number 3 is where the automated guided vehicle delivers the pre-assembled mufflers to the assembly line. Number 4 is the engine crossing: the completed engine is transported over the road from the engine completion to the assembly line. Figure B.3 shows on the right part the engine drop, after the engine crossed special crossing number 4. Number 5 is where the chassis is placed on a carrier at the Castor line, which Figure B.3 shows on the left part. Number 6 is the start of the frame construction, which Figure B.2 shows on the left part.

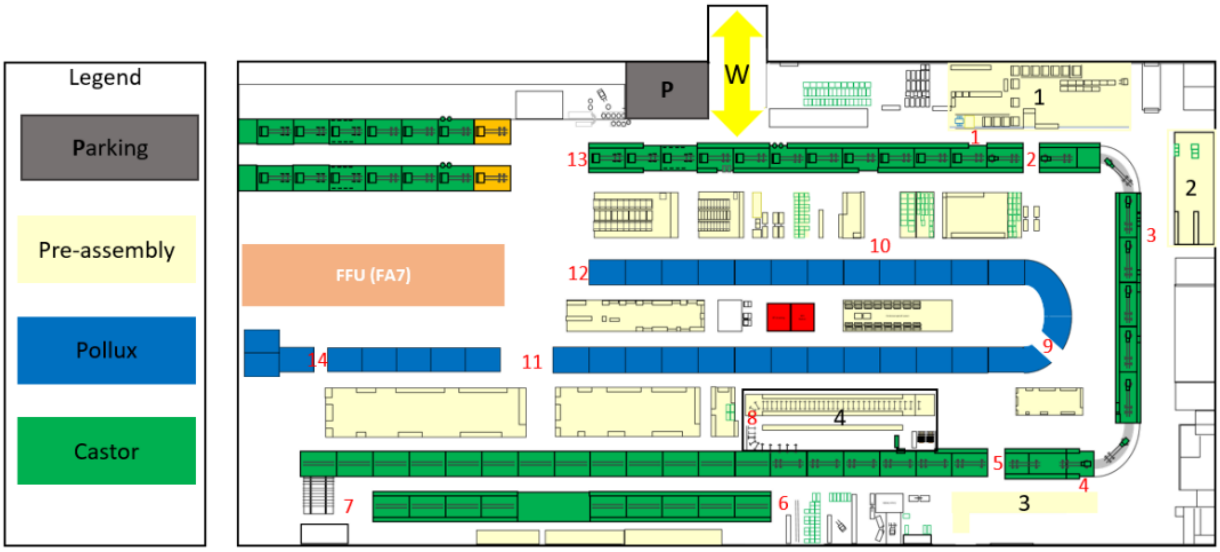

Figure C.1. Special crossings

The ending of the frame construction (number 7) can also be disruptive, because the chassis crosses the road before it goes to the next FA. Number 8 is the axle crossing, which can also be disruptive. Number 9 is where we can cross the Pollux assembly line. Here, we sometimes have to wait until the truck on the carrier has passed. Number 10 is where a forklift truck delivers the cabin for the Pollux assembly line. Number 11 is where the chassis goes from the frame construction to the next FA of the Pollux assembly line. At the end of the assembly lines, the trucks go to the test & repair function area. Therefore, number 12 (Pollux) and number 13 (Castor) are possible disruptions. Lastly, number 14 is where we can cross the Pollux assembly line.

Appendix D. Example of a BSK flow train: the AD1 train

Figure D.1 shows the individual train scheme of the AD1 train, which is the same figure as Figure 2.8. Based on this scheme, the routing schemes are made. Figure 2.9 already showed the first route of the AD1 train. Here, Figures D.2, D.3, and D.4 show the other 3 routes of the AD1 train.

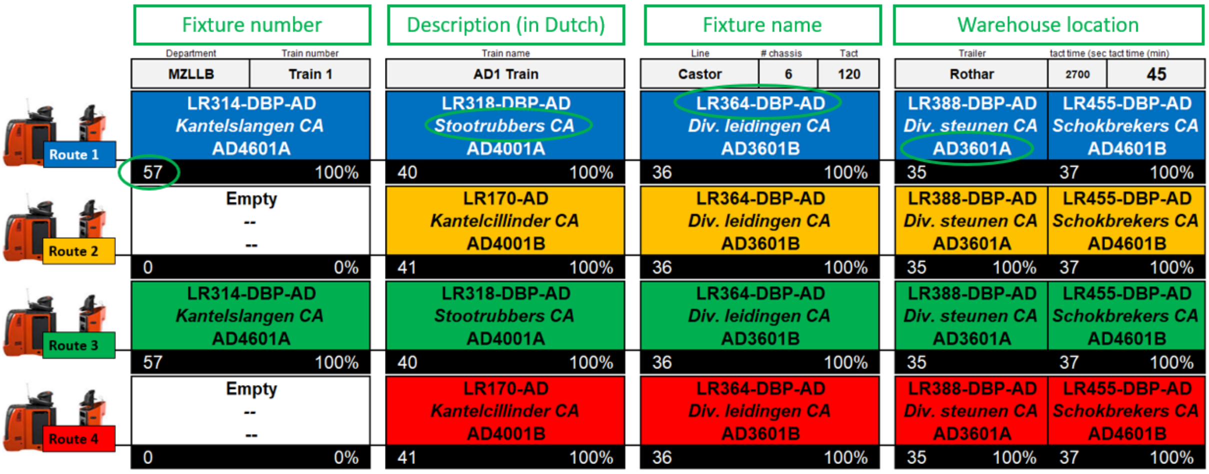

Figure D.1. Example of a train: AD1 train – individual train scheme

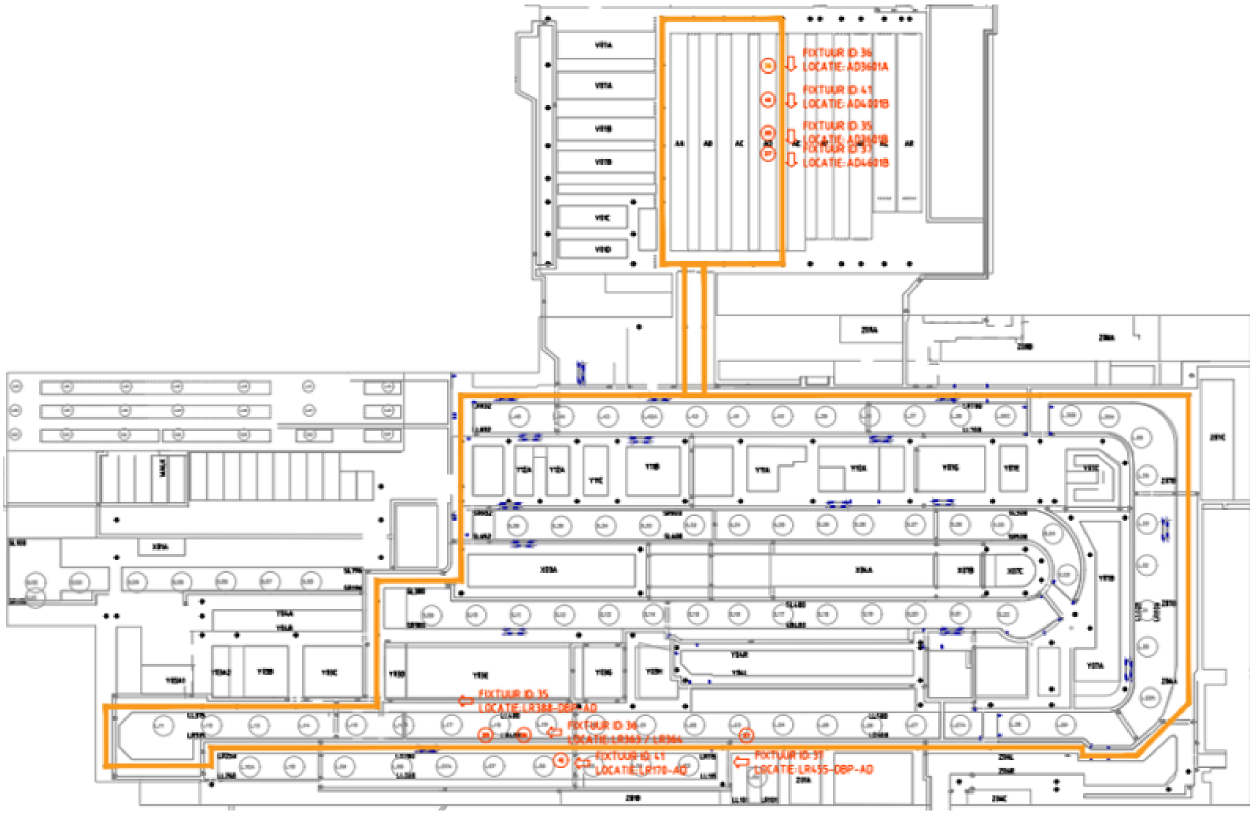

Figure D. 2. Route 2 of the AD1 train

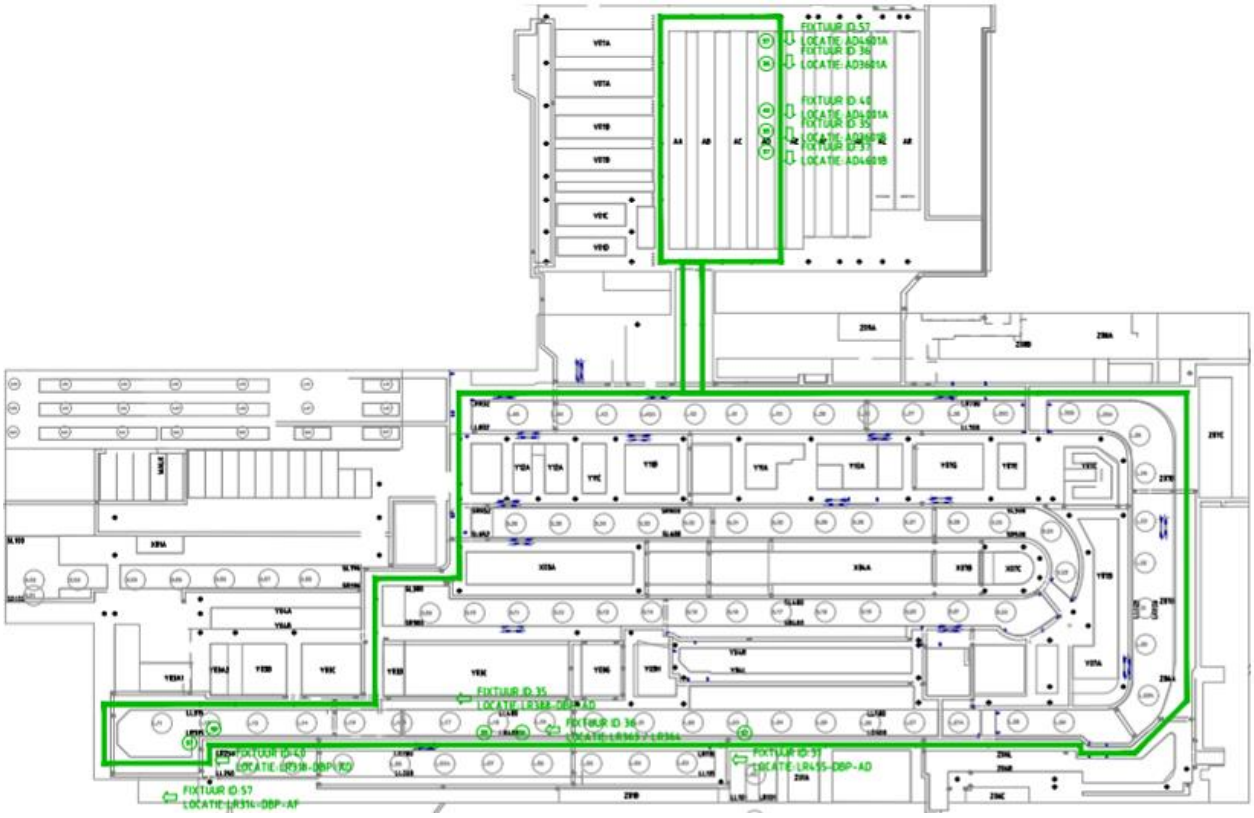

Figure D. 3. Route 3 of the AD1 train

Figure D. 4. Route 4 of the AD1 train

Appendix E. Current routes of Principle15minutes with possibility to improve the BSK flow: 1 type of trailer

Figure E.1 shows the current routes of the trains in Principle15minutes, which shows train 2 (Rothar), train 5 (Rothar, route 1 & 3), train 10 (Still, route 1&3), and train 11 (Still). Figure E.2 shows the current routes of the trains in Principle15minutes, which shows train 2 (Rothar), train5 (Rothar, route 2 & 4), train 10 (Still, route 2 & 4) and train 11 (Still). Figures E.1 and E.2 show that some parts of the routes of the Principle15minutes trains overlap.

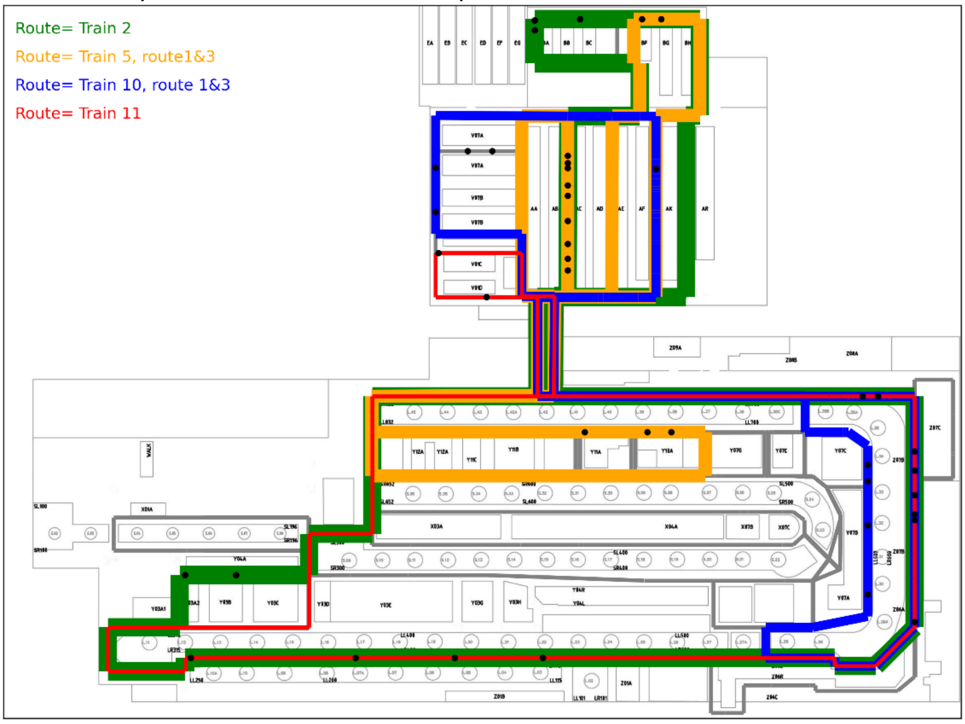

Figure E. 1. Current routes of the trains in Principle15minutes: trains 2 (Rothar), 5 (Rothar, route 1 & 3), 10 (Still, route 1 & 3) and 11 (Still).

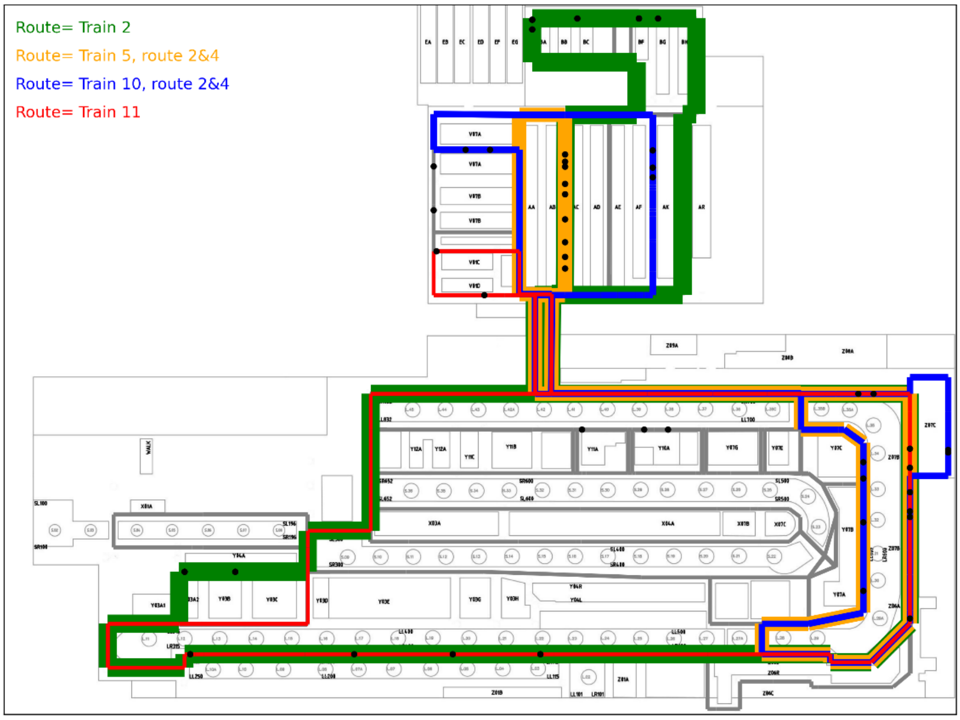

Figure E. 2. Current routes of the trains in Principle15minutes: trains 2 (Rothar), 5 (Rothar, route 2 & 4), 10 (Still, route 2 & 4) and 11 (Still)

Appendix F. Construction of dataset 3 and an example of analysed datasets

This appendix explains the construction of dataset 3, which is the artificially generated dataset resembling the normal situation of the BSK flow. This dataset is based on the fixture overview and the individual train schemes from practice. We have constructed this dataset, based on our knowledge about the BSK flow and with the help of the BSK flow engineers. Analysing the three datasets of the BSK flow, showed that there are discrepancies in each train of the BSK flow, when we compare datasets 1 and 2 (real data from practice) with dataset 3. Appendix F.2 shows an example of these discrepancies.

Appendix F.1. Construction of dataset 3: artificially generated dataset resembling the normal situation

To keep the production line running smoothly, Scania Production Zwolle works in shifts. There are 2 shifts: the morning shift starts at 6:00 and finishes at 14:00. The afternoon shift starts at 14:45 and ends at 23:15. The lower and upper bound are based on the shifts:

- For the morning shift, the earliest lower bound is 6:00 and the latest upper bound is 14:00.
- For the afternoon shift, the earliest lower bound is 14:45 and the latest upper bound is 23:15.

The artificially generated dataset is build-up according to the principle each fixture is in, based on the fixture overview. Recall that the used principles are Principle 1 (Pollux), Principle 2 (Castor), Principle 3 (Castor), Principle 4 (Castor), and Principle 6 (Castor). Table F.1 shows the first 8 lower and upper bounds for these principles. The lower and upper bound of each time period is labelled as route 1, 2, 3 or 4, like the routes of the individual train schemes.

Principle 1	Start	06:00:00
	Logistical tact time	00:07:30
Route	Lower bound	Upper bound
1	06:00:00	06:07:30
2	06:07:30	06:15:00
3	06:15:00	06:22:30
4	06:22:30	06:30:00
1	06:30:00	06:37:30
2	06:37:30	06:45:00
3	06:45:00	06:52:30
4	06:52:30	07:00:00

Principle 2	Start	06:00:00
	Logistical tact time	00:15:00
Route	Lower bound	Upper bound
1	06:00:00	06:15:00
2	06:15:00	06:30:00
3	06:30:00	06:45:00
4	06:45:00	07:00:00
1	07:00:00	07:15:00
2	07:15:00	07:30:00
3	07:30:00	07:45:00
4	07:45:00	08:00:00

Principle 3	Start	06:00:00
	Logistical tact time	00:22:30
Route	Lower bound	Upper bound
1	06:00:00	06:22:30
2	06:22:30	06:45:00
3	06:45:00	07:07:30
4	07:07:30	07:30:00
1	07:30:00	07:52:30
2	07:52:30	08:15:00
3	08:15:00	08:37:30
4	08:37:30	09:00:00

Principle 4	Start	06:00:00
	Logistical tact time	00:30:00
Route	Lower bound	Upper bound
1	06:00:00	06:30:00
2	06:30:00	07:00:00
3	07:00:00	07:30:00
4	07:30:00	08:00:00
1	08:00:00	08:30:00
2	08:30:00	09:00:00
3	09:00:00	09:30:00
4	09:30:00	10:00:00

Principle 6	Start	06:00:00
	Logistical tact time	00:45:00
Route	Lower bound	Upper bound
1	06:00:00	06:45:00
2	06:45:00	07:30:00
3	07:30:00	08:15:00
4	08:15:00	09:00:00
1	09:00:00	09:45:00
2	09:45:00	10:30:00
3	10:30:00	11:15:00
4	11:15:00	12:00:00

Table F. 1. Build-up of artificially generated dataset – Principles 1, 2, 3, 4 and 6

The individual train schemes are used to construct dataset 3. Figure D.1 shows the individual train scheme of the first train, the AD1 Train. The time periods of route 1 are assigned to each fixture in route 1 of this train. The same method is applied to the other routes of this train, and to the routes of the other trains. This way, an artificially generated dataset is constructed.

Table F.2 shows a part of the Castor Train 1 in dataset 3. This table shows the data of the first four routes of the AD1 train: routes 1, 2, 3, and 4. For these routes, the upper bound and lower bound from Table F.1 are used: route 1 has a lower bound of 6:00 and upper bound of 6:45; route 2 has a lower bound of 6:45 and an upper bound of 7:30; route 3 has a lower bound of 7:30 and an upper bound of

8:15; route 4 has a lower bound of 8:15 and an upper bound of 9:00. Moreover, Table F.2 shows that the fixtures from the AD1 train scheme are in the same route as in the train scheme: fixtures 57, 40, 36, 35 and 37 are in routes 1 and 3; fixtures 41, 36, 35 and 37 are in routes 2 and 4. The same methodology is used for the rest of the Castor Train 1. Moreover, we have used this methodology for the other trains, resulting in the artificially generated dataset: dataset 3.

FixtureNumber	Route	Train	LowerBoundTimePeriod	UpperBoundTimePeriod
57	1	Castor Train 1	06:00:00	06:45:00
40	1	Castor Train 1	06:00:00	06:45:00
36	1	Castor Train 1	06:00:00	06:45:00
35	1	Castor Train 1	06:00:00	06:45:00
37	1	Castor Train 1	06:00:00	06:45:00
41	2	Castor Train 1	06:45:00	07:30:00
36	2	Castor Train 1	06:45:00	07:30:00
35	2	Castor Train 1	06:45:00	07:30:00
37	2	Castor Train 1	06:45:00	07:30:00
57	3	Castor Train 1	07:30:00	08:15:00
40	3	Castor Train 1	07:30:00	08:15:00
36	3	Castor Train 1	07:30:00	08:15:00
35	3	Castor Train 1	07:30:00	08:15:00
37	3	Castor Train 1	07:30:00	08:15:00
41	4	Castor Train 1	08:15:00	09:00:00
36	4	Castor Train 1	08:15:00	09:00:00
35	4	Castor Train 1	08:15:00	09:00:00
37	4	Castor Train 1	08:15:00	09:00:00

Table F. 2. Part of Castor Train 1 in dataset 3

Appendix F.2. Discrepancies between datasets 1 and 2 in comparison with dataset 3

Figure F.1 shows the occurrence of fixtures in datasets 1 and 2, in comparison with their occurrence in dataset 3. This comparison is for the Castor Train 1, and this figure shows that there are many discrepancies in occurrence. These discrepancies appear in all figures when we compare for each train the occurrence of fixtures in datasets 1 and 2, with their occurrence in dataset 3.

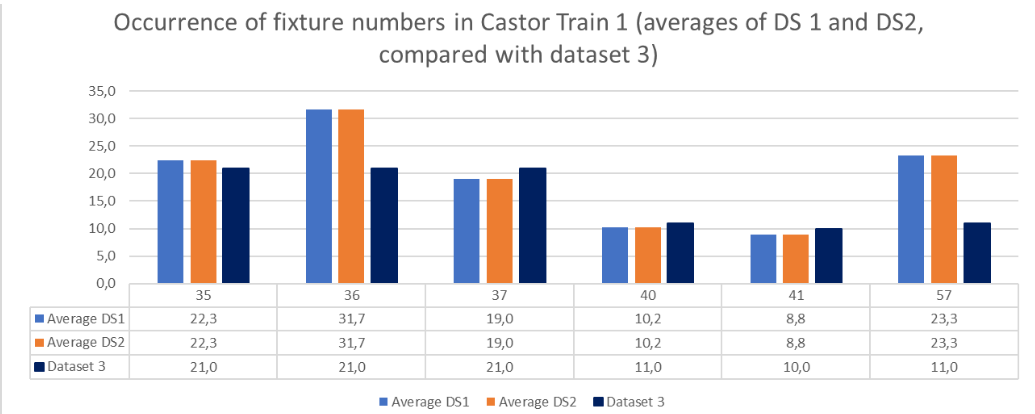

Figure F. 1. Comparison of datasets 1, 2 and 3 – Castor Train 1

Appendix G. Systematic Literature Review

This appendix shows the Systematic Literature Review that we have conducted, so we can support our research questions theoretically by relevant literature and theoretical principals. Appendix G.1 explains the used methodology for the SLR. Appendix G.2 shows the SLR used for Section 3.1, which explains the Vehicle Routing Problem. Appendix G.3 is about the used literature for the popular VRP variants (Section 3.2), which is based on articles found in the first SLR. Appendix G.4 is about the SLR for the Vehicle Routing Problem with Pickup and Delivery and LIFO loading constraints. The SLR in Appendix G.5 substantiates the choice for Tabu Search as the metaheuristic to solve the BSK flow-VRP.

G.1. Used methodology

For each SLR, we have used the Scopus database for an advanced search in available literature. This database was used since it covers a wide range of peer-reviewed academic publications. This way, we can support our research questions theoretically by relevant literature and theoretical principals. An article, book (chapter), review or survey is considered relevant when it is applicable to our problem. During our search, we have excluded conference papers and conference reviews. This way, articles, book chapters, reviews, books, and (short) surveys remained included in our search. Moreover, regarding the source type, we excluded conference proceeding while journals, book series and books were included. Lastly, only final publications and publications in English are considered. Moreover, each section shows the used key theoretical concepts of that SLR. The key theoretical concepts are the used search terms. For each SLR, an overview is made that shows:

- The number of results;
- The number of articles that are relevant after reading the first parts: title, abstract, the introduction, and the discussion;
- The number of articles that are relevant after reading the complete article;
- The total number of articles the SLR resulted in after removing duplicates.

G.2. SLR for the introduction to the Vehicle Routing Problem (Section 3.1)

Section 3.1 introduces the VRP, so our first search term is “Vehicle Routing Problem” or “VRP”. The Capacitated VRP is sometimes referred to as the Basic VRP. Therefore, articles about the Capacitated VRP are also relevant for the introduction. Moreover, VRP publications that give an overview, classification, taxonomy, or review of the VRP are also relevant. Besides that, the state of the art regarding the VRP is also relevant. Therefore, our literature search started with the following search terms in titles, abstracts, and keywords:

- “Vehicle Routing Problem” or “VRP”;
- “Capacitated Vehicle Routing Problem” or “CVRP” or “basic Vehicle Routing Problem” or “basic VRP”;
- “Vehicle Routing Problem” or “VRP” and “overview”;
- “Vehicle Routing Problem” or “VRP” and “classification”;
- “Vehicle Routing Problem” or “VRP” and “taxonomy”;
- “Vehicle Routing Problem” or “VRP” and “review”;
- “Vehicle Routing Problem” or “VRP” and “state of the art”.

For each search term the number of results is documented, where for the first search term only the results with at least 100 references are included. Afterwards, the titles of the results were scanned, and the relevant titles were selected. Next, the abstracts from the selected articles were read. If the abstract was relevant, the introduction and discussion parts were read, before the complete article was read. If the article was still relevant after reading the complete article, it was added to our literature list. Our SLR resulted in 32 articles. Removing duplicates resulted in 23 articles. While reading these 23 articles, we added five articles to our literature list because a relevant article was found as a reference in one of these articles. So, the first SLR resulted in 28 articles.

G.3. Used literature for the popular VRP variants (Section 3.2)

In the first SLR (Appendix G.2), two articles were found that give a taxonomic review or classification about the VRP variants. These two articles describe the most popular VRP variants. Therefore, these articles were primarily used for the description of the popular VRP variants. Moreover, we also used references from those articles when more information was needed.

G.4. SLR for the VRP with Pickup and Delivery and LIFO loading constraints

The BSK flow-VRP is the Vehicle Routing Problem with Pickup and Delivery and loading constraints for internal logistics. We incorporate multiple loading constraints into our solution approach. We use literature on the VRP with Pickup and Delivery and LIFO loading constraints to substantiate the choice on how to solve the BSK flow-VRP. Therefore, Appendix G.4.2 explains the Systematic Literature Review for the VRP with Pickup and Delivery and LIFO loading constraints. First, Appendix G.4.1 focusses only on the SLR for the VRPPD. Since the VRPPD is sometimes referred to as the Pickup and Delivery Problem, Appendix G.4.3 describes the SLR on Pickup and Delivery Problem and LIFO loading constraints.

G.4.1. SLR for the VRP with Pickup and Delivery

For this SLR, our used Scopus search is: “Vehicle Routing Problem with Pick up and Delivery” or “Vehicle Routing Problem with Pickup and Delivery” or “Pickup and delivery Vehicle Routing Problem” or “Pickup-and-delivery Vehicle Routing Problem” or “Pick-up-and-delivery Vehicle Routing Problem” or “Vehicle Routing Problem with Pick-up and Delivery” or “VRPPD”. This search resulted in 1386 documents. Afterwards, we limited the results to:

- Written in English;
- Articles, books, book chapter(s), reviews, and short surveys;
- Final publication stage;
- Published in journals or books.

These limitations resulted in 800 documents about the VRPPD. Although there are a lot of documents available, an important difference between available literature and the BSK flow-VRP, is that the BSK flow is part of the internal logistics process. After the addition of “in-plant” to the previous search, 2 documents remained, which Table G.1 shows. One article is about making flow paths for automated guided vehicles which is different than the trains from the BSK flow. The other article is about the milk-run VRP, which is different than the BSK flow-VRP because the milk-run VRP also incorporates other constraints, besides the constraints from the BSK flow-VRP. Another difference is that both articles do not incorporate the loading constraints that the BSK flow-VRP has.

Results of Scopus search on “Vehicle Routing Problem with Pick up and Delivery” or “Vehicle Routing Problem with Pickup and Delivery” or “Pickup and delivery Vehicle Routing Problem” or “Pickup-and-delivery Vehicle Routing Problem” or “Pick-up-and-delivery Vehicle Routing Problem” or “Vehicle Routing Problem with Pick-up and Delivery” and “in-plant”	
#	Title
1.	Engine routing and scheduling at industrial in-plant railroads
2.	Blockage-Free Route Planning for In-Plant Milk-Run Material Delivery Systems

Table G. 1. Two articles from Scopus search for the Vehicle Routing Problem with Pickup and Delivery and in-plant

Afterwards, we conducted a Scopus search on VRPPD and internal logistics: our Scopus search on “Vehicle Routing Problem with Pick-up and Delivery” or “Vehicle Routing Problem with Pick up and Delivery” or “Vehicle Routing Problem with Pickup and Delivery” or “Pickup and delivery Vehicle Routing Problem” or “Pickup-and-delivery Vehicle Routing Problem” or “Pick-up-and-delivery Vehicle Routing Problem” or “VRPPD” and “internal logistics” resulted in 10 documents. After executing the same limitations, the search resulted in 6 documents, which Table G.2 shows. The first article is about a heterogeneous VRP with cross-docking which is different than the BSK flow-VRP, because of the heterogenous and cross-docking aspects. The second article is about the vehicle routing problem with simultaneous pickup and delivery problem, which is also different than the BSK flow-VRP because of the simultaneous aspect. The third article is about a milk-run VRP, which incorporates time constraints that the BSK flow-VRP does not incorporate. Moreover, the LIFO loading constraints are also not incorporated in that article. The fourth article is also different than the BSK flow-VRP because of time constraints and the LIFO loading constraints. The fifth article incorporates heterogeneous constraints and does not have the LIFO loading constraints, which makes it different than the BSK flow-VRP. The sixth article also incorporates heterogenous and time constraints, without the LIFO loading constraints, which is also different than the BSK flow-VRP. Based on the preceding, 0 articles are found in literature that resemble the BSK flow-VRP when searching on “VRPPD” and “in-plant” or “internal logistics”.

Results of Scopus search on “Vehicle Routing Problem with Pick up and Delivery” or “Vehicle Routing Problem with Pickup and Delivery” or “Pickup and delivery Vehicle Routing Problem” or “Pickup-and-delivery Vehicle Routing Problem” or “Pick-up-and-delivery Vehicle Routing Problem” or “Vehicle Routing Problem with Pick-up and Delivery” and “internal logistics”	
#	Title
1.	The heterogeneous vehicle routing and truck scheduling problem in a multi-door cross-dock system
2.	Optimization for vehicle scheduling in iron and steel works based on semi-trailer swap transport
3.	An ordered-fuzzy-numbers-driven approach to the milk-run routing and scheduling problem
4.	Optimal vehicle route schedules in picking up and delivering cargo containers considering time windows in logistics distribution networks: A case study
5.	Scheduling heterogeneous delivery tasks on a mixed logistics platform
6.	Green last mile distribution system: Heterogeneous fleet vehicle routing problem with time window and external cost

Table G. 2. 6 articles from Scopus search for the Vehicle Routing Problem with Pickup and Delivery and internal logistics

G.4.2. Scopus search for VRP with Pickup and Delivery and LIFO loading constraints

A Scopus search on “Vehicle Routing Problem with Pickup and Delivery and LIFO loading constraints” results in 10 documents and after the same limitations are executed, there are 8 documents left. Table G.3 shows the titles of the articles found in this Scopus search. The first article is different from the BSK flow-VRP because of simultaneous pickups and deliveries and the use of two-dimensional loading constraints instead of LIFO loading constraints. The second, third, fourth, sixth and seventh article all have time windows which are not incorporated in the BSK flow-VRP. The fifth and eight article both describe the double traveling salesman problem, which is different than the BSK flow-VRP. Based on the preceding, 0 articles are found in literature that resemble the BSK flow-VRP when searching on “Vehicle Routing Problem with Pickup and Delivery and LIFO loading constraints”.

Results of Scopus search on "Vehicle Routing Problem with Pickup and Delivery and LIFO loading constraints"	
#	Title
1.	The Vehicle Routing Problem with Simultaneous Pick-ups and Deliveries and Two-Dimensional Loading Constraints
2.	Branch-price-and-cut algorithms for the pickup and delivery problem with time windows and last-in-first-out loading
3.	Branch-price-and-cut algorithms for the pickup and delivery problem with time windows and multiple stacks
4.	The multiple vehicle pickup and delivery problem with LIFO constraints
5.	A dynamic programming based local search approach for the double traveling salesman problem with multiple stacks
6.	A Fast Decomposition and Reconstruction Framework for the Pickup and Delivery Problem with Time Windows and LIFO Loading
7.	An exact algorithm for the pickup and delivery problem with time windows and last-in-first-out loading
8.	The double traveling salesman problem with partial last-in-first-out loading constraints

Table G. 3. 8 articles on Scopus search for the Vehicle Routing Problem with Pickup and Delivery and LIFO loading constraints

G.4.3. SLR for Pickup and Delivery Problem and LIFO loading constraints

Since the VRPPD is sometimes referred to as the Pickup and Delivery problem, we also executed a Scopus search on “Pickup and Delivery Problem” and “LIFO loading constraints” or “last-in first out”, which results in 48 documents. After the same limitations are executed, 36 documents remain, of which 20 articles were found in previous searches. Because of that, this search results in 16 new articles, that Table G.4 shows, while using the number from the Scopus search. Articles 1, 2, 3, 5, 7, 8, 10, 11, 17, 18, 24, 31, 32 and 34 describe the (double) traveling salesman problem, which is different than the BSK flow-VRP. Articles 28 and 36 are not about a VRP but uses pickup and delivery in their abstract. Based on the preceding, 0 articles are found in literature that resemble the BSK flow-VRP when searching on “Pickup and Delivery Problem” and “LIFO loading constraints” or “last-in first out”.

#	Title
	Results of Scopus search on "Pickup and Delivery Problem" and "LIFO loading constraints" or "last-in first out"
1.	Variable neighborhood search for the pickup and delivery traveling salesman problem with LIFO loading
2.	The double travelling salesman problem with multiple stacks - Formulation and heuristic solution approaches
3.	A branch-and-cut algorithm for the Pickup and Delivery Traveling Salesman Problem with LIFO loading
5.	An additive branch-and-bound algorithm for the pickup and delivery traveling salesman problem with LIFO or FIFO loading
7.	Multiple pickup and delivery traveling salesman problem with last-in-first-out loading and distance constraints
8.	Exact solutions to the double travelling salesman problem with multiple stacks
10.	A branch-and-cut algorithm for the double traveling salesman problem with multiple stacks
11.	A branch-and-bound algorithm for the double travelling salesman problem with two stacks
17.	The tree representation for the pickup and delivery traveling salesman problem with LIFO loading
18.	A branch-and-cut algorithm for the pickup and delivery traveling salesman problem with multiple stacks
24.	Formulations and algorithms for the Pickup and Delivery Traveling Salesman Problem with Multiple Stacks
28.	A Branch-and-Cut algorithm for factory crane scheduling problem
31.	Approximation of the Double Traveling Salesman Problem with Multiple Stacks
32.	What are the worst cases in constrained Last-In-First-Out pick-up and delivery problems?
34.	Valid inequalities and branch-and-cut algorithm for the pickup and delivery traveling salesman problem with multiple stacks
36.	The ground handler dock capacitated pickup and delivery problem with time windows: A collaborative framework for air cargo operations

Table G. 4. 16 new articles from Scopus search for Pickup and Delivery Problem and LIFO loading constraints

G.4.4. Conclusion on the SLR for the VRPPD and LIFO loading constraints

Our Scopus searches show that many articles about the VRP with Pickup and Delivery exists. However, including "in-plant" or "internal logistics" into our Scopus search, resembling the BSK flow that is part of the internal logistics at Scania Production Zwolle, results in a total of only 8 articles, of which all articles are different than the BSK flow-VRP. Moreover, our Scopus search on "Vehicle Routing Problem with Pickup and Delivery and LIFO loading constraints" resulted in 8 articles, of which all articles are different than the BSK flow-VRP. Based on the preceding, 0 articles are found in literature that resemble the BSK flow-VRP.

G.5. SLR for using metaheuristics to solve the VRPPD and LIFO loading constraints

Appendix G.5.1 explains the SLR for the VRPPD and Appendix G.5.2 explains the SLR for the VRPPD and LIFO loading constraints to substantiate our choice for a metaheuristic to solve the BSK flow-VRP.

G.5.1. SLR for the VRPPD

Section 3.1.3 explains that metaheuristics is chosen as our solution approach for solving the BSK flow-VRP. Figure 3.2 shows that metaheuristics are divided into local search and population search. Because of that, we conducted a SLR for the local search and population search metaheuristics. Our Scopus search consisted of: "Vehicle Routing Problem with Pick-up and Delivery" or "Vehicle Routing Problem with Pick up and Delivery" or "Vehicle Routing Problem with Pickup and Delivery" or "Pickup and delivery Vehicle Routing Problem" or "Pickup-and-delivery Vehicle Routing Problem" or "Pick-up-and-delivery Vehicle Routing Problem" and "local search", which resulted in 180 documents. After the same limitations are executed, 101 documents remain. Executing a similar search on Scopus for the population search instead of local search, results in 30 documents and after the same limitations are executed, 15 documents remain. Based on that, we conclude that the local search method is the most used method for solving a Vehicle Routing problem with Pickup and Delivery. From the local search methods, Tabu Search is the most used metaheuristic for solving a VRPPD. Moreover, from the local search methods, the Variable Neighbourhood Search and Simulated Annealing are the second and third most used metaheuristic for solving a VRPPD. Regarding the population search, Genetic Algorithms is the most used method to solve the VRPPD.

G.5.2. SLR for the VRPPD and LIFO loading constraints

Our Scopus search on "Vehicle Routing Problem with Pick-up and Delivery" or "Vehicle Routing Problem with Pick up and Delivery" or "Vehicle Routing Problem with Pickup and Delivery" or "Pickup and delivery Vehicle Routing Problem" or "Pickup-and-delivery Vehicle Routing Problem" or "Pick-up-and-delivery Vehicle Routing Problem" and "LIFO loading constraints" or "last-in first-out" resulted in

27 documents. After the same limitations are executed, there are 20 documents left, which Table G.5 shows. This Scopus search is used to get an overview of used metaheuristics for articles about VRPPD and LIFO loading constraints.

"Vehicle Routing Problem with Pick-up and Delivery" or "Vehicle Routing Problem with Pick up and Delivery" or "Vehicle Routing Problem with Pickup and Delivery" or "Pickup and delivery Vehicle Routing Problem" or "Pickup-and-delivery Vehicle Routing Problem" or "Pick-up-and-delivery Vehicle Routing Problem" and "LIFO loading constraints" or "last-in first-out"	
#	Title
1.	A population-based metaheuristic for the pickup and delivery problem with time windows and LIFO loading
2.	The Vehicle Routing Problem with Simultaneous Pick-ups and Deliveries and Two-Dimensional Loading Constraints
3.	Exact algorithms for the double vehicle routing problem with multiple stacks
4.	Branch-price-and-cut algorithms for the pickup and delivery problem with time windows and last-in-first-out loading
5.	Branch-price-and-cut algorithms for the pickup and delivery problem with time windows and multiple stacks
6.	Large neighborhood search for the pickup and delivery traveling salesman problem with multiple stacks
7.	The pickup and delivery traveling salesman problem with handling costs
8.	The multiple vehicle pickup and delivery problem with LIFO constraints
9.	A variable neighborhood search heuristic algorithm for the double vehicle routing problem with multiple stacks
10.	A dynamic programming based local search approach for the double traveling salesman problem with multiple stacks
11.	New formulation and branch-and-cut algorithm for the pickup and delivery traveling salesman problem with multiple stacks
12.	A learning-based memetic algorithm for the multiple vehicle pickup and delivery problem with LIFO loading
13.	Route design for last-in, first-out deliveries with backhauling
14.	The traveling purchaser problem, with multiple stacks and deliveries: A branch-and-cut approach
15.	A Fast Decomposition and Reconstruction Framework for the Pickup and Delivery Problem with Time Windows and LIFO Loading
16.	An exact algorithm for the pickup and delivery problem with time windows and last-in-first-out loading
17.	A study of perturbation operators for the pickup and delivery traveling salesman problem with LIFO or FIFO loading
18.	The double traveling salesman problem with partial last-in-first-out loading constraints
19.	The pickup and delivery problem with time windows, multiple stacks, and handling operations
20.	Pickup and delivery problem in the collaborative city courier service by using genetic algorithm and nearest distance

Table G. 5. 20 articles on solving VRPPD and LIFO loading constraints

Articles 1, 3, 4, 5, 8, 13, 15, 16 and 19 differ from the BSK flow-VRP because these articles incorporate time windows that are not incorporated into the BSK flow-VRP. Articles 8, 13 and 15 incorporate Tabu Search, or use Tabu Search to augment their GRASP, to solve their VRPPD with LIFO loading constraints and time windows. These articles that use Tabu Search are different from the BSK flow-VRP because of the incorporation of time windows. In article 15, Tabu Search is used to solve a VRP with time windows and LIFO loading constraints. The results show that Tabu Search is able to improve over 85% of the best-known solutions on 119 instances. Moreover, the required computational time is 1/50 of the comparative results, which confirms their efficiency. This shows that Tabu Search is able to produce good results for a VRPPD with Time Windows and LIFO loading constraints. The second article is about a VRP with simultaneous pickups and deliveries, which is different from the BSK flow-VRP because of the simultaneous aspect and the use of two-dimensional loading constraints instead of LIFO loading constraints. Articles 3, 6, 7, 10, 11, 12, 14, 17 and 18 describe the (double) traveling salesman problem, which is different than the BSK flow-VRP. Moreover, article 6 describes vehicles with a number of (horizontal) stacks of finite capacity for loading items from the rear of the vehicle, which is different than loading the fixtures onto the trailers in the BSK flow-VRP. Similarly, article 9 describes that the load compartment of all vehicles is divided into rows (horizontal stacks), which is also different than the fixtures that are loaded onto the trailers in the BSK flow-VRP. Article 20 is about collaborative pickup delivery problem, with internal jobs and outsourced jobs, which is different than the BSK flow-VRP that does not have a collaborative component.

From the 20 articles found in the Systematic Literature Review for VRP with Pickup and Delivery and LIFO loading constraints, 0 articles describe the BSK flow-VRP. This is because some articles incorporate time windows, (double) traveling salesman problem, the (horizontal) stacks of the vehicles, or a collaborative component, which is not present in the BSK flow-VRP. Based on the preceding, there is no Tabu Search available in literature that solves a problem that is the same as the BSK flow-VRP. Moreover, the 20 articles found in this Scopus Search are not used for internal logistics or in-plant.

Appendix H. Example from the BSK flow-VRP solution approach

Appendix H.1 shows via an example the construction of a route via the Nearest Neighbour Heuristic of our solution approach. Next, Appendix H.2 compares the routes from the NNH with the routes after Tabu Search. Afterwards, Appendix H.3 shows examples of neighbours to the initial solution from the NNH, as well as part of the candidate table to explain an iteration of Tabu Search. For readability of the plots, the figures in this appendix only show the warehouse nodes. Therefore, the Route_WH and the Route_WHBack are the same in the plots.

H.1. Construction of a route via the Nearest Neighbour Heuristic

This appendix explains the construction of the route of train 0, using our Nearest Neighbour Heuristic. This route uses the Strict LIFO strategy for time period 0, and Principle15minutes with type of trailer 2. Table H.1 shows the fixtures that are not yet assigned and shows that fixture 104 has the lowest travel distance from their warehouse location to their line location, shortened to Distance. Therefore, fixture 104 is assigned as the first fixture to train 0, as Figure H.1 shows the route.

Assigning the First Fixture: Time Period=0, Train=0
Minimum Distance from WH to LL=281.8, FixtureNR=104

FixtureNR	UniqueNR	IndexNR	LowerBound	Distance	Capacity
104	0	5	6:00:00	281.8	1.0
104	1	5	6:00:00	281.8	1.0
106	2	7	6:00:00	392.6	1.0
106	3	7	6:00:00	392.6	1.0
112	4	14	6:00:00	486.8	1.0
112	5	14	6:00:00	486.8	1.0
114	6	16	6:00:00	488.8	1.0
116	7	18	6:00:00	487.3	1.0

Table H. 1. Assigning the first fixture to train 0

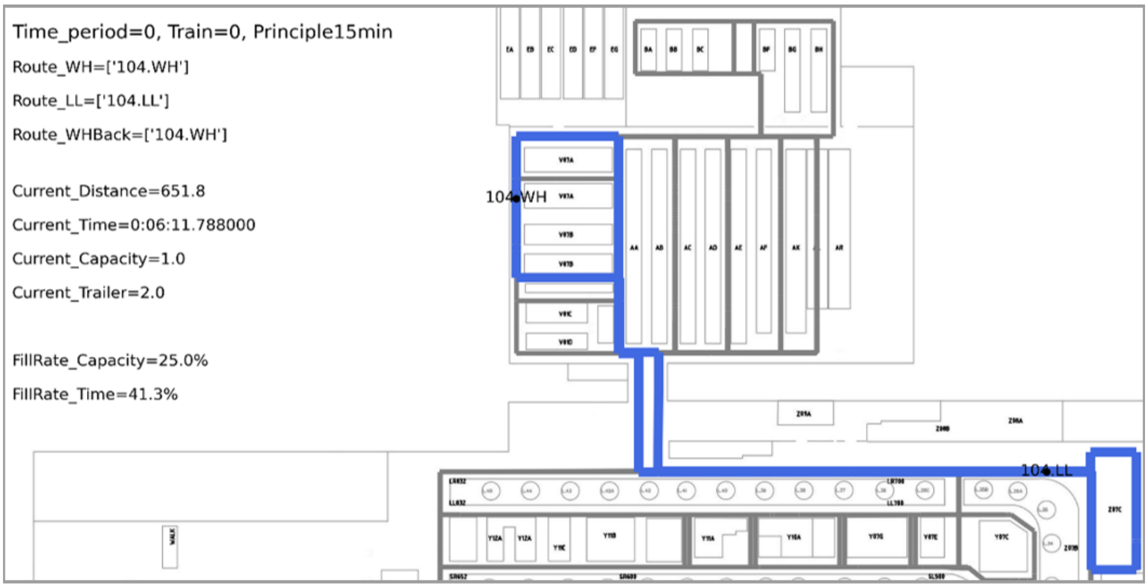

Figure H. 1. Route after the first fixture is assigned to train 0

Table H.2 gives an overview of the fixtures that are not yet assigned, and that can be assigned to train 0 as the Nearest Neighbour, after the first fixture is assigned. This table shows that fixture 104 has the lowest Total Travel Distance (shortened to TotalDistance) and is therefore assigned to train 0 as the Nearest Neighbour. Figure H.2 shows the route after fixture 104 is assigned as the second fixture to the route of train 0.

Assigning the Nearest Neighbour: Time Period=0, Train=0
Minimum Total Distance=651.8, FixtureNR=104

FixtureNR	UniqueNR	IndexNR	Capacity	TotalDistance	TotalTravelTime
104	1	5	1.0	651.8	0 days 00:07:25.288000
106	2	7	1.0	823.1	0 days 00:08:52.372000
106	3	7	1.0	823.1	0 days 00:08:52.372000
112	4	14	1.0	1106.1	0 days 00:11:02.223000
112	5	14	1.0	1106.1	0 days 00:11:02.223000
114	6	16	1.0	1280.5	0 days 00:12:20.711000
116	7	18	1.0	1282.0	0 days 00:12:21.386000

Table H. 2. Assigning the Nearest Neighbour to train 0 – second fixture

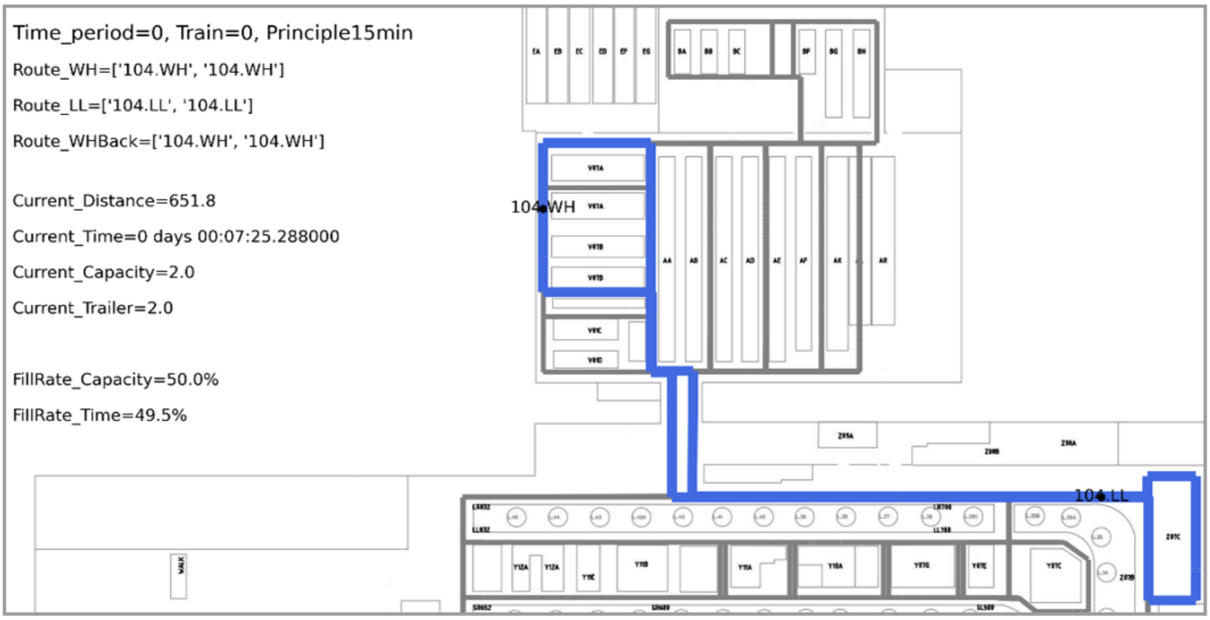

Figure H. 2. Route after the second fixture is assigned to train 0

Table H.3 gives an overview of the fixtures that are not yet assigned, and that can be assigned to train 0 as the Nearest Neighbour, after fixture 104 is assigned as the second fixture. This table shows that fixture 106 has the lowest Total Travel Distance and is therefore assigned to train 0 as the Nearest Neighbour. Figure H.3 shows the route after fixture 106 is assigned as the third fixture to the route of train 0.

Assigning the Nearest Neighbour: Time Period=0, Train=0
Minimum Total Distance=823.1, FixtureNR=106

FixtureNR	UniqueNR	IndexNR	Capacity	TotalDistance	TotalTravelTime
106	2	7	1.0	823.1	0 days 00:10:05.872000
106	3	7	1.0	823.1	0 days 00:10:05.872000
112	4	14	1.0	1106.1	0 days 00:12:15.723000
112	5	14	1.0	1106.1	0 days 00:12:15.723000
114	6	16	1.0	1280.5	0 days 00:13:34.211000
116	7	18	1.0	1282.0	0 days 00:13:34.886000

Table H. 3. Assigning the Nearest Neighbour to train 0 – third fixture

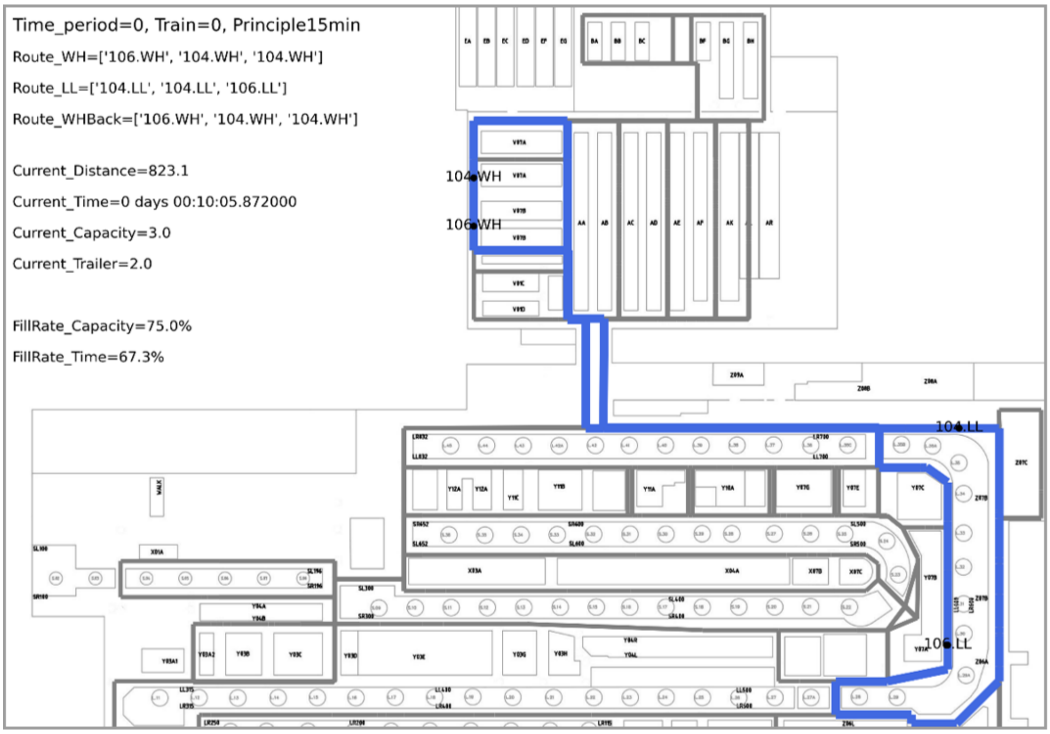

Figure H. 3. Route after the third fixture is assigned to train 0

Table H.4 shows that fixture 106 is the only fixture that can be assigned to the route of train 0, after fixture 106 is assigned to train 0 as the third fixture. Therefore, fixture 106 is assigned to train 0 as the Nearest Neighbour. Figure H.4 shows the final route of train 0, after fixture 106 is assigned as the fourth fixture to the route of train 0.

Assigning the Nearest Neighbour: Time Period=0, Train=0
Minimum Total Distance=823.1, FixtureNR=106

FixtureNR	UniqueNR	IndexNR	Capacity	TotalDistance	TotalTravelTime
106	3	7	1.0	823.1	0 days 00:11:19.372000

Table H. 4. Assigning the Nearest Neighbour to train 0 – fourth fixture

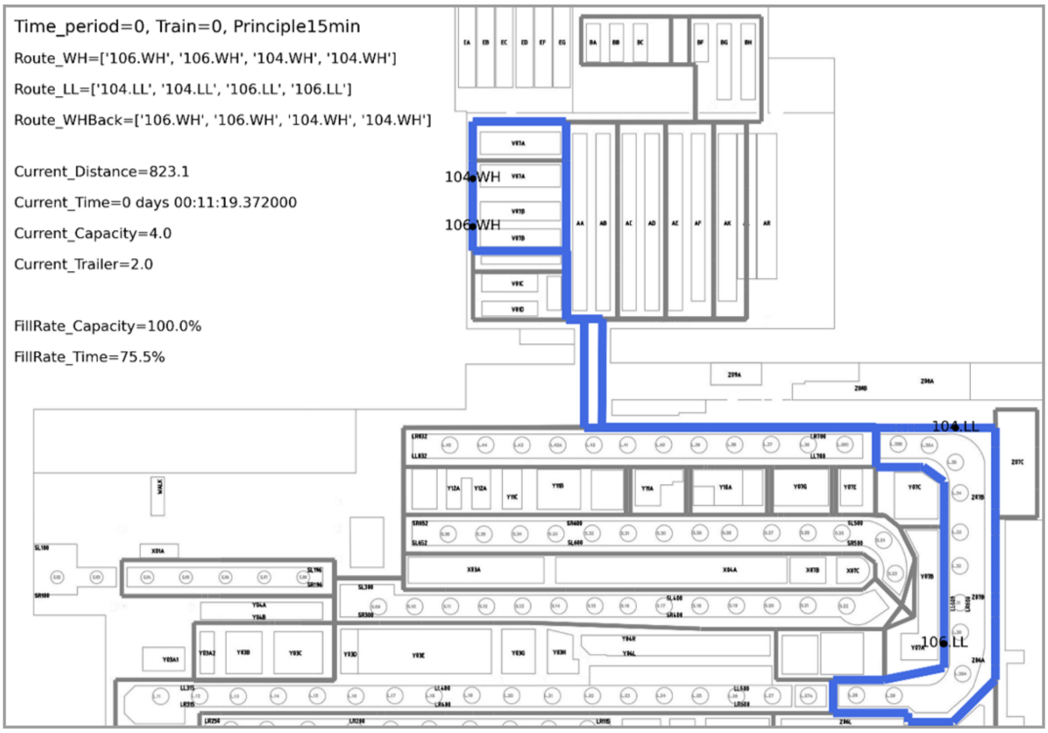

Figure H. 4. Route after the fourth fixture is assigned to train 0

H.2 Comparison of routes from the Nearest Neighbour Heuristic and Tabu Search

In this section we compare the routes from the Nearest Neighbour Heuristic with the routes after Tabu Search. This comparison is made for a solution example. The solution example consists of the results while using the Strict LIFO strategy for time period 0, and Principle15minutes with type of trailer 1. Table H.5 shows the results of the NNH and Tabu Search for this instance. This table shows for the 5 trains the Route_LL (FixtureNr), the Route_LL (UniqueNR), the used capacity (CurrentCapacity), the total travel distance (CurrentDistance), the total travel time (CurrentTime), the physical fill rate (FillRateCapacity), and the time fill rate (FillRateTime). The sum of the total travel distance after the NNH is 5347.7 meters, which decreases to 4718.1 after Tabu Search. Because the routes improve, the total travel distance as well as the travel time decreases. The total travel time also decreases, from 58 minutes and 28 seconds to 53 minutes and 35 seconds. For this instance, the number of required trains remains the same. Since the total travel time decreases and the number of required trains remains the same, the average time fill rate decreases from 77.9% to 71.4%. Furthermore, the average physical fill rate is 65.0% after the NNH. Since the number of required trains remains the same after Tabu Search, the average physical fill rate remains the same. The route of train 0 did not change during Tabu Search.

Results after Nearest Neighbour Heuristic	Route_LL (FixtureNR)	Route_LL (UniqueNR)	CurrentCapacity	CurrentDistance	CurrentTime	FillRateCapacity	FillRateTime
Train0_NNH	[122, 123, 4, 8]	[12, 13, 0, 1]	3.5	782.6	00:10:59	87.5%	73.2%
Train1_NNH	[10, 11, 14, 87]	[3, 4, 5, 6]	3.5	1246.5	00:14:27	87.5%	96.4%
Train2_NNH	[9, 118, 107]	[2, 11, 10]	3	1447.1	00:14:57	75.0%	99.6%
Train3_NNH	[91, 88]	[8, 7]	2	1220.3	00:11:49	50.0%	78.7%
Train4_NNH	[105]	[9]	1	651.2	00:06:17	25.0%	41.8%
Results after Tabu Search	**Route_LL (FixtureNR)**	**Route_LL (UniqueNR)**	**CurrentCapacity**	**CurrentDistance**	**CurrentTime**	**FillRateCapacity**	**FillRateTime**
Train0_TabuSearch	[122, 123, 4, 8]	[12, 13, 0, 1]	3.5	782.6	00:10:59	87.5%	73.2%
Train1_TabuSearch	[10, 11]	[3, 4]	2	696.7	00:07:51	50.0%	52.3%
Train2_TabuSearch	[118, 9, 14]	[11, 2, 5]	2.5	1181.1	00:12:47	62.5%	85.2%
Train3_TabuSearch	[88, 91, 87]	[7, 8, 6]	3	1236.1	00:13:12	75.0%	88.0%
Train4_TabuSearch	[105, 107]	[9, 10]	2	821.6	00:08:47	50.0%	58.5%

Table H. 5. Output of trains 0 to 4 from Strict LIFO in time period 0 of Principle15minutes with type of trailer 1

Figures H.5 and H.6, on Page 88, show the routes of the NNH in two plots. Figure H.5 shows in one plot the train routes from the NNH of trains 1 and 2 of this instance. Moreover, Figure H.6 shows for the same instance the train routes of trains 3 and 4. Figures H.5 and H.6 show the total travel distances of the individual routes. Furthermore, the total travel distance of the two routes in Figure H.5 is 2693.6 meters and in Figure H.6 is 1871.5 meters, which is a total of 4565.1 meters. The total travel distance of train 0 is 782.6 meters, resulting in a total travel distance of 5347.7 meters for this instance after the NNH.

Figures H.7 and H.8, on Page 89, show the routes after Tabu Search in two plots. Figure H.7 shows in one figure the train routes of trains 1 and 2 after Tabu Search of this instance. Moreover, Figure H.8 shows for the same instance the train routes of trains 3 and 4 after Tabu Search. The total travel distances of the individual routes are shown. The total travel distance of the two routes in Figure H.7 decreases after Tabu Search to 1877.8 meters and in Figure H.8 to 2057.7 meters, which is a total of 3935.5 meters. Recall from Table H.5 that the route of train 0 remains the same after Tabu Search, with a total travel distance of 782.6 meters. Therefore, the total travel distance for this instance after Tabu Search decreases from 5347.7 meters to 4718.1 meters.

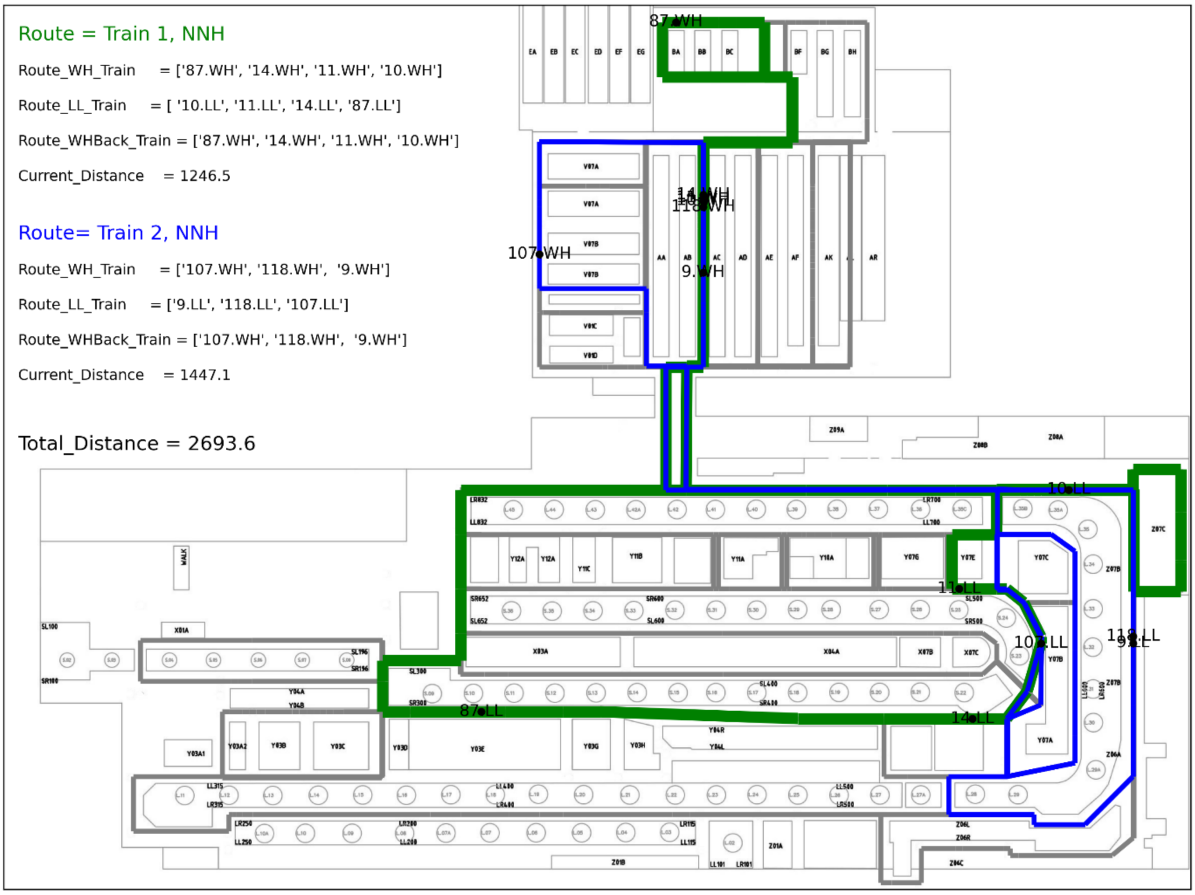

Figure H. 5. NNH routes of trains 1 and 2

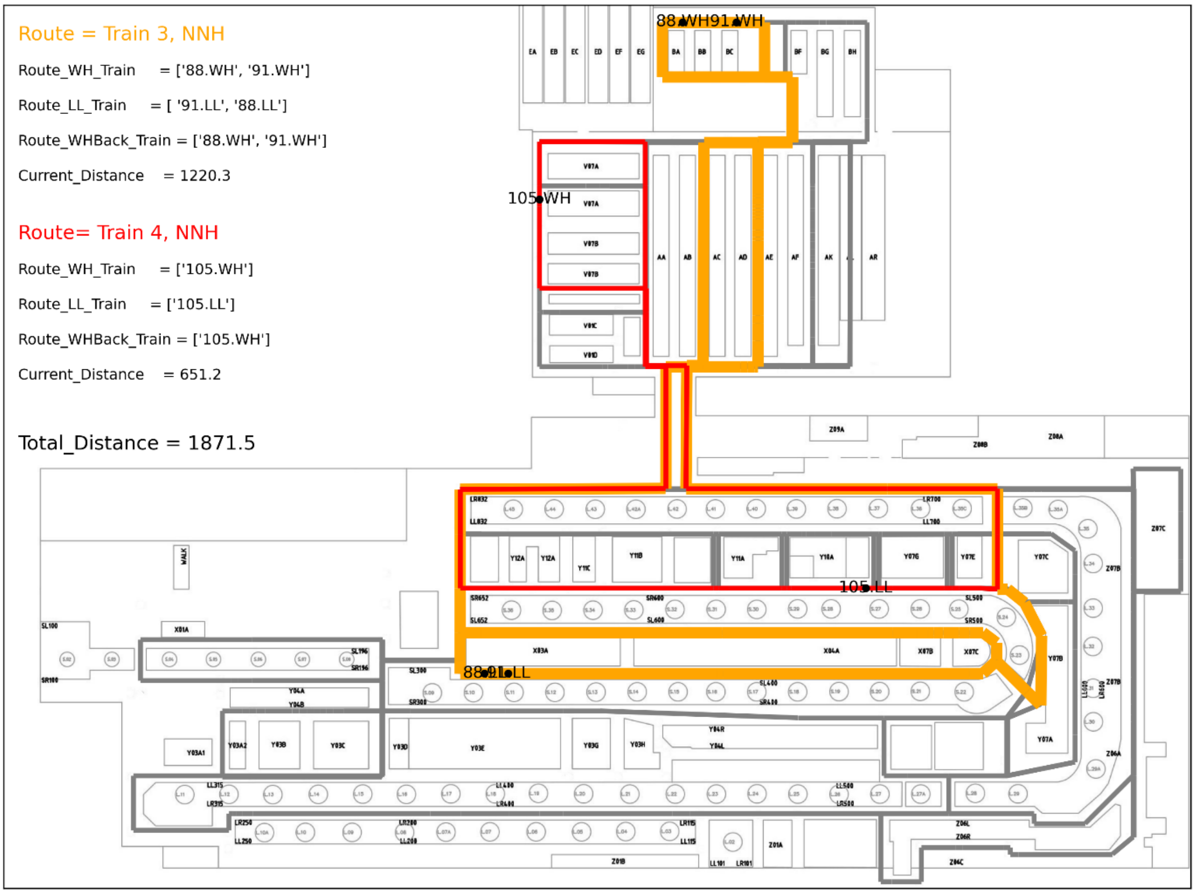

Figure H. 6. NNH routes of trains 3 and 4

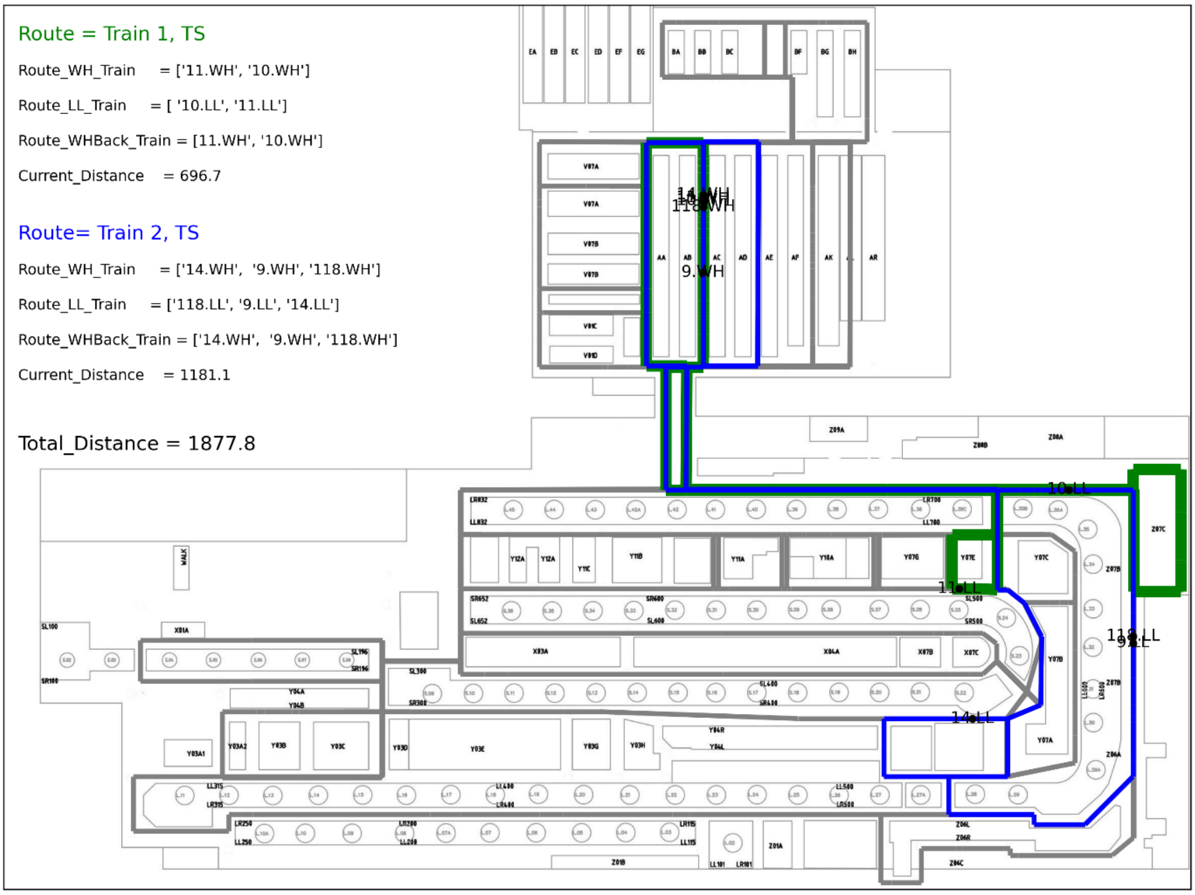

Figure H. 7. Tabu Search routes of trains 1 and 2

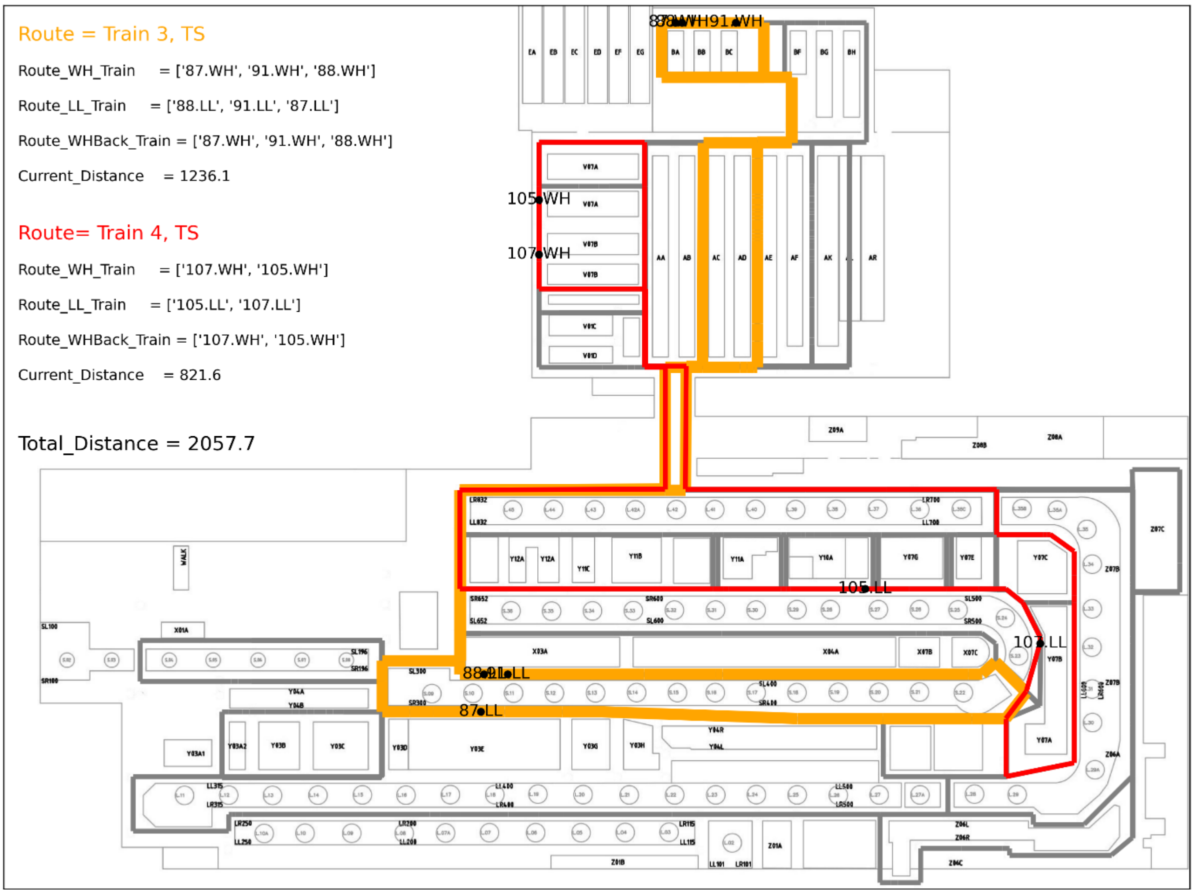

Figure H. 8. Tabu Search routes of trains 3 and 4

H.3. Example of neighbours and a part of the candidate table from Tabu Search

Table H.6 shows the information from the summary file after the Nearest Neighbour Heuristic is executed while using the Strict LIFO strategy for time period 0, and Principle15minutes with type of trailer 1. The total travel distance at the beginning of Tabu Search is 24420.7 meters, which is the Best Solution S* and the Current Solution S. This initial total travel distance is the total travel distance after the NNH is executed for all time periods of Principle15minutes and type of trailer 1. Based on the current routes, we execute swaps and moves. This way, we create a candidate table of neighbours to the current solution.

Results after Nearest Neighbour Heuristic	Route_LL (FixtureNR)	Route_LL (UniqueNR)	CurrentCapacity	CurrentDistance	CurrentTime	FillRateCapacity	FillRateTime
Train0_NNH	[122, 123, 4, 8]	[12, 13, 0, 1]	3.5	782.6	00:10:59	87.5%	73.2%
Train1_NNH	[10, 11, 14, 87]	[3, 4, 5, 6]	3.5	1246.5	00:14:27	87.5%	96.4%
Train2_NNH	[9, 118, 107]	[2, 11, 10]	3	1447.1	00:14:57	75.0%	99.6%
Train3_NNH	[91, 88]	[8, 7]	2	1220.3	00:11:49	50.0%	78.7%
Train4_NNH	[105]	[9]	1	651.2	00:06:17	25.0%	41.8%

Table H. 6. Summary file of the NNH for time period 0, and Principle15minutes with type of trailer 1.

For time period 0, we show examples of neighbours as well as a part of the candidate table. An important notion is that we use the Unique fixture number (UniqueNR) while we execute the swaps and moves. Table H.7 shows the new route of Route_i and Table H.8 shows the new route of Route_k, both after executing move 2342: we move Unique fixture number 10 (fixture place 3) from train 2 to the second fixture place on train 4. This move results in 2 fixtures per train. For each neighbour, we calculate the new total travel distance, the new total travel time, and the new used capacity. In case the neighbour solution violates the total travel time or the maximum capacity constraints, it is deleted from the candidate table.

Calculation_i: Distances, TravelTime, CurrentCapacity_i, Route_i, iteration= 0, Train_i, Fixture_j, Train_k, Fixture_l =2342

WH_pickup_distance	WHtoLine_distance	LL_distance	LLtoWH_distance	WH_delivery_distance	TotalDistance_Route
19.2	256.6	310.2	469.7	19.2	1074.9

WH_pickup_time	WHtoLine_time	LL_time	LLtoWH_time	WH_delivery_time	TotalTime_Route
0:00:57.640000	0:02:00.463000	0:03:18.595000	0:03:41.376000	0:00:57.640000	0:10:55.714000

TS_CurrentCapacity_i	Route_i
2.0	[2, 11]

Table H. 7. Route_i after executing move 2342

Calculation_k: Distances, TravelTime, CurrentCapacity_k, Route_k,iteration= 0, Train_i, Fixture_j, Train_k, Fixture_l =2342

WH_pickup_distance	WHtoLine_distance	LL_distance	LLtoWH_distance	WH_delivery_distance	TotalDistance_Route
16.0	363.9	60.9	364.8	16.0	821.6

WH_pickup_time	WHtoLine_time	LL_time	LLtoWH_time	WH_delivery_time	TotalTime_Route
0:00:56.200000	0:02:48.759000	0:01:16.416000	0:02:49.164000	0:00:56.200000	0:08:46.739000

TS_CurrentCapacity_k	Route_k
2.0	[9, 10]

Table H. 8. Route_k after executing move 2342

Tables H.9 and H.10 show the results of swap 0011: swapping Unique fixture number 12 (fixture place 0) from train 0, with Unique fixture number 4 (fixture place 1) from train 1. Table H.10 shows that the total travel time of the new route from train k violates the maximum travel time of 15 minutes. Therefore, this neighbour is deleted from the candidate table.

Calculation_i: Distances, TravelTime, CurrentCapacity_i, Route_i, iteration= 0, Train_i, Fixture_j, Train_k, Fixture_l =0011

WH_pickup_distance	WHtoLine_distance	LL_distance	LLtoWH_distance	WH_delivery_distance	TotalDistance_Route
140.7	237.6	90.2	411.1	140.7	1020.3

WH_pickup_time	WHtoLine_time	LL_time	LLtoWH_time	WH_delivery_time	TotalTime_Route
0:02:41.293000	0:01:51.905000	0:02:21.108000	0:03:10.002000	0:02:41.293000	0:12:45.601000

TS_CurrentCapacity_i	Route_i
3.5	[4, 13, 0, 1]

Table H. 9. Route_i after executing swap 0011

Calculation_k: Distances, TravelTime, CurrentCapacity_k, Route_k,iteration= 0, Train_i, Fixture_j, Train_k, Fixture_l =0011

WH_pickup_distance	WHtoLine_distance	LL_distance	LLtoWH_distance	WH_delivery_distance	TotalDistance_Route
276.0	213.8	469.1	392.9	276.0	1627.8

WH_pickup_time	WHtoLine_time	LL_time	LLtoWH_time	WH_delivery_time	TotalTime_Route
0:03:42.193000	0:01:38.715000	0:05:11.610000	0:03:04.308000	0:03:42.193000	0:17:19.019000

TS_CurrentCapacity_k	Route_k
3.5	[3, 12, 5, 6]

Table H. 10. Route_k after executing swap 0011

After all possible neighbours are added to the candidate table, we find the best Solution S' with the lowest Total Travel Distance, shortened to TS_TotalDistance, from the candidate table. Table H.11 shows a part of the candidate table, where we sorted the Total Travel Distance from low to high for the possible neighbours. This table shows that for Index 34, which is move 2342, results in the lowest Total Travel Distance of 24218.9 meters, which is a decrease of 201.8 meters.

Index	Train_i	Fixture_j	Train_k	Fixture_l	TS_NewRoute_i	TS_NewRoute_k	TS_TotalDistance
34	2	3	4	2	[2, 11]	[9, 10]	24218.9
1	3	1	3	2	[7, 8]	[7, 8]	24238.8
23	1	3	3	3	[3, 4, 5]	[8, 7, 6]	24257.8
30	2	2	4	1	[2, 9, 10]	[11]	24301.4
33	2	3	4	1	[2, 11, 9]	[10]	24385.1
0	2	1	2	2	[11, 2, 10]	[11, 2, 10]	24416.7
27	2	1	4	0	[11, 10]	[2, 9]	24503.2
29	2	2	4	0	[2, 10]	[11, 9]	24503.2
32	2	3	4	0	[2, 11]	[10, 9]	24518.4
17	1	0	4	0	[4, 5, 6]	[3, 9]	24526.2

Table H. 11. Part of the candidate table

Appendix I. Inputs and outputs of the solution approach for the BSK flow-VRP

Section 4.4 describes the solution approach for the BSK flow-VRP. This appendix shows the input and the output of the solution approach.

I.1. Input of the solution approach

To be able to calculate the travel distance and the travel time between locations, we use the network of Scania Production Zwolle (I.1.1). This network results in the travel distances and the travel times between all warehouse and line locations of each fixture. Other input data is the data of each instance, which consists of information about the fixtures (I.1.2) as well as time information and time periods (I.1.3). Moreover, we import tables from Excel (I.1.4.) that will be filled during the execution of the NNH. Since Tabu Search is executed after the NNH, the same data about the instance is available.

I.1.1. Network of Scania Production Zwolle

The train drivers use the network of Scania Production Zwolle to drive their routes. We model the network of SPZ as a graph. As Section 3.1.1 explained, a VRP can be defined on graph $G = (V, E)$ (Cordeau et al, 2005). A graph G consists of a vertex set V and an edge set E. The graph G of SPZ is modelled as a directed weighted graph. This means that each edge goes in only one direction and each edge has a numerical weight. The numerical weight consists of the travel distance and travel time, separately, as explained further in this appendix.

The trains cannot make a U-turn. Because of that, the network needs to be a directed graph. However, some roads can be traversed both ways. Therefore, in consultation with the BSK flow engineers, we created parallel vertexes where needed. This way, all line locations and warehouse locations can be reached without making U-turns. Figure I.1 shows in grey the edges that are connected to the line and the warehouse locations. Therefore, the grey edges are used for the delivery and the pickup of fixtures. Moreover, the parallel edges are shown in brown. Those edges are used to make the necessary connections possible, without the trains being able to make a U-turn. The use of parallel edges is necessary because with an undirected graph, U-turns are possible, which is in reality not possible.

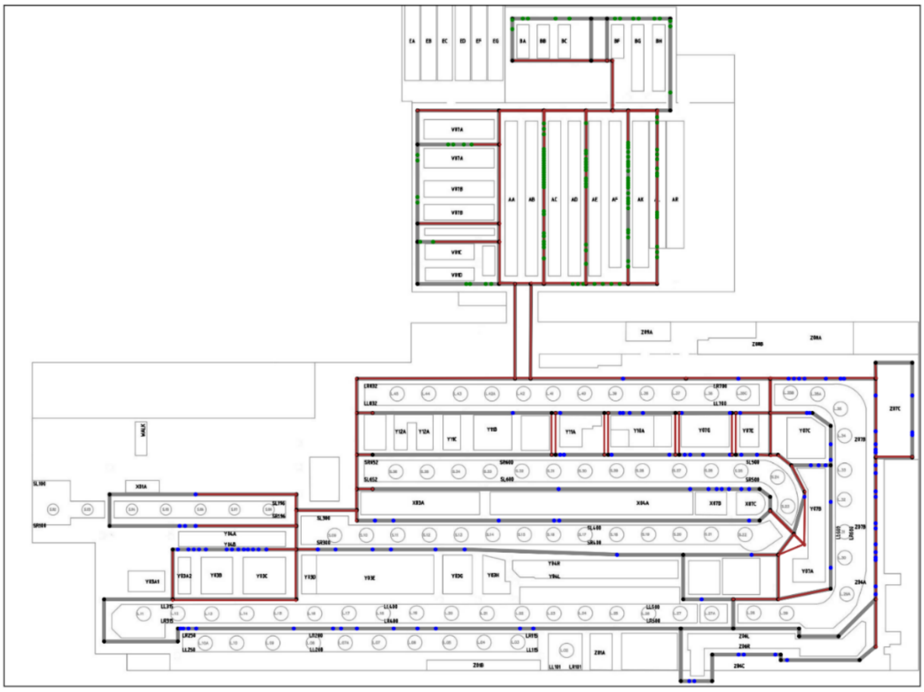

Figure I. 1. Network of Scania Production Zwolle

To determine the travel distance and the travel time in the network of SPZ, we use Dijkstra's algorithm. Dijkstra's algorithm determines the shortest routes between the source node and every other node in the network (Taha, 2018). For our solution approach, using Dijkstra's algorithm results in the shortest paths between all source nodes and every other node in the network of SPZ. Moreover, depending on the weight, the output of the shortest paths shows the travel time or the travel distance of the shortest paths.

I.1.2. Information about the fixtures

Table I.1 shows the input data of the first four fixtures of dataset 3 of Principle15minutes and type of trailer 1. Each dataset consists of the same columns, which are: Fixture Number; Unique number; Index Number; Logistical Tact Time (Tact time * principle); Tact Time Castor/Pollux; Lower Bound Time Period (LowerBoundTP); Upper Bound Time Period (UpperBoundTP); Principle; Size of the fixture; Type of trailer (Name); Castor/Pollux; Percentage (Regular = 1, or Special).

Fixture number	Unique number	Index number	Logistical Tact Time	Tact Time Castor/Pollux	Lower Bound Time Period	Upper Bound Time Period	Principle	Size Of The Fixture	Type Of Trailer(Name)	Castor/Pollux Tact Time	Percentage
4	0	55	00:15:00	00:15:00	06:00:00	06:15:00	1	0.5	Rothar	P	1
8	1	96	00:15:00	00:15:00	06:00:00	06:15:00	1	1	Rothar	P	1
9	2	106	00:15:00	00:07:30	06:00:00	06:15:00	2	1	Rothar	C	1
10	3	0	00:15:00	00:07:30	06:00:00	06:15:00	2	1	Rothar	C	1

Table I. 1. Part of the input data of the fixtures with a logistical tact time of 15 minutes

I.1.3. Time information and time periods

Table I.2 shows the time information for all principles. The start time, the end time and the tact time (Castor and Pollux) are given. Moreover, for each principle the logistical tact time is calculated, as Tact time * Principle. Principle 1 is the only Pollux principle, resulting in a logistical tact time of 15:00 minutes. Besides the time, also the number of time periods is given per principle. Based on the start time, the end time and the logistical tact time, the time periods are determined per principle. Table I.3 shows the first 3 time periods for Principle 1 (Pollux) and Principle 2 (Castor).

Time information - all principles

Time info	StartTime	EndTime	TactTime_Castor	TactTime_Pollux	Principle2	Principle3	Principle4	Principle6	Principle1_Pollux
Time	06:00:00	23:15:00	00:07:30	00:15:00	00:15:00	00:22:30	00:30:00	00:45:00	00:15:00
NumberOfTimePeriods	nan	nan	nan	nan	69	46	34.5	23	69

Table I. 2. Time information for all principles

Time periods for Logistical Tact Time of 15 minutes (Principle 1 Pollux and 2 Castor)

TimePeriods
06:00:00
06:15:00
06:30:00

Table I. 3. First 3 time periods for the principles with logistical tact time of 15 minutes

I.1.4. Importing or construction of lists and tables and setting parameters

Besides the input data about the fixtures and time information, we also import tables from Excel that we use during the execution of our solution approach. Besides importing tables, we also construct tables in our solution approach. Moreover, we construct lists in our solution approach. After the data is imported and lists and tables are imported or constructed, we initialise parameters. We initialise the following parameters: Maximum Travel Time; Number of trains; Train Capacity; Number of time periods; Changing time per fixture.

I.2. Output of the solution approach

The output of the Nearest Neighbour Heuristic consists of a Summary file, an Output file and Route plots. Once Tabu Search is executed, our solution approach also creates the following Tabu Search output: a Summary file, an Output file and Route plots.

I.2.1. Summary file

The summary file contains a summary sheet for each time period. Table I.4 shows the summary of using the Strict LIFO strategy of time period 0 for Principle15minutes and type of trailer 1. Each summary sheet shows per train the following information: the Route_LL (FixtureNr), the Route_LL (UniqueNR), the used capacity (CurrentCapacity), the total travel distance (CurrentDistance), the total travel time (CurrentTime), the physical fill rate (FillRateCapacity), and the time fill rate (FillRateTime).

Results after Nearest Neighbour Heuristic	Route_LL (FixtureNR)	Route_LL (UniqueNR)	CurrentCapacity	CurrentDistance	CurrentTime	FillRateCapacity	FillRateTime
Train0_NNH	[122, 123, 4, 8]	[12, 13, 0, 1]	3.5	782.6	00:10:59	87.5%	73.2%
Train1_NNH	[10, 11, 14, 87]	[3, 4, 5, 6]	3.5	1246.5	00:14:27	87.5%	96.4%
Train2_NNH	[9, 118, 107]	[2, 11, 10]	3	1447.1	00:14:57	75.0%	99.6%
Train3_NNH	[91, 88]	[8, 7]	2	1220.3	00:11:49	50.0%	78.7%
Train4_NNH	[105]	[9]	1	651.2	00:06:17	25.0%	41.8%

Table I. 4. Summary from Strict LIFO of time period 0 for Principle15min and type of trailer 1

I.2.2. Output file

The output file is based on the fixture input file. Three columns are added that show per fixture their pickup and delivery times. Due to the many columns, Table I.5 shows only the first 10 columns. The columns after the Principle column are the same as in Table I.1, which shows the input data.

	FixtureNumber	UniqueNR	IndexNR	LogisticalTactTime	LowerBoundTimeWindow	UpperBoundTimeWindow	WH_pickup	LL_delivery	WH_empty_delivery	Principle
0	4	0	55	00:15:00	06:00:00	06:15:00	06:00:53	06:05:39	06:10:08	1
1	8	1	96	00:15:00	06:00:00	06:15:00	06:00:24	06:06:05	06:09:39	1
2	9	2	106	00:15:00	06:00:00	06:15:00	06:02:07	06:04:32	06:14:57	2
3	10	3	0	00:15:00	06:00:00	06:15:00	06:02:29	06:04:32	06:14:27	2
4	11	4	11	00:15:00	06:00:00	06:15:00	06:02:04	06:06:30	06:14:03	1
5	14	5	31	00:15:00	06:00:00	06:15:00	06:01:39	06:07:25	06:13:38	1
6	87	6	103	00:15:00	06:00:00	06:15:00	06:00:24	06:08:55	06:12:23	1
7	88	7	104	00:15:00	06:00:00	06:15:00	06:00:24	06:06:41	06:11:17	1
8	91	8	108	00:15:00	06:00:00	06:15:00	06:00:56	06:03:49	06:11:49	1
9	105	9	6	00:15:00	06:00:00	06:15:00	06:00:24	06:03:38	06:06:17	1

Table I. 5. Part of the output file

The output file also has the following sheets that show the following data as output: the Route_LL (FixtureNr), the Route_LL (UniqueNR), the used capacity (CurrentCapacity), the total travel distance (CurrentDistance), the total travel time (CurrentTime), the physical fill rate (FillRateCapacity), and the time fill rate (FillRateTime). In our solution approach we call them “Currents” because they give the current total travel distance, the current capacity, and the current total travel time of the route.

I.2.3. Plots

Our solution approach creates individual train routes that are generated automatically and saved individually per figure. Besides the train routes, these figures also present information about the time period, the train, and the principle. Moreover, the plot shows the Total Route: the Total Route consists of the route inside the warehouse to pick up the full fixtures (Route_WH), the route at the assembly line to deliver the full fixtures and to pick up the empty fixtures (Route_LL), and the route inside the warehouse to deliver the empty fixtures (Route_WHBack). The figures also give the following information about the route: the total travel distance (CurrentDistance), the total travel time (CurrentTime), the used capacity (CurrentCapacity), the physical fill rate (FillRateCapacity), and the time fill rate (FillRateTime). Figure 4.4 show an example of a plot from our solution approach.

Appendix J. All results of experiment 4

Section 5.6 shows the results of the random experiments for the No Policy strategy. This appendix shows the complete tables for each random experiment for the No Policy, Adapted Partial LIFO, and Strict LIFO strategy. We run each instance 5 times to generate the results of the random experiments. This results in the maximum, minimum, and average results per Key Performance Indicator in comparison with the standard Nearest Neighbour Heuristic and Tabu Search results. Recall that for experiment 4, the standard NNH is the NNH that is adapted to the BSK flow-VRP. In the remainder of this appendix this is shortened to the standard NNH.

J.1. Experiment 4.1: random run of 4 times periods for all principles

Table J.1 shows the results of Experiment 4.1 for all used loading constraints. This experiment executes 4 time periods of all principles. This table shows that the random Tabu Search results are worse in comparison to the results of Tabu Search after the standard Nearest Neighbour Heuristic. This is traced back to the larger instances (Principle15min_Type1 and Principle15min_Type2), which yields worse Tabu Search results in comparison to the results of Tabu Search after the standard NNH.

Experiment	Used loading constraints	Experiment name		Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E4.1 Random: 4 time periods	No Policy	No Randomness	NNH	53.30	0.43	12	11	11.50	87.21%	63.66%	00:00:54
		No Randomness	TS	47.20	0.40	12	11	11.50	87.21%	58.62%	00:09:05
		Random: minimum	NNH	72.50	0.54	15	12	13.25	78.43%	67.98%	00:00:25
		Random: minimum	TS	48.50	0.41	14	12	12.75	79.69%	53.71%	00:08:11
		Random: maximum	NNH	78.20	0.57	16	13	14.00	80.19%	72.91%	00:00:49
		Random: maximum	TS	51.80	0.42	14	12	13.50	81.33%	55.68%	00:09:08
		Random: average	NNH	75.28	0.55	15.6	12.4	13.60	79.26%	69.67%	00:00:33
		Random: average	TS	50.72	0.42	14	12	13.00	80.72%	54.65%	00:08:31
	Adapted Partial LIFO	No Randomness	NNH	57.40	0.45	12	11	11.50	87.21%	67.15%	00:00:16
		No Randomness	TS	47.90	0.40	12	11	11.25	87.96%	60.62%	00:06:17
		Random: minimum	NNH	74.40	0.55	15	12	13.50	77.26%	67.86%	00:00:15
		Random: minimum	TS	50.40	0.42	13	11	12.50	81.13%	55.58%	00:05:40
		Random: maximum	NNH	79.00	0.57	16	13	14.25	79.69%	71.23%	00:00:16
		Random: maximum	TS	51.50	0.42	14	12	13.00	82.28%	57.22%	00:06:03
		Random: average	NNH	76.04	0.56	15.4	12.6	13.85	78.71%	69.28%	00:00:15
		Random: average	TS	51.00	0.42	13.8	11.4	12.65	81.87%	56.51%	00:05:51
	Strict LIFO	No Randomness	NNH	58.70	0.46	12	11	11.50	87.21%	68.00%	00:00:16
		No Randomness	TS	51.20	0.42	12	11	11.50	87.21%	62.25%	00:08:05
		Random: minimum	NNH	79.70	0.58	15	12	14.00	77.26%	71.85%	00:00:15
		Random: minimum	TS	53.70	0.43	14	11	12.75	78.89%	56.45%	00:06:04
		Random: maximum	NNH	82.40	0.59	17	13	14.50	78.43%	72.88%	00:00:15
		Random: maximum	TS	55.80	0.45	16	12	13.75	81.68%	59.61%	00:06:47
		Random: average	NNH	81.60	0.59	16.2	12.6	14.20	77.85%	72.37%	00:00:15
		Random: average	TS	55.10	0.44	14.8	11.6	13.20	80.44%	57.86%	00:06:32

Table J. 1. Results of experiment 4.1 for all used loading constraints

J.2. Experiment 4.2: random run of 4 times periods for small principles

Table J.2 shows the results of experiment 4.2 for all used loading constraints. This experiment executes 4 time periods of the small principles: Principle3_Type1, Principle3_Type2, Principle 4 and Principle 6. This table shows that the random Tabu Search results of the small principles for the No Policy loading constraints are better in comparison to the results of Tabu Search after the standard Nearest Neighbour Heuristic. For the Adapted Partial LIFO and Strict LIFO loading constraints, the random Tabu Search results are comparable with the Tabu Search results after the standard NNH.

Experiment	Used loading	Experiment name		Total Distance	Total Travel Time	Maximum number	Minimum number	Average number	Average Physical	Average Time fill	Computational Time
E4.2. Random 4 time periods: Small Principles	No Policy	No Randomness	NNH	26.60	0.21	5	5	5.00	88.28%	54.66%	00:00:31
		No Randomness	TS	22.40	0.19	5	5	5.00	88.28%	48.68%	00:04:10
		Random: minimum	NNH	32.40	0.24	5	5	5.00	88.28%	60.97%	00:00:10
		Random: minimum	TS	19.20	0.17	5	5	5.00	88.28%	45.07%	00:03:35
		Random: maximum	NNH	35.70	0.26	5	5	5.00	88.28%	65.85%	00:00:21
		Random: maximum	TS	21.70	0.19	5	5	5.00	88.28%	47.91%	00:04:12
		Random: average	NNH	33.54	0.25	5	5	5.00	88.28%	62.81%	00:00:14
		Random: average	TS	20.72	0.18	5	5	5.00	88.28%	46.93%	00:03:52
	Adapted Partial LIFO	No Randomness	NNH	29.10	0.23	5	5	5.00	58.86%	38.61%	00:00:06
		No Randomness	TS	21.90	0.19	5	5	5.00	58.86%	32.59%	00:02:22
		Random: minimum	NNH	32.20	0.24	5	5	5.00	57.29%	40.87%	00:00:05
		Random: minimum	TS	21.90	0.19	5	5	5.00	58.86%	32.37%	00:01:54
		Random: maximum	NNH	35.10	0.26	6	5	5.25	58.86%	42.76%	00:00:06
		Random: maximum	TS	22.10	0.19	5	5	5.00	58.86%	32.69%	00:02:09
		Random: average	NNH	33.66	0.25	5.2	5	5.05	58.54%	41.80%	00:00:06
		Random: average	TS	22.00	0.19	5	5	5.00	58.86%	32.56%	00:01:58
	Strict LIFO	No Randomness	NNH	29.00	0.22	5	5	5.00	58.86%	38.63%	00:00:06
		No Randomness	TS	23.60	0.20	5	5	5.00	58.86%	33.98%	00:02:44
		Random: minimum	NNH	35.60	0.26	5	5	5.00	57.29%	42.54%	00:00:05
		Random: minimum	TS	23.50	0.19	5	5	5.00	58.86%	33.94%	00:02:07
		Random: maximum	NNH	38.00	0.27	6	5	5.25	58.86%	46.04%	00:00:06
		Random: maximum	TS	24.20	0.20	5	5	5.00	58.86%	34.43%	00:02:33
		Random: average	NNH	36.56	0.27	5.2	5	5.05	58.54%	44.61%	00:00:05
		Random: average	TS	23.90	0.20	5	5	5.00	58.86%	34.23%	00:02:23

Table J. 2. Results of experiment 4.2 for all used loading constraints

J.3. Experiment 4.3: random run for all times periods of small principles

Since the results of 4 time periods of the small principles yields better or comparable results, experiment 4.3 executes all time periods of the small principles. Tables J.3 (No Policy), J.4 (Adapted Partial LIFO), and J.5 (Strict LIFO) only show the results of Principle3_Type1 and Principle 4. This is because the results of Principle3_Type1 and Principle 4 are comparable with the results of Tabu Search after the standard NNH, although the random runs require more computational time. The random Tabu Search results of Principle3_Type2 and Principle 6 are worse than the results of Tabu Search after the standard NNH.

Experiment	Used loading constraints	Principle	Experiment name		Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E4.3. Random: all time periods Principle 3 Type 1 and Principle 4	No Policy	Principle 3 Type 1	No Randomness	NNH	42.10	0.33	1	1	0.93	69.19%	48.74%	00:00:08
			No Randomness	TS	38.80	0.31	1	1	0.93	69.19%	46.03%	00:01:50
			Random: minimum	NNH	49.40	0.37	1	1	0.93	69.19%	54.69%	00:00:08
			Random: minimum	TS	38.80	0.31	1	1	0.93	69.19%	46.03%	00:01:51
			Random: maximum	NNH	51.50	0.38	1	1	0.93	69.19%	56.44%	00:00:08
			Random: maximum	TS	39.00	0.31	1	1	0.93	69.19%	46.17%	00:01:58
			Random: average	NNH	50.10	0.37	1	1	0.93	69.19%	55.28%	00:00:08
			Random: average	TS	38.84	0.31	1	1	0.93	69.19%	46.06%	00:01:54
		Principle 4	No Randomness	NNH	35.00	0.25	1	1	0.88	55.83%	40.72%	00:00:06
			No Randomness	TS	28.20	0.22	1	1	0.88	55.83%	34.74%	00:02:06
			Random: minimum	NNH	33.00	0.24	1	1	0.88	55.83%	38.93%	00:00:06
			Random: minimum	TS	28.20	0.22	1	1	0.88	55.83%	34.69%	00:02:06
			Random: maximum	NNH	34.60	0.25	1	1	0.88	55.83%	40.31%	00:00:20
			Random: maximum	TS	28.50	0.22	1	1	0.88	55.83%	34.96%	00:04:08
			Random: average	NNH	33.86	0.25	1	1	0.88	55.83%	39.67%	00:00:11
			Random: average	TS	28.38	0.22	1	1	0.88	55.83%	34.86%	00:03:03

Table J. 3. Results of experiment 4.3 for No Policy

Figure J.1 shows the assembly line, where blue boxes show some of the fixture locations of Principle 4: there are blue dots above boxes A and B which resemble the fixture locations. When there are fixtures above boxes A and B that need to be routed, the following happens: the fixtures above box B have a lower travel distance from their warehouse location to their line location, in comparison with the fixtures above box A. Because of that, a fixture above box B is routed as the first fixture in the standard Nearest Neighbour Heuristic. Afterwards, the Nearest Neighbour is added, based on the lowest travel distance of the new Total Route. This means that a fixture above box A is added after the fixture above box B in the standard NNH. During Tabu Search, the routes are optimised, resulting in that the route goes from fixtures above box A to the fixtures above box B at the assembly line. When we randomly assign fixtures, it can happen that fixtures above box A are assigned before the fixtures above box B, resulting in that the random NNH has a lower total travel distance in comparison to the standard NNH. Table J.3 shows that this happens in the random NNH with No Policy, and Table J.4 shows that this happens in the random NNH with Adapted Partial LIFO.

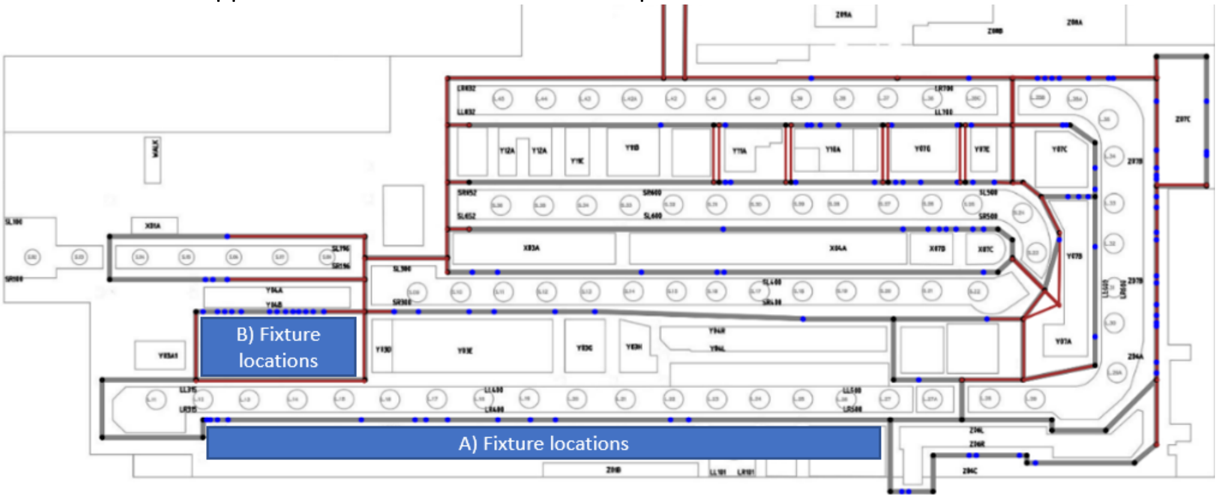

Figure J. 1. Assembly line with fixture locations of Principle 4

Experiment	Used loading constraints	Principle	Experiment name		Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E4.3. Random: all time periods Principle 3 Type 1 and Principle 4	Adapted Partial LIFO	Principle 3 Type 1	No Randomness	NNH	44.90	0.34	1	1	0.93	69.19%	50.87%	00:00:07
			No Randomness	TS	42.10	0.33	1	1	0.93	69.19%	48.57%	00:01:37
			Random: minimum	NNH	45.90	0.35	1	1	0.93	69.19%	51.73%	00:00:07
			Random: minimum	TS	42.10	0.33	1	1	0.93	69.19%	48.57%	00:01:37
			Random: maximum	NNH	49.20	0.37	1	1	0.93	69.19%	54.41%	00:00:08
			Random: maximum	TS	42.20	0.33	1	1	0.93	69.19%	48.70%	00:01:43
			Random: average	NNH	47.50	0.36	1	1	0.93	69.19%	53.04%	00:00:08
			Random: average	TS	42.12	0.33	1	1	0.93	69.19%	48.60%	00:01:39
		Principle 4	No Randomness	NNH	35.70	0.26	1	1	0.88	55.83%	41.30%	00:00:05
			No Randomness	TS	30.50	0.23	1	1	0.88	55.83%	36.61%	00:01:29
			Random: minimum	NNH	34.80	0.25	1	1	0.88	55.83%	40.51%	00:00:05
			Random: minimum	TS	30.40	0.23	1	1	0.88	55.83%	36.54%	00:01:32
			Random: maximum	NNH	35.80	0.26	1	1	0.88	55.83%	41.41%	00:00:06
			Random: maximum	TS	30.60	0.23	1	1	0.88	55.83%	36.72%	00:01:35
			Random: average	NNH	35.30	0.26	1	1	0.88	55.83%	40.96%	00:00:05
			Random: average	TS	30.50	0.23	1	1	0.88	55.83%	36.63%	00:01:34

Table J. 4. Results of experiment 4.3 for Adapted Partial LIFO

Experiment	Used loading constraints	Principle	Experiment name		Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E4.3. Random: all time periods Principle 3 Type 1 and Principle 4	Strict LIFO	Principle 3 Type 1	No Randomness	NNH	45.60	0.35	1	1	0.93	69.19%	51.40%	00:00:14
			No Randomness	TS	43.50	0.33	1	1	0.93	69.19%	49.68%	00:01:44
			Random: minimum	NNH	49.50	0.37	1	1	0.93	69.19%	54.54%	00:00:07
			Random: minimum	TS	43.50	0.33	1	1	0.93	69.19%	49.68%	00:01:46
			Random: maximum	NNH	50.50	0.37	1	1	0.93	69.19%	55.41%	00:00:08
			Random: maximum	TS	43.50	0.33	1	1	0.93	69.19%	49.68%	00:01:48
			Random: average	NNH	50.14	0.37	1	1	0.93	69.19%	55.09%	00:00:08
			Random: average	TS	43.50	0.33	1	1	0.93	69.19%	49.68%	00:01:47
		Principle 4	No Randomness	NNH	36.20	0.26	1	1	0.88	55.83%	41.70%	00:00:09
			No Randomness	TS	31.80	0.24	1	1	0.88	55.83%	37.75%	00:01:36
			Random: minimum	NNH	37.80	0.27	1	1	0.88	55.83%	43.03%	00:00:05
			Random: minimum	TS	31.80	0.24	1	1	0.88	55.83%	37.75%	00:01:37
			Random: maximum	NNH	39.20	0.28	1	1	0.88	55.83%	44.27%	00:00:05
			Random: maximum	TS	32.00	0.24	1	1	0.88	55.83%	37.93%	00:01:42
			Random: average	NNH	38.54	0.27	1	1	0.88	55.83%	43.67%	00:00:05
			Random: average	TS	31.84	0.24	1	1	0.88	55.83%	37.79%	00:01:39

Table J. 5. Results of experiment 4.3 for Strict LIFO

J.4. Experiment 4.4: long random run for all times periods of small principles

Experiment 4.4 executes a long run of all instances of Principle3_Type2 and Principle 6. Tables J.6 (No Policy), J.7 (Adapted Partial LIFO), and J.8 (Strict LIFO) show the results of these principles. These tables show that for Principle3_Type2 and Principle 6, the random Tabu Search results are comparable with the results of Tabu Search after the standard NNH, although the random runs require more computational time.

Experiment	Used loading constraints	Principle	Experiment name		Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E4.4. Long random run: all time periods of Principle 3 Type 2 and Principle 6	No Policy	Principle 3 Type 2	No Randomness	NNH	116.40	0.91	2	2	1.87	84.01%	67.42%	00:01:15
			No Randomness	TS	75.50	0.69	2	2	1.87	84.01%	51.08%	00:16:55
			Random: minimum	NNH	141.00	1.04	2	2	1.87	83.05%	76.44%	00:00:41
			Random: minimum	TS	75.40	0.69	2	2	1.87	84.01%	51.04%	00:46:10
			Random: maximum	NNH	152.20	1.10	3	2	1.89	84.01%	81.23%	00:00:42
			Random: maximum	TS	75.90	0.69	2	2	1.87	84.01%	51.46%	00:52:28
			Random: average	NNH	147.18	1.07	2.6	2	1.88	83.43%	79.25%	00:00:41
			Random: average	TS	75.62	0.69	2	2	1.87	84.01%	51.17%	00:49:33
		Principle 6	No Randomness	NNH	29.90	0.24	1	1	0.91	88.10%	36.99%	00:00:06
			No Randomness	TS	21.20	0.20	1	1	0.91	88.10%	29.81%	00:04:43
			Random: minimum	NNH	50.20	0.35	1	1	0.91	88.10%	53.95%	00:00:06
			Random: minimum	TS	21.20	0.20	1	1	0.91	88.10%	29.81%	00:13:11
			Random: maximum	NNH	53.40	0.37	1	1	0.91	88.10%	56.56%	00:00:06
			Random: maximum	TS	21.20	0.20	1	1	0.91	88.10%	29.81%	00:13:48
			Random: average	NNH	51.64	0.36	1	1	0.91	88.10%	55.12%	00:00:06
			Random: average	TS	21.20	0.20	1	1	0.91	88.10%	29.81%	00:13:34

Table J. 6. Results of experiment 4.4 for No Policy

Experiment	Used loading constraints	Principle	Experiment name		Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E4.4. Long random run: all time periods of Principle 3 Type 2 and Principle 6	Adapted Partial LIFO	Principle 3 Type 2	No Randomness	NNH	126.50	0.96	2	2	1.87	84.01%	71.38%	00:00:37
			No Randomness	TS	88.90	0.76	2	2	1.87	84.01%	56.41%	00:13:10
			Random: minimum	NNH	144.00	1.05	3	2	1.89	82.10%	77.56%	00:00:31
			Random: minimum	TS	88.40	0.75	2	2	1.87	84.01%	56.16%	00:35:15
			Random: maximum	NNH	150.80	1.09	3	2	1.91	83.05%	79.32%	00:00:32
			Random: maximum	TS	89.20	0.76	2	2	1.87	84.01%	56.51%	00:38:30
			Random: average	NNH	146.92	1.07	3	2	1.90	82.86%	78.50%	00:00:31
			Random: average	TS	88.78	0.76	2	2	1.87	84.01%	56.33%	00:36:47
		Principle 6	No Randomness	NNH	32.40	0.26	1	1	0.91	88.10%	38.99%	00:00:06
			No Randomness	TS	24.60	0.21	1	1	0.91	88.10%	32.47%	00:01:54
			Random: minimum	NNH	42.60	0.31	1	1	0.91	88.10%	47.47%	00:00:05
			Random: minimum	TS	24.60	0.21	1	1	0.91	88.10%	32.47%	00:10:02
			Random: maximum	NNH	47.30	0.34	1	1	0.91	88.10%	51.39%	00:00:06
			Random: maximum	TS	24.60	0.21	1	1	0.91	88.10%	32.47%	00:10:21
			Random: average	NNH	44.82	0.32	1	1	0.91	88.10%	49.30%	00:00:06
			Random: average	TS	24.60	0.21	1	1	0.91	88.10%	32.47%	00:10:11

Table J. 7. Results of experiment 4.4 for Adapted Partial LIFO

Experiment	Used loading constraints	Principle	Experiment name		Total Distance (km)	Total Travel Time (decimal)	Maximum number of trains	Minimum number of trains	Average number of trains	Average Physical fill rate	Average Time fill rate	Computational Time
E4.4. Long random run: all time periods of Principle 3 Type 2 and Principle 6	Strict LIFO	Principle 3 Type 2	No Randomness	NNH	123.30	0.94	2	2	1.87	84.01%	70.05%	00:00:49
			No Randomness	TS	94.70	0.79	2	2	1.87	84.01%	58.62%	00:17:40
			Random: minimum	NNH	151.00	1.09	3	2	1.89	81.18%	79.44%	00:00:27
			Random: minimum	TS	94.20	0.79	2	2	1.87	84.01%	58.43%	00:32:31
			Random: maximum	NNH	158.00	1.13	3	2	1.93	83.05%	82.14%	00:00:31
			Random: maximum	TS	94.70	0.79	2	2	1.87	84.01%	58.62%	00:35:25
			Random: average	NNH	153.80	1.10	3	2	1.91	82.30%	80.48%	00:00:28
			Random: average	TS	94.40	0.79	2	2	1.87	84.01%	58.50%	00:34:08
		Principle 6	No Randomness	NNH	32.40	0.26	1	1	0.91	88.10%	38.99%	00:00:08
			No Randomness	TS	26.20	0.22	1	1	0.91	88.10%	33.75%	00:02:08
			Random: minimum	NNH	49.10	0.35	1	1	0.91	88.10%	52.76%	00:00:05
			Random: minimum	TS	26.20	0.22	1	1	0.91	88.10%	33.75%	00:09:26
			Random: maximum	NNH	52.50	0.36	1	1	0.91	88.10%	55.53%	00:00:05
			Random: maximum	TS	26.20	0.22	1	1	0.91	88.10%	33.75%	00:10:13
			Random: average	NNH	51.30	0.36	1	1	0.91	88.10%	54.57%	00:00:05
			Random: average	TS	26.20	0.22	1	1	0.91	88.10%	33.75%	00:09:54

Table J. 8. Results of experiment 4.4 for Strict LIFO