Line layout and assembly line balance proposal to reduce output loss due to long trucks at Scania

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Master's Thesis Industrial Engineering and Management

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Date:

02-04-2021

MANAGEMENT SUMMARY

To stay competitive, Scania Production Zwolle (SPZ) continuously needs to improve its operations. To be able to realize the planned volume and productivity targets, output loss on the assembly line should be reduced. Long trucks are a regular cause of output loss on the assembly line. Using a problem cluster, we found the root cause of this central problem: the mismatch between truck length and workstation length at SPZ. This leads to the following research question:

How should the workstation length and layout of the Castor assembly line at SPZ be redesigned to reduce the output loss caused by long trucks?

Long trucks cause problems in output loss, reduced safety levels, ergonomics and operator efficiency along the complete Castor assembly line. The assembly line has workstation lengths of 12 meters currently. There is a potential of increasing the yearly production by 278 to 370 trucks, depending on the market demand when addressing this output loss problem. The output loss is incurred on the second part of the Castor assembly line after the truck is placed on a carrier system. Long trucks require additional distance on top of the standard 12-meter carrier distance resulting in output loss. Therefore the scope of this research is narrowed down to the second part of the Castor line. As a result of this identified output loss reduction, the project is placed on the investment plan. This research is the basis, as a preliminary study, to build and assess the feasibility of a business case to modify the line layout and address the central problem.

We focus on longer workstations to address the current mismatch between truck length and workstation length, resulting in a new line layout. Such a new layout requires a balance of the tasks along the assembly line to conclude on the new layout's implications. It is not possible to significantly extend the current assembly line. Therefore, given the available line space, the workstation length determines the layout of the assembly line. This layout is used as input to the balancing model, providing the number of workstations to consider. It is important that the proposed solution operates at the highest current takt. When considering longer and thus fewer workstations along the assembly line at the current output rate, we have to increase the line speed. The full potential of the output gain regarding long trucks can be utilized when 14-meter workstations are implemented. However, this proposal increases the line speed and occupancy rate of installations along the line the most. Based on the produced truck lengths' distribution in recent years, we identified another promising workstation lengths of 13.6 meters. This proposal utilizes 96.8% of the output potential while being practically easier to implement.

We reviewed methods of addressing an assembly line balancing problem in a literature study. Several methods and classifications to mathematically formulate the problem into a model are assessed. This mathematical formulation of the problem can be solved using exact or approximate methods where the exact methods are more suitable for the simpler or smaller problem instances. The approximate methods give a better trade-off between solution quality and computation time on larger or more complex problem instances. We present an assembly line balancing model based on the core problem from literature with some important additions regarding the problem at hand. These additions are the use of multiple operators, mixed model product type, work zones within workstations, multiple operators required for a single task and technological constraints. Given the problem size and complexity, we use the approximate method simulated annealing to optimize the problem. We minimizes the cycle time as a primary objective and as a secondary objective we minimize the number of active operators. This is in line with the important KPIs within SPZ of increasing the line output and line efficiency. The detail level of the task data we consider is in accordance with the globally prescribed assembly sequence (SAMS) within Scania. We use a Monte-Carlo simulation to study the effects of varying task times.

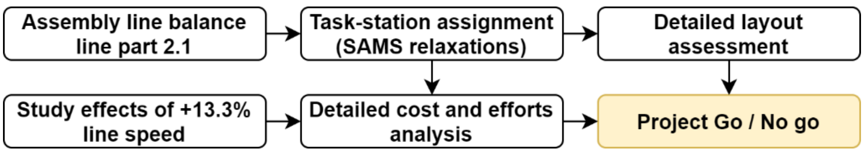
The installations with the current highest occupancy rates are situated at line part 2.2, from station 36 until 45. Therefore we focus the assembly line balance on this part of the line. The experiments we perform consist of balancing the tasks along 9, 10 or 11 workstations, corresponding with 14-, 13.6- or 12-meter workstations. All experiments consider the technological constraints of the cabin placement and tire assembly processes, having a fixed position along the line. We add additional technological constraints and tasks based on near-future task

introductions on top of these constraints, resulting in 12 experiments in total. This set of 12 experiments is performed with and without organisational constraints from the global assembly sequence (SAMS). When deviating from this global assembly sequence, future introductions require more efforts to be introduced on the assembly line and are therefore relevant to consider in the experiments. Throughout both experiment sets, we see the following main effects when reducing the number of workstations. The cycle time increases, the operator efficiency decreases, the operator density increases, and the average overload time increases.

The cycle time increases by around 21.2% when considering a 14-meter workstation layout compared to the current fastest takt time. This conflicts with the solution requirement of yielding the same output as the current line setup. In contrast, the 13.6-meter workstation proposal is able to operate at the required output level. Also, the 14-meter workstation layout is practically more challenging to implement and requires a higher line speed (+3.3%) compared to the 13.6-meter workstation proposal. Therefore we consider the 14-meter workstation proposal not feasible and recommend the 13.6-meter workstation proposal yielding 96.8% of the total output gain. The experiments with additional organisational constraints consider limited task-area displacements making the solution more robust to future task introductions. However, this experiment set is more restrictive than the experiment set not considering these organisational constraints and therefore operate at increased cycle time with an increased number of operators. The 5.3% operator increase can be translated into adding 2 operators at most at line part 2.2. Relaxing the organisational constraints results in mitigating the effects of cycle time and operator increase. The table below presents the study's outcomes and results from both experiment sets with and without organisational constraints of the 13.6-meter workstation layout.

	No organisational constraints	**With organisational constraints**
Output gain	269 to 358 trucks yearly	
Assembly line speed	+13.3%	
Cycle time % of current fastest takt time	99.4%	100.3%
Average operator increase line part 2.2	+0.6%	+5.3%
Operator density	+10.7%	+15.8%

To conclude, there is a significant output loss reduction to gain in the 13.6-meter workstation proposal of 269 to 358 trucks yearly. This proposal is in line with the requirement of operating at the same output level as the current assembly line regarding the assembly line balance. The proposal requires 2 additional operators at most when considering the full organisational constraints. This results in increased operator density per workstation and decreased operator efficiency given the fixed task set. The proposal requires a relatively small investment in additional operators in contrast to the significant output gain the solution yields. Therefore, it is interesting to further assess the business case's feasibility of implementing 13.6-meter workstations. This research focussed on the part of the Castor line with the most severe bottlenecks. We recommend performing a balancing study for the line part from station 29A until 35C to validate this study's results. These results can be used to define the task to station assignment at this line part and on the deviations of the organisational (SAMS) restrictions, indicating the effort of future task introductions. We recommend studying the effects of the increased line speed on operator efficiency and the occupancy rate of installations. Some installations will perform over their limit and require adjustments to be able to cope with the higher line speed. The task displacements from the balance, together with the occupancy rate assessment of installations, can be used to make a detailed cost and effort analysis to realize the new line layout. Furthermore, we recommend having a detailed layout assessment on where to place the future workstation boundaries. It became clear that logistical cross aisles and the buffer location at station 35B have to be adjusted. In this detailed assessment, all relevant parties, such as logistics, production and engineering, should be included to establish consensus on this item. This information combined should be the basis to decide on the project's execution, as shown in the road map below.



PREFACE

With great pleasure, I present my Master thesis. This thesis finalizes my Master in Industrial Engineering and Management. After a visit to Scania Production Zwolle, it was clear that I wanted to write my thesis at this company. At the end of the graduation period, I was given the opportunity to continue my career at Scania, which I gratefully accepted. I want to express my gratitude to some people who helped and guided me during the thesis and my studies.

I would like to thank my colleagues from the MZEP department for welcoming and introducing me to the company. More in general, I would like to thank all people within Scania Production Zwolle for making time for me when I needed help or information. Special thanks to Frank Beverdam for creating this thesis opportunity and his guidance during this extensive project. Your input and alternative view helped me get back on track when I was stuck during the thesis.

Moreover, I want to express my gratitude to my supervisors from the university, Marco Schutten and Peter Schuur. They gave excellent constructive feedback and helped a great deal in structuring the report. Also, their guidance during the Thesis helped me to get back in the right direction without getting lost in the many details of the problem.

Most of all, I would like to thank my family and loved ones for their endless support over the years. You helped me to keep the most important goals insight and were always willing to discuss my thesis and concerns whenever I needed it.

Enjoy reading the report!

Jaap Juurlink

April 2, 2021

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

Abbreviation	Definition	Introduced on page
SPZ	Scania Production Zwolle	1
KPI	Key Performance Indicator	8
SES	Scania Ergonomic Standard	14
CV	Coefficient of Variation	15
MMAL	Mixed-model assembly line	17
MuMAL	Multi-model assembly line	17
ALB	Assembly line balancing	18
SALB	Simple assembly line balancing	19
GALB	General assembly line balancing	20
SA	Simulated Annealing	23
LP	Linear program	24
MMALBP	Mixed-model assembly line balancing problem	24
B&B	Branch and bound	24
MILP	Mixed Integer Linear Programming	24
MP	Master Problem	25
SP	Slave Problem	25
SPCT	Scania Production Computer Tool	30

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

This chapter introduces the research performed at Scania Production Zwolle (SPZ), which comprises the final assignment to complete my Master's degree in Industrial Engineering and Management. First, Section 1.1 describes the background of the company and provides motivation for the research. Next, we describe the design of the research in Section 1.2.

1.1 COMPANY BACKGROUND AND RESEARCH MOTIVATION

This section introduces the company, Scania. First on a global level in Section 1.1.1 and next into more detail, focusing on SPZ. Then Section 1.1.2 provides the motivation for the research.

1.1.1 SCANIA

Scania AB is a globally operating company with sales of trucks, buses, engines, and services in more than 100 countries with around 51,000 employees. Scania was established in 1891, and since 1912 its head office is located in Södertälje in Sweden. Since 2014, Scania AB is fully owned by Volkswagen Group. Scania has production facilities in Sweden, France, Poland, Finland, Russia, the Netherlands, India, Argentina, and Brazil, and there are additional assembly locations in 10 countries in Africa, Asia, and Europe. Over the years, the number of produced trucks are steadily growing, and in 2019, Scania reached its highest market share in Europe so far: 18.7% (Facts and figures, 2020).

The plant in Zwolle (SPZ), in the Netherlands, is Scania's largest assembly facility employing around 2500 people. A wide variety of trucks are produced on the modular production system, enabling the production of a broad range of truck specifications while using a limited number of parts. SPZ builds trucks upon customer request on two assembly lines. In addition to the two large assembly lines, there are other smaller activities performed by SPZ, e.g., pre-assembly of axles, engines, and cabins.

1.1.2 RESEARCH MOTIVATION

The vision of SPZ is to be the number one truck production location, as stated in the strategic plan of 2020 onwards (Strategie plan 2020+, 2020), and grow as a high volume production plant. To achieve this goal, SPZ focuses on implementing processes with high efficiency while maintaining maximum flexibility in the product mix (Oolman, 2017). SPZ aims to reduce output loss to be able to realize the planned volume and productivity targets. A part of SPZ's total production is long trucks. A long truck is defined as a truck being over 12 meters. This 12 meter includes the four dimensions from Figure 1, and towbar if applicable. The free space is used as a safety distance toward the consecutive truck to prevent collisions and entrapment hazards. Long trucks cause problems in the plant's production output, reduce efficiency, and safety issues. We discuss more details on these problems in Section 1.2.1.

The management of SPZ sees reducing the output loss influenced by long trucks as one of the crucial initiatives to achieve its goal. A preliminary study performed by SPZ identified opportunities to mitigate the effects due to long trucks on the plant's output. One of these opportunities is to re-evaluate the workstation length, which results in a new line layout to reduce the assembly line's output loss. This initiative benefits a stable production output and increase the overall safety of the assembly line. Safety in production is one of the core values of Scania's house of quality, the Scania Production System.

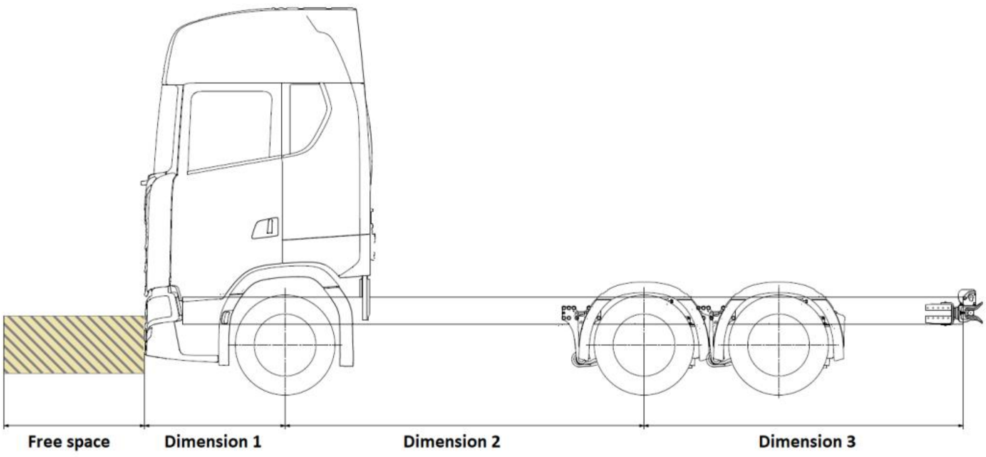


Figure 1: Truck length layout

1.2 RESEARCH PLAN

This section presents the research plan. First, Section 1.2.1 provides the problem description and core problem. Next, we describe the research objective in Section 1.2.2. Then Section 1.2.3 gives the scope of the research. Finally, Section 1.2.4 presents the research approach and research questions.

1.2.1 PROBLEM DESCRIPTION

The core problem can be identified by using a problem cluster. The problem cluster depicts the cause and effect relationships of the problem used to bring order to the problem context and identify the core problem (Heerkens & van Winden, 2017). Figure 2 presents the problem cluster regarding long trucks on the assembly line. The red box indicates the experienced problem by SPZ. The yellow boxes indicate problems that are hard to influence or out of scope, and the green box the core problem. The core problem is the problem that does not have preceding causes or causes that are hard to change and are less effective in solving the problem context. When looking at Figure 2 on the right-hand side, the effects are depicted, problem number (13) until (16), with their preceding causes more to the figure's left.

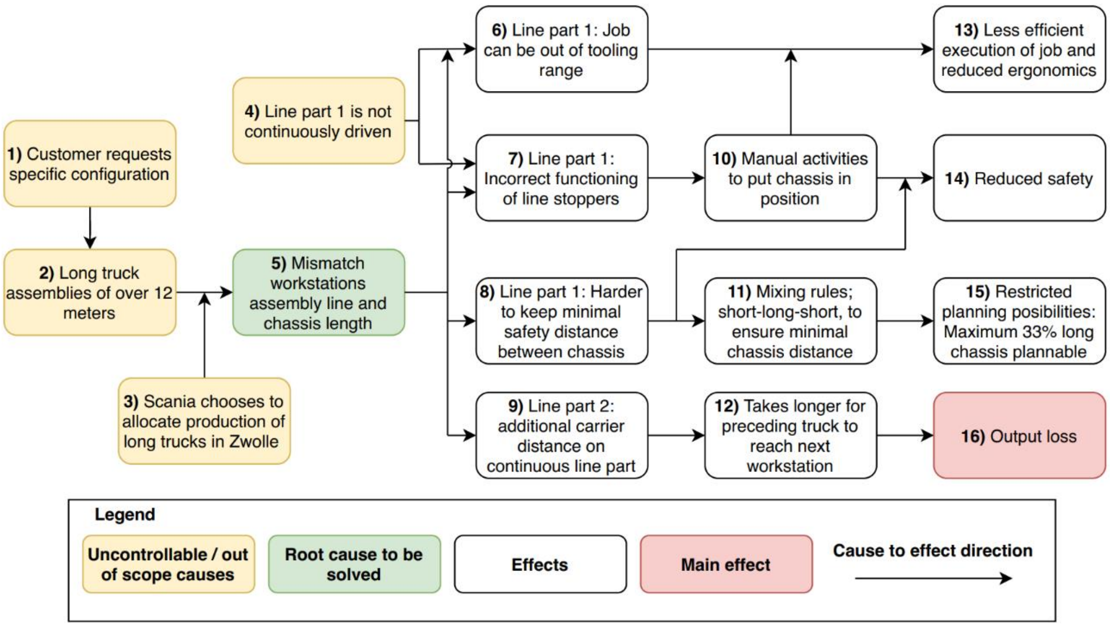


Figure 2: Problem cluster

SPZ assembles trucks with a great variety on two mixed-model assembly lines. Jobs are assigned to workstations and have to be finalized within takt time. This takt time is the time window during which all jobs have to be performed at a workstation. When a job on an arbitrary workstation is not finalized within takt time, the complete assembly line is put on hold, and stoppage time is incurred. Each of the two assembly lines at SPZ, the Castor- and Pollux-line, are divided into two parts. In the first line part, trucks are suspended from a rail and not in motion while being worked on. After the job is performed at the workstation, the trucks are synchronously transported to the next workstation. On the second part of the line, the truck is placed on a carrier system. On this part of the line, the trucks are in continuous movement while being worked on. The carriers are programmed to keep a minimum distance towards successive trucks.

On the first line part, a long truck forces a preceding truck to be placed further backwards in its workstation. When there are multiple long trucks in a sequence present on the assembly line, SPZ faces aggravate problems. Because the long trucks "push" the preceding trucks further backward in the workstations, this preceding truck cannot be mounted in the prescribed workstations stop position. At this stop position, the so-called line stopper mechanism stops the truck from moving and locks its position on the line until being released to proceed to the next workstation. Therefore the preceding truck has to be placed in position manually (problem (7) and (10) of Figure 2). Also, there is the possibility of less than the prescribed space between two consecutive trucks (8), resulting in safety issues (14), e.g., entrapment hazards. Another problem caused by long trucks is that jobs at the back of the truck can be out of the workstations tooling hoist range because the truck is physically exceeding the workstation (6). These problems result in reduced levels of safety (14), ergonomics and quality (13) as shown in Figure 2. Because of the possibility of less than the prescribed safety distance between consecutive trucks on the line, SPZ introduced mixing rules for the planning department (11). These rules aim to plan a long truck between two short trucks to ensure a minimum safety distance. However, this does not address the main problem and restricts the maximum plannable long trucks per period to around one-third of planned trucks (11). On the continuously driven, second line part, the longer trucks require physically more space than the standard planned carrier distance of 12 meters (9). Due to the extra length needed for the longer truck, the preceding trucks reach their workstations later (12). This results in lost time to the production system and thus resulting in direct output loss (16). As stated in the research motivation, SPZ aims to improve the reliability of the plant's output. When there are many long trucks planned, the plant's total output will be lower compared to a production plan with fewer or no long trucks. Because SPZ plans its production scheme with a standard average percentage of total production time the line is stopped due to long trucks. While with specific production schemes, the time the line is on hold is in fact higher.

Looking at the causes of the problems described above, these are partly due to the assembly line's different types of driving mechanisms. Because line part one is not continuously driven, problem (4) of Figure 2, the truck can be out of tooling range (6), and the line stoppers do not work optimally (7). Another cause of the problems is that at SPZ, most assembly line workstations have a length of 12 meters. Some of the customer's truck configurations result in relatively long trucks, for example, due to multiple axles on the truck. Orders with certain specifications can result in long truck assemblies, together with the prescribed safety distance between consecutive trucks exceeding the 12-meter workstation length. So there can be a mismatch between workstation length and truck length (5). In turn, this is the result of the customer's request for particular specifications of trucks (1). Also, adding to this mismatch (5) it is Scania's choice to assign part of the long truck production to SPZ (3). In the past, these long truck types were not assembled at SPZ.

To conclude the discussion on the problem context, the main effect SPZ wants to have solved is the output loss on the assembly line due to long trucks, problem (16) of Figure 2. When analyzing the causes by moving from the right-hand side to the left-hand side of the problem cluster, Figure 2, we end up at problem (5) as the core problem. The preceding causes of problem (5), namely (1), (2), and (3), are causes that are hard to change and not within the influence of SPZ alone and thus being less effective at solving the main effect. Problem (4) of Figure 2 does not address the main effect (16) SPZ wants to solve; however, this cause is relevant for the problem context. There are opportunities to mitigate the effects of problem number (13) until (16) by proposing a longer workstation length. So the identified core problem is:

There is a mismatch between truck length and workstation length on the assembly lines at SPZ.

The problem owner is the head of the production engineering department of SPZ. The discrepancy between norm and reality of the action problem is that the truck, including safety distance, does not always physically fit within the workstations.

1.2.2 RESEARCH OBJECTIVE

The research objective is to report on the possibilities to reduce the assembly lines' output loss due to long truck production. The identified core problem is the mismatch between workstation length and truck length resulting in the effects discussed in the previous section. The research focuses on the workstation length and the resulting line layout. As a secondary objective, adjusted workstations help increase the overall assembly line safety level. Additionally, the workstations setup can help improve the assembly line ergonomics and increase the production plan's flexibility. SPZ wants to receive advice on workstation length, line layout, and the implications of these results on the SPZ plant. This research is the basis, as a preliminary study, to build and assess the feasibility of a business case to adjust the current line layout and mitigate the negative consequences of long trucks.

1.2.3 RESEARCH SCOPE

The scope of the research is limited to the high volume Castor-line. This line is the most important of the two assembly lines at SPZ and yields the largest part of the plant's output. As both assembly lines have the same setup in principle, the Castor-line results can be projected to the smaller Pollux-line.

Logistical processes are essential for the material supply to the assembly line. However, the logistical processes are not the main topic of this research. We assume that the supply methods, material feed, and logistical processes to the new assembly line concepts are feasible and do not result in logistical problems.

Planning practices, such as cleverly sequencing long and short trucks, can have a mitigating effect on the experienced problems due to long trucks. Some of these planning practices, focusing on long trucks, are already in place and restrict the already extensive sequencing problem even more. Therefore not all planning rules can be respected at all times. SPZ is aiming to reduce the number of planning rules and therefore this research excludes the option to introduce additional planning rules to mitigate negative consequences of long trucks.

1.2.4 RESEARCH DESIGN

From the core problem, research objective, and scope, we derive the following main research question:

How should the workstation length and layout of the Castor assembly line at SPZ be redesigned to reduce the output loss caused by long trucks?

This section defines several sub-research questions and describes the research approach to gain the knowledge to answer the sub-research question needed to answer the main research question.

1. ***What is the current situation of the production output and problems faced regarding long trucks?***

Chapter 2 provides answers to the first sub-research question. Chapter 2 outlines the current situation of producing trucks at SPZ, and we investigate the potential gains of solving the core problem. Chapter 2 answers the following questions regarding sub-research question 1:

1.1 *What is the production process at SPZ?*
1.2 *What is the current situation of the line layout and workstation length?*
1.3 *What are the problems SPZ faces regarding long trucks?*
1.4 *What are the potential gains of solving the problem regarding long trucks?*

We answer these questions by interviewing different actors within SPZ who have relevant knowledge and views on the production process. Interviews are conducted on all levels from operators up until management. In addition, to visualize and validate these process descriptions, observations in production along the assembly line are performed. Also, data is gathered from the SPZ servers and ERP system. This information combined is used to map the current line layout and identify bottlenecks and restrictions on the current and possible future line layout. Also, the information is used to analyse and quantify the current performance and problem magnitude. Based on a prediction of long truck's future demand, we elaborate on the potential gains of solving the problem.

2. ***What methods of designing a line layout and solving an assembly line balancing problem are described in the literature that can be used to improve the output of the Castor line at SPZ?***

The above sub-question is answered in Chapter 3; in Chapter 3 a study is performed on similar problems found in literature. Chapter 3 elaborates on the following questions:

2.1 *How can the assembly line and balancing problem be characterized?*
2.2 *Which methods for designing an assembly line layout are discussed in literature?*
2.3 *Which methods for solving an assembly line balancing problem are discussed in literature?*

The chapter presents a literature study on relevant assembly line layout problems. Furthermore the Chapter gives line balancing problems that have similarities to the situation at SPZ.

3. ***Which workstation length and assembly line layout should be chosen to reduce the output loss regarding long trucks?***

Chapter 4 discusses the benefits and disadvantages of certain workstation lengths that reduce the output loss caused by long trucks. Also, we consider bottleneck processes along the Castor assembly line regarding the new layout proposal. Chapter 4 provides answers to the following questions:

3.1 *What are the benefits and disadvantages of longer workstation lengths than currently deployed?*
3.2 *What are the bottleneck processes along the Castor assembly line?*
3.3 *Which new assembly line layout reduces the output loss caused by long trucks?*

Chapter 4 elaborates on the ideal workstation length based on the potential output gain and required line speeds. Also, bottleneck processes along the line are considered taking the longer workstation lengths into account. Finally, layout proposals are presented that effectively reduce the output loss regarding long trucks. These layout proposals consider the potential output gain, bottleneck processes along the line and available line space.

4. ***What method can be used to balance the tasks of a new layout proposal given the specific problem?***

The assembly line's primary goal is to facilitate the execution of a task package to assemble a truck. Chapter 5 presents a method, based on the outcomes of Chapter 3, to balance the tasks along the assembly line given a predetermined line length. Chapter 5 elaborates on the following questions:

4.1 *What elements from the literature can be applied and used to solve the balancing problem at SPZ?*
4.2 *What are the modelling choices to represent the specific problem at SPZ?*
4.3 *What are the important inputs to the model and how is this data gathered?*
4.4 *How can we solve the specific assembly line balancing problem at SPZ?*

This chapter presents the choices made to arrive at the selected method to balance the assembly line. Furthermore, the chapter presents the balancing procedure and inputs to the model in more depth.

5. ***What are the implications of the new assembly line layout regarding the balancing of tasks?***

Chapter 6 presents the results of the assembly line balancing method, described in Chapter 5, given the layout proposal as determined in Chapter 4. Chapter 6 elaborates on the following questions:

5.1 *How should the workload on the new line layout be distributed across workstations?*
5.2 *What are the implications of the new line layout on the performance of the assembly line?*

This chapter presents and explains the experiments performed with our assembly line balancing method. Then using the outcomes of the method and quantitative analysis techniques, the chapter elaborates on the implications of the proposed line layout considering important performance indicators. Finally, Chapter 7 presents the conclusions and recommendations of this research.

CHAPTER 2 CURRENT SITUATION

This chapter describes the current situation at SPZ. First, Section 2.1 explains the production process. Next, Section 2.2 presents the performance of the current assembly line. Section 2.3 provides the problems regarding long trucks and the potential benefits if the problem is solved. Finally, Section 2.4 contains the conclusions of this chapter.

2.1 PRODUCTION PROCESS

This section describes the production process and the assembly line layout of SPZ. First Section 2.1.1 gives the production process of SPZ. Next, Section 2.1.2 describes the concept of takt time in more detail. Then Section 2.1.3 provides the workstation setup and assembly line layout. Finally, Section 2.1.4 elaborates on the adjustment possibilities and restrictions of the assembly line.

2.1.1 PRODUCTION PROCESS

As briefly introduced in Chapter 1, SPZ produces a wide variety of trucks on two mixed-model assembly lines. These two assembly lines are the Castor-line, which delivers the most output of the two, and the Pollux-line. Mixed-model assembly lines enable the assembly of many different variants of a common product in consecutive cycles without setup time (Emde, Boysen, & Scholl, 2009). At SPZ both assembly lines are configured as parallel assembly lines. When the truck is fully assembled, after the side skirt assembly, both the Castor- and Pollux-line end and merge together on common tracks. On these joint tracks, functional tests on the trucks are performed. The Castor-line consists of consecutive workstations on which the truck is gradually built. The line is divided into two parts; at the first line part, the trucks are transported utilizing a suspension conveyor. This system latches the trucks' frame onto a suspended carrier which is attached to a rail positioned above the frame, see Figure 3. The trucks are not in motion while work is performed at the workstation. After the assigned tasks of a workstation are done, the operator releases the carrier system and the trucks synchronously move to the next workstation. At the beginning of the second line part, the trucks are placed on a carrier system, see Figure 4. This carrier system moves at a constant pace through the second line part after workstation 29, see Figure 5 for the Castor-line layout. The jobs performed on the second line part are better suited for carrier transport because some heavy components, such as the motor and cabin, are mounted on the truck. While the trucks move through the second line part, the required job in each workstation is performed when the truck is in continuous motion. Figure 4 depicts the continuous transport on the carrier system.

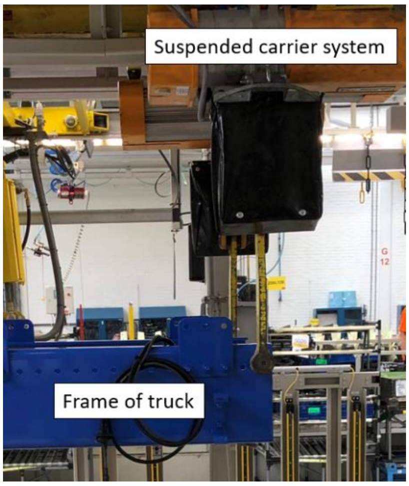


Figure 3: Suspended conveyor system

Figure 4: Long truck on the carrier system

Next to the two assembly lines, on which the trucks are produced, there are many pre-assembly stations to support the assembly lines and reduce the truck's time on the main assembly line. Two major pre-assembly stations are the engine and cabin completion stations. Each workstation and the pre-assembly stations have their own inventory of parts. The parts that are highly consumed are kept on stock at the station. Due to limited space around the assembly line, less consumed parts are offered to the line according to the just-in-time philosophy using different types of part feeding methods, e.g., one-piece supply or multiple parts supplied in a batch.

2.1.2 TAKT TIME

The assembly lines work with takt time, which is the time in which each workstation has to perform all the required tasks before the truck moves to the next workstation. Takt time is based on the demand for trucks and is determined by the available time divided by the number of finished products required in that time (Beachum, 2005). The production process and many logistical processes are paced according to the takt time. Each operator is assigned to a fixed workstation and has a predetermined set of tasks to perform within the takt time. If the required tasks on a workstation are not performed within this takt time, an overload situation occurs, and the complete assembly line has to be stopped until the specific task is finalized. To cope with the variable truck models and thus variable workload on the line there are, in addition to the regular operators, so-called floater operators available to assist on peak workloads. These floater operators are not assigned to a fixed workstation but available to assist regular operators on large workload trucks along the assembly line.

2.1.3 ASSEMBLY LINE LAYOUT AND WORKSTATION SETUP

Trucks are assembled on two U-shaped assembly lines at SPZ. The longer outer assembly line is the high volume Castor-line, and the inner assembly line is the Pollux-line, as can be seen in Figure 5. The assembly lines differ in the number of workstations, takt time, and capacity. The Castor-line operates at a shorter takt time and thus higher line speed compared to the Pollux-line operating at a slower pace and larger takt time. Both assembly lines are divided into supervisor areas. Focussing on the Castor-line, this line is divided into ten supervisor areas. The supervisor areas are further divided into team leader areas. The team leaders are responsible for a number of workstations and around five operators per workstation, depending on the line speed. Each operator has its own role and responsibility, which is described in a so-called standard.

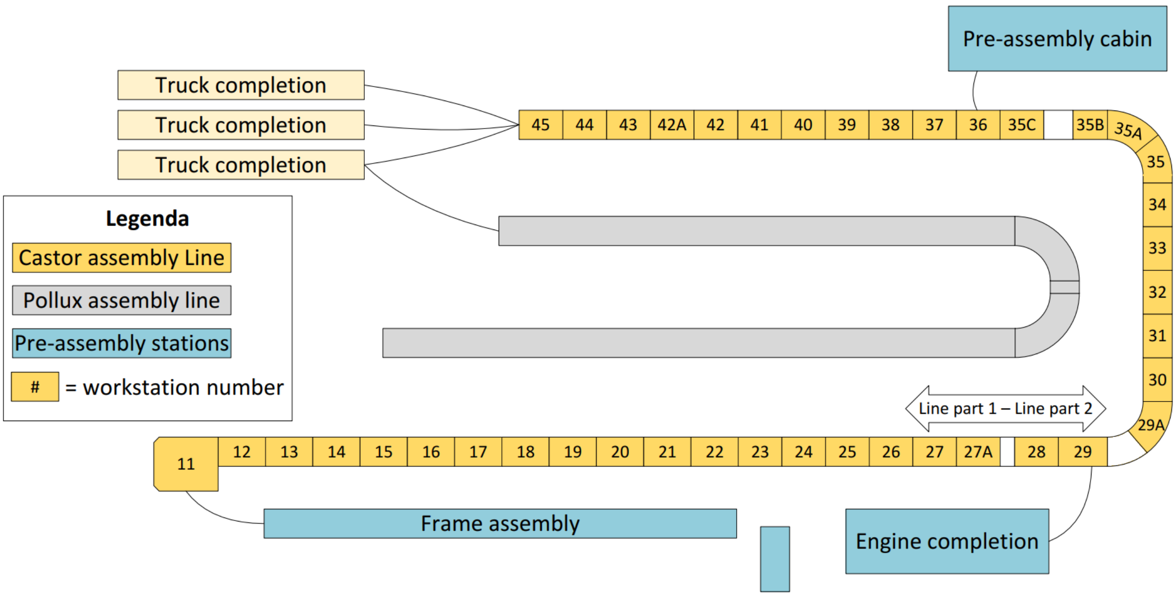


Figure 5: Assembly line layout

The complete assembly process of a truck is sub-divided into work packages and assigned to workstations. From start to finish of the truck assembly, the process comprises, roughly speaking, the assembly of the frame, wiring, axles, motor, cooling, battery, cabin, wheels, skirts and necessary fluids. The general assembly sequence is determined globally within Scania and prescribes the truck's sequence of jobs and transport method on the assembly line. Within a workstation, the job is further divided into six work areas around the truck, e.g., front and left-hand side rear. All specific jobs that have to be performed at a workstation are specified in work standards for the operator. Together with the general assembly instruction and the work standard of the specific truck type, the operators are able to perform their required job on the extensive variety of truck types.

2.1.4 ADJUSTMENT POSSIBILITIES LINE LAYOUT AND RESTRICTIONS

In this section, we discuss the adjustment possibilities and restrictions of the Castor assembly line. The Pollux assembly line is out of scope, as stated in Chapter 1. The research aims to find a line layout that addresses the output loss while keeping the same position and length of the current line. So the adjustment possibilities are the redetermination of workstation lengths and the workstation sequence while respecting the current line area. Extensions of the line are not allowed, which means that the same area to position materials and equipment along the line is available for the new line layout. We assume that a new material layout, which is the responsibility of logistics engineering, is feasible because the same area to position materials is available on the new line layout, according to J. Schuitema (personal communication, 30-06-2020). We address bottleneck equipment later, in Section 4.2, including processes that require adjustments to facilitate the new line layout. Another restriction is of financial nature; investments at SPZ should have a payback period of two years.

2.2 CURRENT PERFORMANCE

This section describes the current performance of the SPZ plant. First, Section 2.2.1 gives the most important performance measures for this research. Next, Section 2.2.2 provides the current and past performance of the line. And finally, Section 2.2.3 elaborates on the bottleneck processes along the assembly line.

2.2.1 PERFORMANCE MEASURES

The main principles of Scania's house of quality are: demand-driven output, defining the baseline work process (normal situation), no mistakes, and continuous improvements. There are several key performance indicators (KPIs) derived from those principles within Scania. This section discusses the KPIs that are relevant to this research.

One of the central steering KPIs of SPZ is the number of trucks produced per day. This KPI determines the takt time and line speed. Also, it is one of the main inputs for workforce planning. At SPZ, a production day consists of two shifts. The total production time per day is defined as the total time of these shifts, excluding the time for breaks. This total production time minus an estimate of time the line is put on hold divided by the number of trucks to produce in a day determines takt time. The takt time is calculated according to the formula below (Linck & Cochran, 1999). An estimate of the time the line is put on hold for a specific production period can be seen as the planned losses. The estimate of the time the line is put on hold is needed upfront to be able to calculate the required takt time to achieve the production plan. From this takt time, the line speed, the speed at which the carrier systems move, can be determined by dividing the workstation length by the takt time. So, the takt time and thus line speed follow from the number of trucks to produce in a day.

$$Takt\ time = \frac{Total\ production\ time\ per\ day - stoppage\ time\ per\ day}{Number\ of\ trucks\ to\ produce\ per\ day}$$

Another important KPI is the stop time percentage. This is the percentage of the total production time per day during which the assembly line is put on hold. The line is put on hold when an overload situation occurs, e.g., a job in a workstation is not finished within takt time. This stop time percentage, as an estimate, is an important input to calculate takt time and line speed. The stop time percentage is based on past experience and is subdivided into a general stop percentage and a percentage due to the lost time of extra transport length of long trucks. When the line speed is high, the stop percentage is generally higher than at lower line speeds because it is more likely that overload situations will occur due to a higher pace and more operators at the line. At the end of the production day, the actual realized stoppage time is determined. As it is SPZ's aim of being more reliable and reduce output loss, the challenge is to find a good equilibrium between takt time and the number of overload situations. SPZ is aiming at an overall stop time percentage of below 10%, as stated in the strategic plan 2020 onwards (Strategie plan 2020+, 2020).

Also important is the number of trucks on the line. The number of trucks on the line together with the takt time determine the pace of the material flow, e.g., for the logistical processes of material line feeding. In a high demand situation the number of trucks on the line is equal to the number of workstations. In a lower demand situation, not all workstations are necessarily filled, and thus, the material flows have a lower pace as well.

Finally, the number of unsafe situations on the assembly line is an important KPI regarding this research. As stated in the research motivation, safety is one of the core values of Scania's house of quality. We focus on the number of unsafe situations regarding long trucks on the assembly line to get an insight into the problem magnitude. An unsafe situation can result in an incident involving people or materials.

2.2.2 ASSEMBLY LINE PERFORMANCE

When both assembly lines run at full capacity, the Castor assembly line produces about twice as much as the Pollux-line. However, in practice, the Castor assembly line account for even a larger share of the total produced yearly volume because, generally speaking, the Pollux-line is shut down for some periods each year. The Pollux-line can be stopped as a strategic choice when the demand for trucks is low. Then the Castor-line is utilized to meet full customer demand. The benefit of shutting down the Pollux-line is that only the Castor-line needs to be fully staffed and supplied with materials. There is a 3 to 4 weeks break when the production is stopped, and maintenance can be performed in the summer. In addition, there is a production stop during the Christmas holidays.

In total, there are 880 minutes per day available to perform productive work by two shifts. A percentage of this time, the line is stopped due to problems in production, e.g., the operator could not finish the job within takt time and puts the line on hold. As said, SPZ aims to have a total stop time percentage of below 10%, which should cover all kinds of line stops. There is 1% of the 880 minutes reserved daily to cover the output loss and stops due to long trucks.

2.3 DESCRIPTION OF CURRENT SITUATION REGARDING LONG TRUCKS

This section presents the current situation regarding long trucks at SPZ. Section 2.3.1 elaborates on the problem magnitude and potential gains of reducing the main effect, the output loss due to long trucks. Next, in Section 2.3.2, we describe additional gains related to safety, ergonomics, line stops, and planning practices. Finally, in Section 2.3.3, we look at the trends in long truck demand.

2.3.1 PROBLEM MAGNITUDE AND POTENTIAL OUTPUT GAIN

This section focuses on the main effect SPZ wants to have solved; the output loss due to long trucks, as discussed in Section 1.2.1. At workstation 28 line, part two starts, see Figure 5. At this workstation, the trucks are placed from a hanging position on the carrier system. The carrier systems are sent out at a continuous pace from workstation 29 at fixed distances called the carrier distance, see Figure 6. The carrier distance is defined as the distance between two consecutive carrier systems. In a normal situation, the carrier distance between two consecutive trucks is 12 meters and includes the chassis, cabin, and free space. This 12-meter carrier distance is in accordance with the workstation lengths of 12 meters on line part two. The free space is used as safety distance and to perform certain jobs at the front of the truck. When there is a long truck on the assembly line, the standard distance of 12 meters, including minimum free space, is exceeded, and the carrier distance is extended. This additional carrier distance causes the successive truck to arrive later at the next workstation. This is lost time to the production system, and thus output loss is incurred. SPZ aims to be less dependable on the production plan and the resulting output. Instead, SPZ prefers a situation with a stable daily output independent of the truck specifications produced on that certain day. A stable daily output enables SPZ to effectively further optimize logistical processes, workforce planning, and production processes.

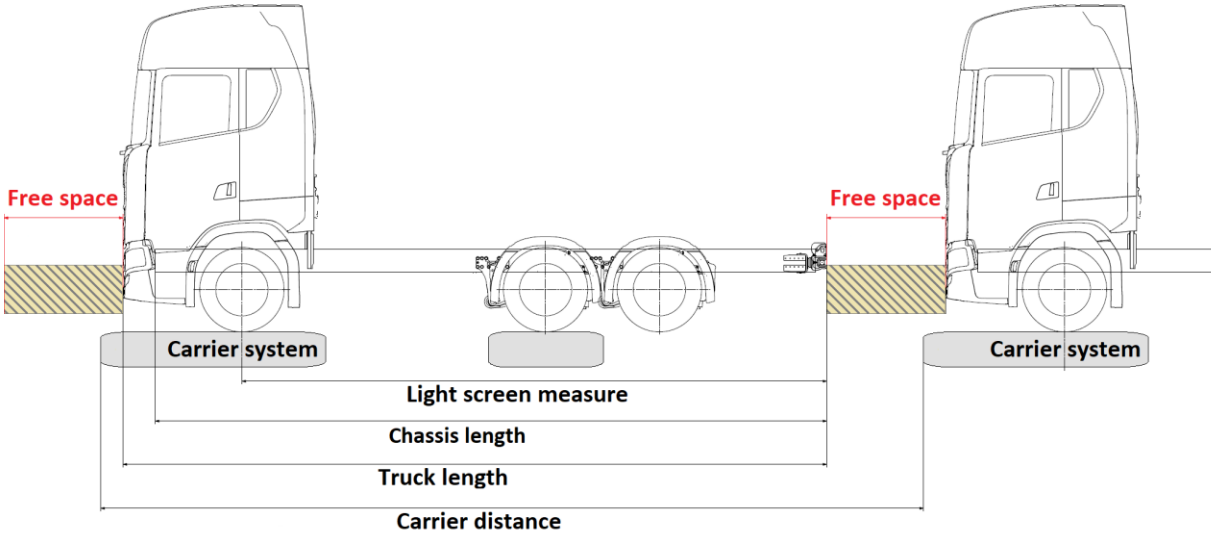


Figure 6: Truck length dimensions and light screen measure

To cope with the long trucks, the length of the truck's chassis is measured. This data is used to adjust the carrier distance of two consecutive carrier systems to ensure a safety distance between the trucks on the line. At workstation 28, the truck is placed on the carrier system. The truck's front axle is placed on the first carrier system at a fixed reference point in the workstation. The second carrier system is positioned depending on the truck's specifications. The truck's length is measured with light screens at workstation 28, based on the front axle's reference point and the truck's stick-out length. If the truck's chassis' rear end does not intersect with one of the light screens, the truck is sent out at the standard carrier distance of 12 meters. We refer to this measure as "light screen measure", see Figure 6. If the chassis does intersect with one or more of the light screens, the carrier is assigned a longer carrier distance. So based on this measurement, the carrier distance to the successive carrier is determined. There are six carrier distances programmed, as can be seen in Figure 7. The truck length, without free space (see Figure 6), is dependent on one of the two groups of truck cabins; the PGRS cabins or low entry cabins. The PGRS cabin group results in a shorter truck than a truck equipped with a low entry cabin. Figure 7 contains a table with the different measures per carrier distance type, e.g., if the light screens measures a chassis of over 9170 mm and below 9670 mm, the carrier distance is 12750 mm, and dependent on the cabin, the truck length is more than 10750 mm or 11210 mm. The available free space is dependent on the cabin type and includes a minimum safety distance of 800 mm. The PGRS cabin group has 1500 mm of free space towards its successive truck for the low entry cabin this free space measure is 1040 mm. Figure 7 also indicates the percentage of total production for each of the six carrier distances taken from a representative production period. In addition, the largest carrier distance class, carrier distance of 12 meters, is virtually subdivided into below 10 meters and 10 to 12 meters. So the largest part of total production, 72.02%, are relatively short trucks. So 9.26% of the total production can be classified as a long truck.

		Truck length	
Carrier distance (mm)	**Light screen measure (mm)**	**PGRS cabin (mm)**	**Low entry cabin (mm)**
12000	<8920	<10500	<10960
12250	>8920	>10500	>10960
12750	>9170	>10750	>11210
13000	>9670	>11250	>11710
13500	>9920	>11500	>11960
13750	>10420	>12000	>12460

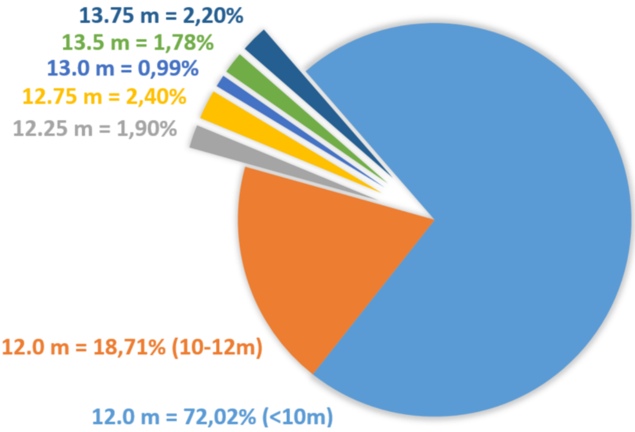


Figure 7: Carrier distance distribution

To quantify the yearly potential saving, we calculate the number of trucks lost due to additional carrier distance under a certain market demand because this is an aggregate measure not dependent on sales prices. The distribution of carrier distance types from Figure 7 is used in combination with a yearly demand for trucks. We use demand scenarios to calculate the potential saving: a low, medium, and high demand scenario. We only report on the potential yearly saving and not on the yearly demand due to confidentiality reasons. Using the distribution of additional required carrier distances from Figure 7, we can calculate the additional meters on top of the 12-meter carrier distance. Finally, we can translate these lost additional meters into lost trucks of 12 meters by dividing this total amount by 12. See Table 1 for the results. So there is a potential to save 278 to 370 trucks due to the additional carrier distance of long truck production depending on the market demand scenario.

Table 1: Potential saving of solving the direct output loss

Demand Scenario	Yearly truck potential
High	370
Medium	324
Low	278

2.3.2 ADDITIONAL POTENTIAL GAINS

This section looks at the additional gains on top of the potential direct output improvement, as discussed in Section 2.3.1. Because the assembly line uses different driving mechanisms, we divide the additional gains into line part 1 and line part 2.

LINE PART ONE

Line part one starts at station 11 and ends after station 27, see Figure 5. On line part one, unlike line part two, there is no fixed distance between the trucks on the assembly line. The length of the chassis determines the distance between two consecutive trucks because the trucks have fixed stopping positions in the workstations. These assigned stopping position are indicated in Figure 8 by the blue triangle. Figure 8 depicts a situation with many long chassis on the line, and below, we explain this in more detail. Therefore, if a truck is long, the distance from the chassis's end towards the truck in the preceding workstation is relatively short. When the trucks arrive at the next workstation, the trucks are stopped and locked in fixed positions by the line stoppers. When the moving truck hatches into the workstation's stopper system, the truck is not directly stopped due to its weight and speed but sways out from the line stopper position. This results in the chance of an unsafe situation like entrapment hazards. Moreover, when the safety distance of 800 mm is compromised, the operator can manually stop and put the truck into position on the suspension railway to ensure minimum safety distance. This can cause a whole sequence of trucks being pushed back from their original workstation position. Figure 8 indicates this problem; the truck's front axle should be aligned with the blue triangle, which is the stopper system. Because of many long trucks in a sequence, the trucks in workstation 2 and 3 cannot be placed in their regular assigned stopping positions. This situation results in additional stoppage time due to the chassis not being in place on the correct workstation and tooling positions. The effects are discussed below in the section "Long truck production planning". These described problems result in less safety on the line, reduced work ergonomics, and less efficient execution of the operator's job. The effects of long trucks on reduced line safety are discussed below in the section "Health and safety". When longer workstations would be implemented, the effects of these problems decrease or can even be eliminated.

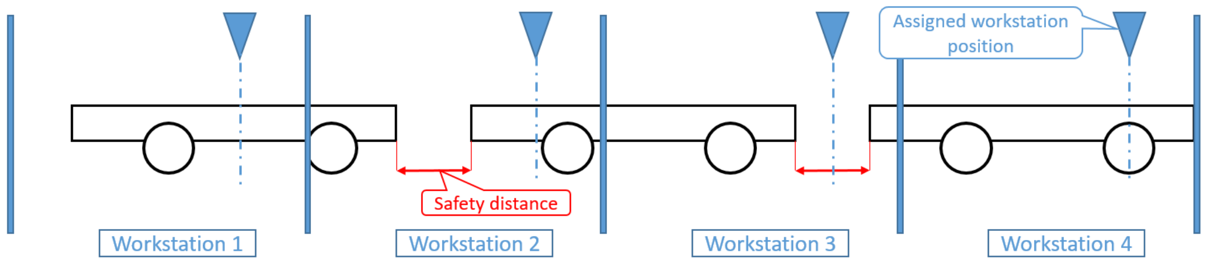


Figure 8: Workstation position at line part one with many long trucks on the line

To indicate the size of this problem on line part one, Figure 9 represents the distribution of long trucks. This distribution starts from a light screen measure of 8920mm and includes the total chassis length (in mm) and safety distance of 800 mm, see Figure 6. For example, bin 10800 of Figure 9 consists of 722 trucks with a chassis length, including free space, between 10700 and 10800 mm. The problem described above of chassis "pushing" consecutive chassis backwards in their workstation starts when the chassis, including safety distance, exceeds the workstation length. The minimum workstation length on line part one is 12 meters. So from Figure 9, we can conclude that around 30%, as of 12000 mm onwards, of the long chassis are accountable for the occurred problems at line part one.

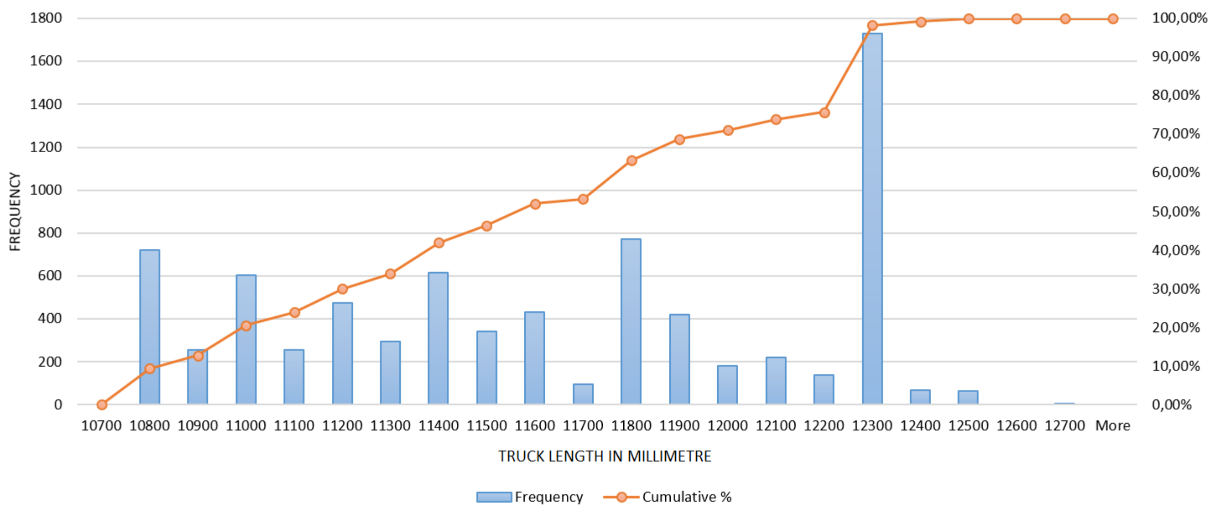


Figure 9: Histogram of long truck distribution: chassis length + safety distance

Another benefit of longer workstations is the reduction in the number of workstations due to space limitations. Fewer workstations on line part one result in a reduction in the trucks' transportation time, which is a form of waste seen from a lean perspective (Theisens, 2017). When a job is finished at line part one, the line stopper system releases the truck to be transported to the next workstation. The reserved time for transportation within the total takt time is between 25 and 30 seconds per workstation. A considerable part of this transportation time is putting the truck in motion, slowing down the truck, and hatching the truck in its assigned stopping position. Longer workstations result in fewer workstations in total and thus in fewer transportation activities during which the operators are not performing value-added work on line part one.

LINE PART TWO

On line part two, where the trucks are transported on continuous driven carrier systems, there are some additional potential gains on top of the gains in direct output loss due to additional carrier distance.

There are some safety issues reported regarding long trucks on line part two, concerning the stick-out length of the chassis' end. For example, the end of the long chassis sticks out when making one of the two turns on the assembly line, creating an unsafe situation. We elaborate on these effects further in the section "Health and safety" found below.

Another potential gain is more of a conceptual nature. In order to achieve a lean balanced production system, the system must be balanced in accordance with takt time. Otherwise, this leads to either underproduction or overproduction and thus in waste (Linck & Cochran, 1999) (Theisens, 2017). Because the carrier systems are sent out at different carrier distances, varying from 12 to 13.75 meters, at equal carrier speeds, there is more time available at each workstation to work on the long trucks. There is almost 15% more time available to work on the longest trucks compared to the standard trucks with a carrier distance of 12 meters. So, effectively, line part two operates at fluctuating takt times. In many cases, the workloads are not necessarily larger for long trucks e.g., every truck needs a cabin, and the truck's length does not increase the workload of placing the cabin. Therefore the workloads are not optimally balanced and reduce the efficiency of the production process. This situation is depicted in the fictive case presented in Figure 10. The first graph indicates an unbalanced workload situation with five consecutive workstations and a takt time of 10 minutes. We assume that the variable workload is handled by the additional operators, the "floaters", to assist the regular operators. The second graph of Figure 10 indicates an ideal balanced situation, which in practice is hard to achieve. The third graph indicates the ideal balanced situation (2) translated to the current situation with the continuous moving carrier systems (3). More time is available to perform the necessary work at workstations that work on long trucks resulting in idle times at those workstations. Longer workstations transform line part two into a situation with equal takt times and provides an opportunity to reduce the line balancing losses.

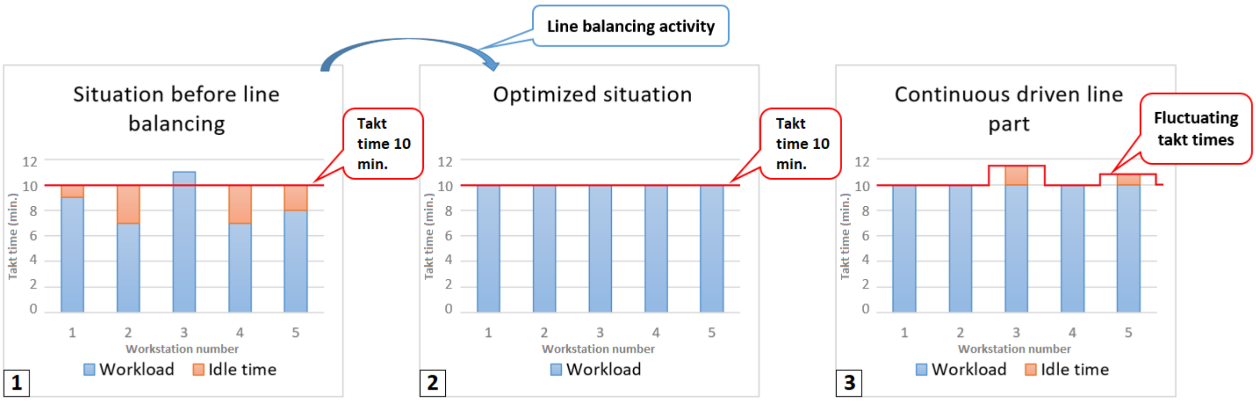


Figure 10: Line balancing scenarios

HEALTH AND SAFETY

A safe working environment is one of SPZ's top priorities. Therefore it is very important to reduce the number of unsafe situations. From the beginning of 2019 until the summer stop in 2020, there are ten unsafe situations regarding long trucks reported. Eight of these could have caused severe injuries, and one of the incidents prevented normal work performance. If longer workstations were present, 9 out of the 10 reported incidents would have mitigated consequence or would not have happened. When an unsafe situation is reported, necessary actions have to be taken and followed up by the responsible employees. So additionally, reducing the number of unsafe situations reduces the needed resources in correcting the problems.

Another point is the incorrect functioning of line stoppers due to the longer chassis. As illustrated in Figure 8, long trucks cannot always latch into their assigned workstation position when there are multiple long trucks in a sequence. As a consequence, the trucks have to be put in place manually. This activity of manually positioning a truck on line part one is assessed according to the Scania Ergonomic Standard (SES). The SES judges a job on 20 ergonomic points. The SES analysis outcome was 4 times a score of high risk on physical symptoms and 1 score of the possibility of physical symptoms in the future. Longer workstations would eliminate the situation of manually placing a truck on position.

LONG TRUCK PRODUCTION PLANNING

When a truck is sold, there is an agreement made on the delivery period. This agreement determines when the truck needs to be produced in order to be delivered on time. The production schedules are planned four weeks ahead for a scheduling period of around five working days. When there are many long trucks planned in a production schedule this can cause additional output problems as described above. To mitigate the effects caused by the long trucks, the production planning department maintains a specific planning practice. They allow a maximum of 30% long trucks to be produced on a single day to maintain a production sequence of truck length types short-long-short. This is one of many planning restrictions making the planning process difficult, and not all restrictions can always be respected. In some specific situations, the number of long trucks in a production period is higher than the allowed 30%. This results in additional stoppage time, as described in the section "Line part one" above, on top of the direct output loss due to longer carrier distance. From 01-09-2019 until 01-09-2020, there is a total stoppage time due to long trucks reported by the operators of over 24 hours on the Pollux-line. We consider the Pollux-line because, in this production period, the choice was made to plan long truck on this line. Because the two assembly lines are similar, we use these results to assess the situation on the Castor assembly line. However, it is hard to judge if the total amount of stop time is solely due to long chassis. It could also be a combination of problems manually reported in the system as a long truck problem. However, we can say that if there are many long trucks planned on a day, above 30%, the stopping time due to long trucks increases. Table 2 shows the ten highest total stoppage times per day, attributed to long trucks, from 01-09-2019 until 01-09-2020. These production days with high stoppage time due to long trucks all have a high percentage of long trucks planned for that day. Longer workstations can mitigate the problems regarding long trucks and thus reduce the additional stoppage times.

Table 2: Largest stopping times on the Pollux line from 01-09-2019 until 01-09-2020

Date	Percentage long trucks planned	Stop time in seconds
25-6-2020	51,28%	14860
10-7-2020	61,54%	14199
30-6-2020	63,16%	12594
26-6-2020	61,54%	10441
15-6-2020	93,33%	6524
2-7-2020	58,18%	5510
8-7-2020	58,33%	4925
7-7-2020	43,24%	2828
22-10-2019	50,98%	1986
29-6-2020	57,78%	1741

2.3.3 TREND IN LONGER CHASSIS

In this section, we look at the trends in long truck demand based on historic data. In Figure 11, the additional carrier distances on top of the standard carrier distance of 12 meters are presented per month for the production period from May 2018, which is the first full production month after the new truck introduction, until August 2020. In this graph, a trend line is depicted, indicating a stable average long chassis demand. However, seasonality patterns are visible, e.g., around October. What is notable is the increased fluctuation in additional carrier distance demand per month over time, which is an indication of volatile long truck demand.

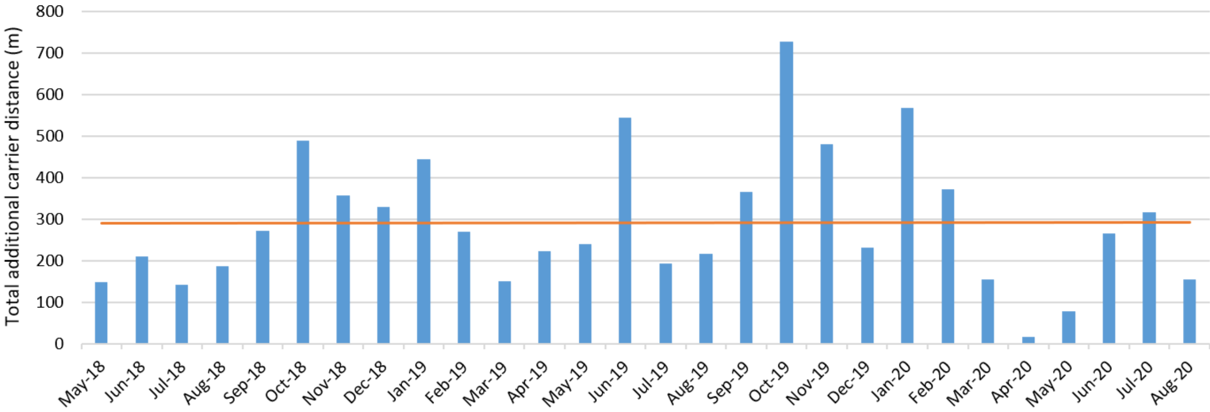


Figure 11: Additional carrier distance from May '18 until August '20

To quantify the statement of increased fluctuation in additional carrier distance demand between the months, we look at the coefficient of variation (CV). The CV is a measure of demand variability (Silver, Pyke, & Thomas, 2017). Figure 12 shows a graph indicating the mean, standard deviation, and CV per yearly quarter. The mean and standard deviation are based on 3 months of additional carrier demand from Figure 11. We calculate the CV by dividing the standard deviation by the mean. The black dotted line is the linear regression line based on the quarterly CV and indicates an increasing CV. This, in turn, indicates on increasing long truck demand variation over time. As discussed in the previous section, large fluctuations in long truck demand can result in additional stoppage time because it is more likely that in periods with peak long truck demand the planning rules to cope with long trucks can not be respected fully.

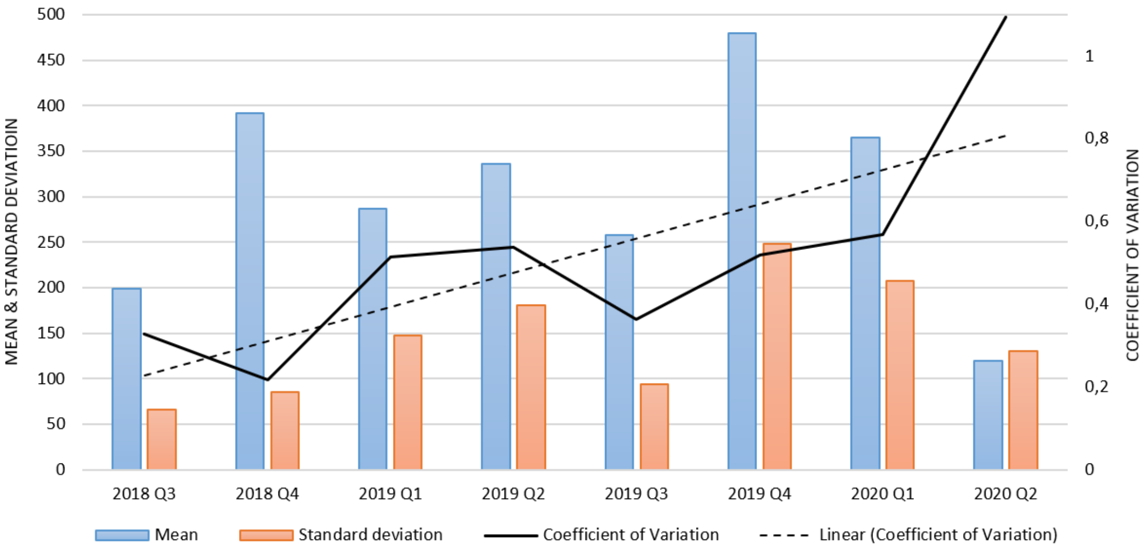


Figure 12: Coefficient of variation per yearly quarter

Figure 11 can be further sub-divided into carrier distance types, providing insight into specific monthly long truck demand. Figure 13 represents the five additional carrier distance classes' trend lines, with on the vertical axis the monthly demand per carrier distance class. The trend line is based on the number of carrier-class types required in the specific month. On average, we see that the demand for longer lengths carrier classes, over 13 meters, increases over time, with a slight decrease in the demand for the carrier length class of 13.5 meters. In contrast, the lower length carrier classes decrease overtime. The longer carrier classes aggravate the perceived problems regarding additional output loss, line balancing inefficiencies, line safety, and ergonomic problems.

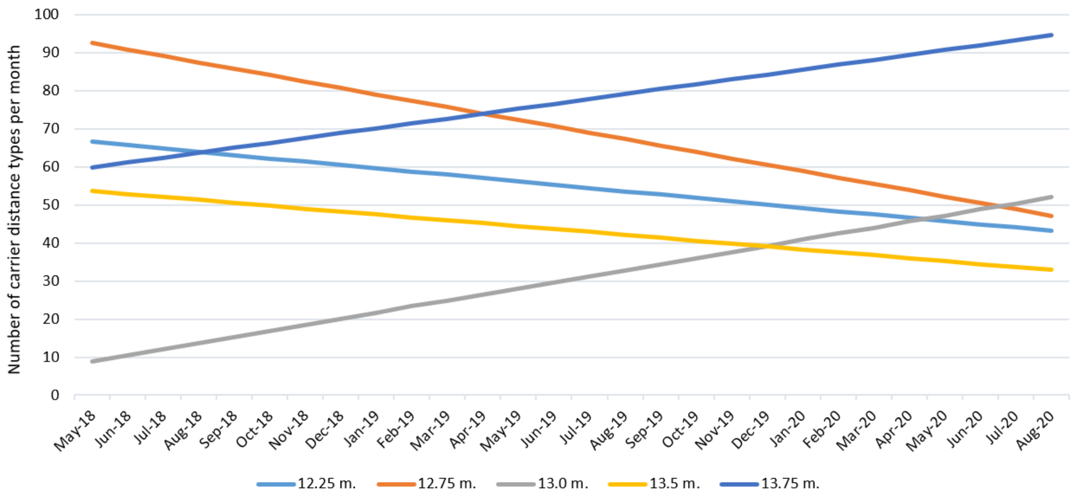


Figure 13: Linear regression of demand per carrier-class from May '18 until August '20

2.4 CONCLUSION

In this chapter, we answer the first research question: "*What is the current situation of the production output and problems faced regarding long trucks?*". First, we describe the production process at SPZ. Next, we elaborate on the current performance of the two assembly lines. Furthermore, we identify potential gains of solving the long truck problem at SPZ.

The problems in output loss, reduced safety level, ergonomics, and efficiency occur due to long trucks that are misaligned with the current workstation length. The main effect SPZ wants to have solved is the direct output loss due to long chassis trucks. There is a potential to increase the yearly production by 278 to 370 trucks by eliminating the additional carrier distance on top of the standard carrier distance of 12 meters. Also, there are potential gains in additional output loss. This additional output loss are line stops attributed to long trucks. It is hard to precisely quantify this problem because the entire stop time is probably not solely due to long trucks. However, it is clear that there is a relation between long trucks and additional line stops when there are many long trucks on the assembly line. Also, increasing the workstation length results in a reduced number of workstations. On line part one, where the trucks are moved synchronously, this reduces the trucks' transportation time and thus reduce operators' waiting time and, in turn, increase operator efficiency. Also, there are potential gains in reducing the number of reported unsafe line situations. From January 2019 until September 2020, there have been ten safety incidents regarding long trucks. Moreover, because of the misalignment of workstation length and long trucks, the assigned stopping position is not always accessible. Solving the mismatch between workstation length and long trucks increases line safety and eliminates the ergonomically poor job of manually positioning long trucks. Another potential gain is the efficiency gains in line balancing. From a lean perspective, an assembly line should operate at equal takt times. Currently, line part two operates at fluctuating takt times because of different carrier distances. The longest trucks operate at a 15% higher takt time than the standard length trucks. Finally, there is a gain in relaxing the planning restrictions of producing maximum 30% long trucks on the assembly line daily, giving the planning department more freedom.

When looking at the trend in long truck demand, we see that the demand is stable on average. However, within the long truck distribution, there is an increased demand for the longest trucks. Also, the long truck demand is increasing in volatility. These two aspects aggravate the following negative consequences concerning long trucks: additional output loss, line balancing inefficiencies, line safety, and ergonomic problems.

CHAPTER 3 LITERATURE REVIEW

Before executing the core of this research, we shape a background of the literature. In this chapter, we answer the research question: "Which methods of designing a line layout and solving an assembly line balancing problem are described in the literature that can be used to improve the output of the Castor-line at SPZ?". The layout of the assembly line is determined by the number and length of workstations along the Castor-line because moving or extending the assembly line is not within the scope of the assignment, as stated in Section 2.1.4. Therefore the focus of the literature review is on redistributing the workload and balancing of assembly lines.

This chapter starts with a broad scope of assembly line classifications and narrows down to specific problem approaches regarding assembly line balancing. First, Section 3.1 gives the general assembly line classifications. Next, Section 3.2 specifies the assembly line balancing problem. Then, in Section 3.3, we discuss solution approaches to combinatorial optimization problems. Next, Section 3.4 presents relevant solution approaches to the assembly line balancing problem. Finally, in Section 3.5, we draw conclusions on the literature study.

3.1 ASSEMBLY LINE TYPES

In this section, we discuss the classifications of assembly lines in manufacturing environments. We discuss assembly line characteristics like production mixture, assembly line layout, workstation setup, and line driving mechanisms.

Assembly lines are specific flow-line production systems. There are different types of assembly lines employed in the field. Traditionally assembly lines were developed for a cost-efficient mass-production of standardized products. However, product requirements and thereby, the requirements of production systems changed dramatically, resulting in different types of assembly lines (Boysen, Fliedner, & Scholl, 2007). The single-model line implies that one homogenous product is produced on the assembly line (Becker & Scholl, 2006). Later in time, most plants shifted from a single-model line to either a mixed-model assembly line (MMAL) or a multi-model assembly line (MuMAL). The MMAL produces a mix of product types without any setup time between different product types and therefore enables a production company to maintain a high level of flexibility. MMAL's require a product that is similar enough between model types to be able to neglect setup times (Boysen, Fliedner, & Scholl, 2007). The MuMAL uses batch production with setup times in between different batches. Figure 14 gives a representation of the three line types where the different shapes on the line represent different model types.

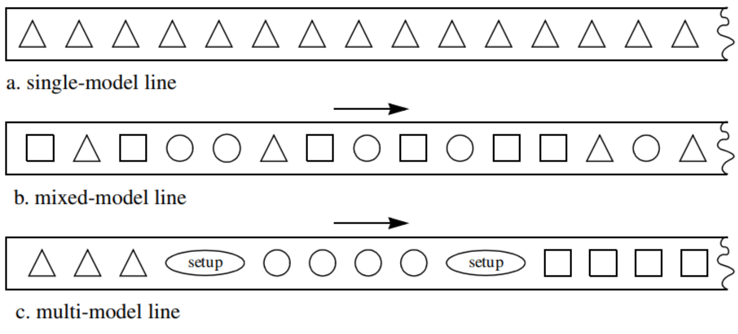
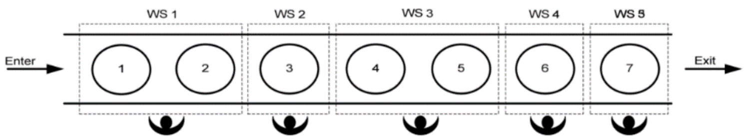


Figure 14: Assembly lines for single and multiple products (Becker & Scholl, 2006)

Tasks that are required to assemble the products on the assembly line are assigned to workstations. These workstations generally are configured in series. However, they can also be configured as parallel workstations. In addition to the different product types being manufactured, the assembly line can be classified as a one-sided or two-sided assembly line. The latter subdivides a workstation into two without the possibility to cross the assembly line. Also, both one-sided and two-sided assembly lines can have workstations with multiple parallel or serial workplaces (Battaïa & Dolgui, 2013). Another classification concerns the layout of the assembly line; the line can be classified as a straight assembly line or a U-shaped assembly line, see Figure 15. A U-shaped assembly line configuration has the benefit of being able to work on two sides of the assembly line by one worker (Rabbani, Moghaddam, & Manavizadeh, 2012). Typically the workstations are arranged in a serial manner along the assembly line. However, in a U-shaped line, there is the possibility to deploy crossover stations. Furthermore, the assembly line can be classified as paced or unpaced. A paced assembly line synchronously transports the product to the next workstation where the job is performed whereas an unpaced assembly line is not restricted by a cycle time but advances the product when all required tasks are performed (Becker & Scholl, 2006).



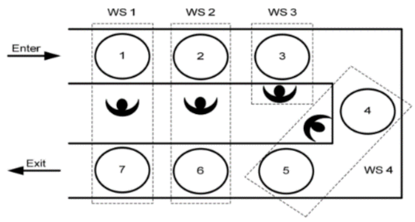


Figure 15: Straight assembly line (left) and U-shaped assembly line (right) (Fathi, Álvarez, & Rodríguez, 2016)

3.2 ASSEMBLY LINE BALANCING

In this section, we introduce the assembly line balancing (ALB) problem. First, Section 3.2.1 presents the core ALB problem. Next, in Section 3.2.2, we discuss relaxations of the core ALB problem and additional constraints and considerations that convert the problem into a better representation of a real-world case. Then, Section 3.2.3 gives the possible objectives of the ALB problem.

3.2.1 THE CORE ASSEMBLY LINE BALANCING PROBLEM

Manufacturing a product on an assembly line requires partitioning the total amount of work into smaller tasks. The assembly line balancing (ALB) problem consists of optimally distributing the assembly work along the workstations of the assembly line. When managing such a system, ALB problems are important decision problems in medium-term production planning (Becker & Scholl, 2006). Due to the practical relevance of the ALB problem, there is a large body of academic literature covering the subject. The first mathematical formalization of the ALB problem by Salveson (1955) focused on the core problem of the configuration, where the assembly line consists of the set $S = \{1, \dots, m\}$ workstations along a material handling device. The total amount of assembly work necessary to manufacture one complete workpiece is split up into a, partially ordered, set of tasks defined by the set (N) (Ritt & Costa, 2018). Partially ordered meaning that there are precedence relations between the tasks in set N, e.g., when building a truck, a frame must be assembled before the tires can be attached. The tasks are performed consecutively on each workstation until the workpiece is finished and reaches the end of the assembly line. So an individual workstation repeatedly performs a particular set of operations to a workpiece that enters the workstation, where the time between two workpieces is referred to as cycle time c. Each task i is an indivisible set of work with a given task time t_i for each task $i \in N$. Performing the specific tasks requires certain equipment, machines, and skills of workers. Due to these technological and organisational requirements, the total amount of work is restricted to a specific sequence resulting in precedence constraints. The general input to the ALB problem can be summarized in a precedence graph (Becker & Scholl, 2006). The graph contains a node for each task with a weight indicating the task time. The arcs of the graph define the precedence constraints, see Figure 16. The aim is to find an assignment $a: N \to S$ of tasks to the set of stations S. A feasible ALB solution cannot violate precedence relations, i.e., all tasks $i, j \in N$ with $i \leq j$ must satisfy $a(i) \leq a(j)$ where i is earlier assigned than j within or across workstations. These precedence relations of a specific task $i \in N$ are captured in a set of immediate followers F_i and a set of immediate predecessors P_i (Ritt & Costa, 2018). For example, an immediate follower of task i can be assigned to the same workstation s if there is room for the task within the cycle time of the specific station. The set N_s of tasks assigned to workstation s is the work content of the station. The cumulative task time of the station $t(N_s) = \sum_{i \in N_s} t_i$ is called the station time. Depending on the objective of the problem, the station time can exceed the cycle time as a feasible solution. When the station time is lower than the cycle time, idle time occurs. In order to achieve high productivity, a good line balance should include as little idle times as possible (Boysen, Fliedner, & Scholl, 2007).

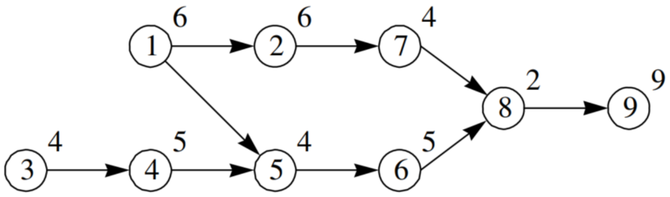


Figure 16: Precedence graph (Boysen, Fliedner, & Scholl, 2007)

Salveson's initial formulation is known as the simple assembly line balancing (SALB) problem, as it features several simplifying assumptions (Boysen, Fliedner, & Scholl, 2007) (Pearce et al. 2019):

1. Mass-production of one homogenous product.
2. Given production process.
3. Paced line with fixed common cycle time c in accordance with a desired output quantity.
4. The line is considered to be configured serially with no parallel or feeder line elements.
5. The processing sequence of tasks is subject to precedence restrictions.
6. Deterministic (and integral) task times.
7. No assignment restrictions of tasks besides precedence constraints.
8. A task cannot be partitioned among two or more stations.
9. All stations are equally equipped in terms of machines and workers.

There have been three kinds of basic SALB models, based on the assumptions defined above, proposed in the literature. Two variants are based on binary assignment variables that assign tasks to workstations, and another variant is based on time variables focusing on physical station limits (Ritt & Costa, 2018). To give an insight into the basic model formulation, according to SALB simplifications, the mathematical model based on task assignment and minimizing cycle time is presented below.

Parameters as defined above with assignment variable x_{si}:

$$x_{si} = \begin{cases} 1, \ if\ task\ i\ \in N\ is\ assigned\ to\ station\ s \in S \\ 0, \ otherwise \end{cases} \tag{1}$$

Objective function:

$$Minimize\ c \tag{2}$$

Subject to:

$$\textstyle\sum_{i \in N} t_i * x_{si} \leq c \qquad \forall s \in S \tag{3}$$

$$\textstyle\sum_{s \in S} x_{si} = 1 \qquad \forall i \in N \tag{4}$$

$$x_{tj} \leq \textstyle\sum_{s \in S | s \leq t} x_{si} \qquad \forall i \in N,\ j \in F_i,\ t \in S \tag{5}$$

$$x_{si} \in \{0,1\} \qquad \forall\ i \in N, s \in S \tag{6}$$

$$c \geq 0 \qquad \forall\ i \in N, s \in S \tag{7}$$

The objective function of the model minimizes the cycle time c (2). Constraint (3) ensures that the total sum of task time, with task time t_i of task i, assigned to each workstation should be lower than the cycle time c. The occurrence constraint (4) specifies that each task should be assigned to precisely one station. Constraint set (5) are the precedence constraints ensuring that precedence relations between tasks are respected using immediate follower set F_i. Constraint set (6) specifies variable x_{si} as a binary variable. Furthermore, constraint set (7) ensures that the cycle time c is a real number.

This model is the basic formulation of the SALB problem. Deviations from the nine assumptions presented above are classified as general assembly line balancing (GALB). Where the SALB problem is very restrictive because of these assumptions, the GALB problems are a better representation of real-life problems. The GALB problems consider practical, relevant extensions, like U-shaped lines, parallel stations, multiple workers per station, processing alternatives, and stochastic processing times (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019). Because of these extensions and relaxations the mathematical formulations of the GALB problems are considerably larger than the formulation of the SALB problems. We discuss these relaxations and additional constraints in Section 3.2.2.

3.2.2 RELAXATIONS AND ADDITIONAL CONSTRAINTS OF THE CORE ALB PROBLEM

One of the simplifying assumptions of the SALB formulation are deterministic task times. However, in practice task times can vary in time, for instance, due to variations in job performance between workers. Instead, one can assume stochastic task times that follow a known distribution. Another variant is the assumption of dynamic processing times, e.g., due to workers' learning effects, processing times can change when workers have performed the task multiple times. Also, sequence-dependent task times could be considered. These task times increment depending on the sequence in which they are performed (Boysen, Fliedner, & Scholl, 2007).

Another important type of constraint are zoning constraints these constraints ensure that activities that should be placed in close proximity or activities that should be separated are modelled accordingly. These neighbouring activities are modelled with positive zoning constraints, for example, certain operations that have to be performed at the same workstation. In contrast, activities that should not be placed near each other are modelled with negative zoning constraints because, e.g., specific tasks disturb each other (Boysen, Fliedner, & Scholl, 2007) (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019). These positive and negative zoning constraints can be captured in the precedence graph. The example in Figure 17 indicates linked tasks, positive zoning constraints, encircled by an oval and incompatible tasks, negative zoning constraints, surrounded by a dashed circle. Also, some tasks must or should not be placed at a particular station or station typeset. Zoning constraints can also capture these requirements. These zoning constraints can differ in the level of detail, e.g., between workstations or within a workstation.

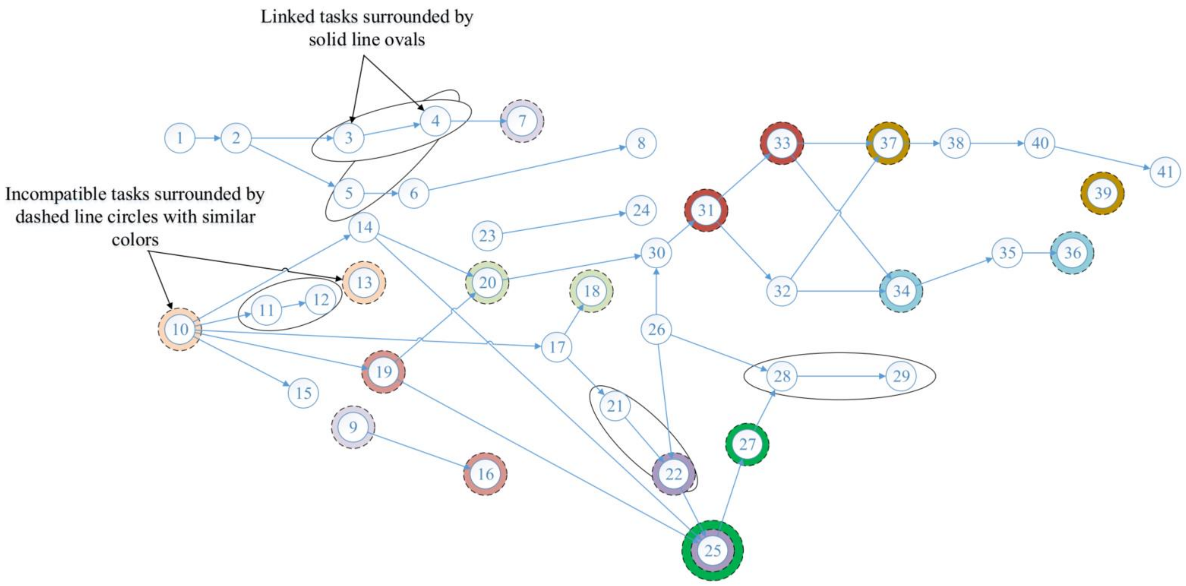


Figure 17: Precedence graph including zoning constraints (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019)

If processing alternatives exist, the production process is subject to change. This brings along an additional decision problem, namely the selection and assignment of processing alternatives. The chosen processing alternative can have an impact on cost and processing times. Also, a processing alternative can affect the precedence relations of tasks because they can alter the production process (Boysen, Fliedner, & Scholl, 2007).

In paced assembly lines, a global cycle time restricts the allowed station time at each workstation. In single model lines, the station time must strictly follow the cycle time. In MMAL problems, however, the average station time of all models must comply with the cycle time, but an individual model can exceed the cycle time depending on the model constraints. An unpaced line is not restricted by cycle time and generally operates with different cycle times between workstations. However, in unpaced ALB problems there can be an additional decision problem of positioning and dimensioning buffers to be able to cope with the different cycle times between workstations (Becker & Scholl, 2006).

A classical line balancing problem assumes that a workstation consists of only one worker. Another relaxation of the SALB problem is the use of multiple workers. These multi-manned assembly lines are commonly found in industries that manufacture large-size products (Michels, Lopes, Sikora, & Magatão, 2019). This, however, introduces the possibility of idle time between jobs in the same workstation because a worker's job is affected by another worker's delay (Yazgan, Beypinar, Boran, & Ocak, 2011). The zoning constraints, together with the addition of multiple workers within a workstation, introduces the work zones constraint to prevent interference between parallel workers in the same station, see Figure 18. Often, in multiple worker ALB problems, the maximum allowable amount of workers present in a workstation is defined. This adds another decision problem to the ALB: that of assigning workers to workstations, and can also include necessary skills of workers for certain kind of operations (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019).

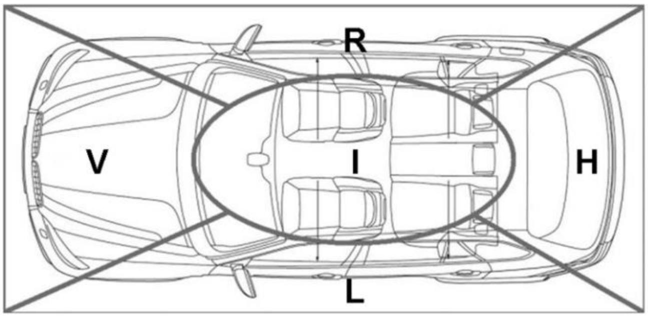


Figure 18: Work zones constraint (Pearce et al., 2019)

Typically, multiple resources at a workstation are required to perform the assigned work such as machines, tools and workers. If the resources are considered explicitly, the ALB problem is connected to an equipment selection problem, which is referred to in the literature as the assembly line design problem. Different types of this problem can be modelled. For example, the selection of exactly one piece of equipment for each workstation or the selection of equipment together with the task assignment for each workstation can be considered. In the latter case, if certain sets of tasks require the same equipment, synergies can be realized by assigning these tasks to the same workstation, for example, expressed in reduced costs. If resources are not considered explicitly, they might influence the ALB problem through processing alternatives or assignment restrictions indirectly (Boysen, Fliedner, & Scholl, 2007).

When using a MMAL in the production system, there is variety in tasks between models. The mixed-model data can be transformed into a SALB version of the problem by averaging the tasks between models based on the task or model occurance (Rabbani, Moghaddam, & Manavizadeh, 2012). When imposing a cycle time restriction for every model variant, the problem is very restrictive and may lead to poor line efficiency. However, it is important that on top of the ALB problem also the sequence of the variants of products is determined to distribute the workload along the assembly line evenly. This is known in the literature as the balance for ordering problem and is best to be determined together with the ALB problem in an iterative manner (Becker & Scholl, 2006). When the balancing is separated from the scheduling a seemingly good balancing according to the desired cycle time can lead to serious blocking problems in the operational phase (Rekiek, Lit, & Delchambre, 2000).

3.2.3 OBJECTIVES OF THE ALB PROBLEM

Two main goals are described in the literature and further subdivide the ALB problem concerning the objective of the model into type-I and type-II. The ALB type-I problem minimizes the number of workstations for a given cycle time and is generally chosen when an assembly line has to be designed from scratch. The ALB type-II problem aims to minimize the cycle time for a given number of workstations (Manavizadeh, Rabbani, Moshtaghi, & Jolai, 2012) (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019). In addition, to type-I and II, type-E ALB problems aim at minimizing the number of workstations m and cycle time c, thus maximising the line efficiency (Zeltzer, Aghezzaf, & Limère, 2017). The line efficiency is defined as, $E = \frac{t_{sum}}{m*c}$ with total task time, $t_{sum} = \sum_{j=1}^{n} t_j$ (Becker & Scholl, 2006). Also there is the type-F problem. This is a problem that assesses the feasibility of a line balance for a given combination of workstations and cycle time. Table 3 gives an overview of the classic objectives of ALB problems. It is also possible to use an objective with a primary and secondary goal, for example, Roshani & Giglio (2017) propose an objective function primarily minimizing the cycle time and as a secondary objective reducing the number of workers. Another possible (secondary) objective of the ALB problem is the horizontal balancing objective, which attempts to equalize stations' work content over all models, which is especially important for MMAL. Because the balancing problem is often based on an average model mix, the horizontal balancing objective anticipates the later sequencing problem (Boysen, Fliedner, & Scholl, 2007). Furthermore, objectives can be assigned to minimize costs, maximize profits or can be related to a bottleneck measure. Also, a compromise of two or more conflicting objectives can be considered. These multi-criteria approaches can be addressed by making use of weighted scoring methods, goal programming or Pareto based ranking (Battaïa & Dolgui, 2013).

Table 3: Objectives overview of ALB problems

Problem	***m***	***c***
Type - I	Minimize	Bound given
Type - II	Bound given	Minimize
Type - E	Minimize	Minimize
Type - F	Bound given	Bound given

3.3 SOLUTION APPROACHES

This section gives solution approaches to the ALB problem. First, Section 3.3.1 introduces the mathematical problem class to which the ALB problem belongs and gives general solution approaches to these kinds of problems. Next, Section 3.3.2 proposes specific solution approaches to the ALB problem. Furthermore, Section 3.3.3 presents a selection of methods to solve the generalised assembly line balancing (GALB) problem.

3.3.1 SOLUTION APPROACHES TO COMBINATORIAL OPTIMIZATION PROBLEMS

Combinatorial optimization aims to find the best solution to a problem from a finite set of solutions. The ALB problems are a class of combinatorial optimization problems known to be NP-hard in general (Battaïa & Dolgui, 2013). NP-hard stands for non-deterministic polynomial-time hardness and basically means that the number of elementary calculations needed to solve the problem cannot be bounded from above by a polynomial. Therefore it is unlikely that the problem can be solved in polynomial time. Consequently, an optimal solution is not guaranteed for problems of significant size.

As stated, the literature differentiates between SALB and GALB. In SALB, the problem complexity is significantly reduced by several simplifying assumptions with respect to practice (Sternatz, 2014). Due to less restrictive assumptions of the GALB problem or due to an increasing number of tasks to be balanced, the ALB problem's finite set of possible solutions rapidly increases. As a result, the problem becomes too large to be solved by complete enumeration, finding an exact solution, in an acceptable time. Approximate methods provide a good trade-off between solution quality and computing time (Kucukkoc & Zhang, 2016). These approximate methods are more suitable for large and complex problem instances. Figure 19 shows the main two method categories of optimization methods exact methods and approximate methods.

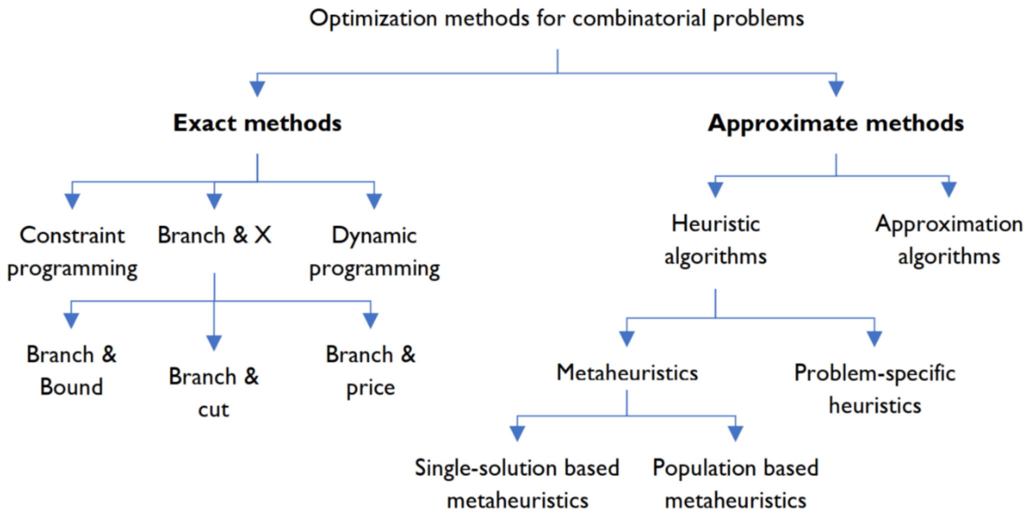


Figure 19: Categorisation of optimization methods (Talbi, 2009)

Exact methods are often applied to smaller problem instances and cover a broad set of methods as can be seen in the categorisation scheme in Figure 19. To solve combinatorial optimization problems, in general, first a mathematical model of the problem is defined. Exact methods to solve these problems can be divided in constraint programming, branch & X and dynamic programming where branch & X is further subdivided in branch & bound, branch & cut and branch and price (Talbi, 2009). There are many solvers available to solve LP problems based on the exact solution methods from Figure 19. Different exact methods are developed for the same problem because different approaches may be more efficient in solving specific problem instances (Battaïa & Dolgui, 2013).

Approximate methods are commonly used to solve combinatorial optimization problems, especially on large NP-hard problem instances. For these NP-hard problems, it is unlikely to find optimal solutions in acceptable computation time and approximate methods are suitable to find good solutions relatively fast. Also, approximate methods are more flexible than exact methods as they are problem independent solution algorithms which can be adapted to fit the needs of real-world optimization problems (Kucukkoc & Zhang, 2016).

Heuristic algorithms can build candidate solutions by using priority rules to assign tasks step by step, constructing a complete solution. These heuristics can be used to be integrated in metaheuristics for further improvements of intermediate solutions (Roshani & Giglio, 2017). Metaheuristics are a class of general-purpose algorithms that can be applied to solve a large number of optimization problems. Where classical heuristics have failed to find solutions effectively, local search methods, as part of the metaheuristics class, can improve initial heuristic solutions. These local search approaches aim to optimise the solution by balancing between intensification and diversification. Intensification concentrates the search on a specific region of the solution space, whereas diversification aims to lead the search to unvisited areas of the solution space (Scholl & Voss, 1997). These approaches, if neighbourhood based, achieve a better result by creating neighbour solutions from the initial solution by executing neighbourhood operators. The neighbourhood operator, for example, swaps a certain task within or across workstations while maintaining a feasible solution aiming to find better results, see Figure 20. Some effective and well-known metaheuristics are tabu-search and simulated annealing (SA). Another type of metaheuristics, not single solution-based, are evolutionary approaches, these approaches work with sequences of heuristics. The categorization framework from Figure 19 distinguishes between exact and approximate methods. However, a hybrid approach could also be considered. These so-called matheuristics consider the combination of a mathematical program and a metaheuristic optimization approach (Battaïa & Dolgui, 2013).

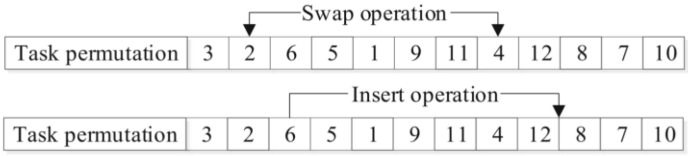


Figure 20: Example of neighbourhood operators (Janardhanan, Li, & Nielsen, 2019)

3.3.2 SOLUTION APPROACHES TO THE ALB PROBLEM

This section starts with the core, simplified, ALB problem. There are various exact and approximate approaches described in the literature to solve the problem. For SALB-I, Scholl & Klein (1997) developed an exact branch and bound (B&B) algorithm. The dynamic programming heuristic of Bautista & Pereira (2009) is comparable with the exact solution of the B&B algorithm. Also, there are various mathematical models formulated in literature solvable using LP techniques. In addition, there are other more flexible heuristic methods suitable to be adjusted for the GALB problem, like the multi-Hoffmann heuristic (Sternatz, 2014). These heuristics typically start with a constructive heuristic building an initial solution. These can be based on popular priority rules in ALB problems like descending task times, descending number of followers or descending positional weights (Scholl & Voss, 1997). The priority rules can be of static nature based on non-changing input like precedence graphs. Alternatively, the assignment of tasks can be dynamic of nature, for example, based on the line efficiency, which is influenced by the solution of the problem. These approximate methods are especially relevant if the problem's solution space is expected to be increased, e.g., by relaxing assumptions or adding tasks.

The GALB problems are a better representation of real-world problems. Different approaches to solve the Mixed Model Assembly Line Balancing problem (MMALBP) type-I and type-II are presented by Becker et al. (2006) in a literature overview study. The study presents solution approaches utilizing techniques like tabu search, two-stage simulated annealing, linear programming (LP), genetic algorithms, shortest path heuristics, and B&B based solutions. Another relevant literature overview is from Fathi et al. (2019); they give an overview of methods to solve the MMALB problem focussing on stochastic task times and zoning constraints in an automotive environment. Also, they present a method to assess the validity and robustness of a found system state considering stochastic task times using simulation approaches. These MMALB problems are addressed by means of mathematical programming, heuristics, genetic algorithms and metaheuristic. According to Battaïa & Alexandre (2013), the most popular algorithms to solve the GALB problem are genetic algorithms, simulated annealing and ant colony optimization. Below we discuss relevant solution approaches to large problem instances of the SALB and GALB problem relevant to the problem at hand.

A mathematical formulation for the formation of teams and workstations in MMAL environments is presented by Cevikcan et al. (2009). As an example, they considered a small problem with only two model types, ten tasks and four workers resulting in a mathematical model with 2620 variables and 472 constraints. If a bigger problem is considered, the mathematical model increases significantly. Therefore, due to the complexity of the mathematical model, the proposed method to solve this problem is a five-step heuristic approach during which the solution is gradually built. One of those steps is a method to sequence the models to mitigate the negative consequences of model variety. Another relevant approach they use is segmenting the assembly line in sections to reduce the problem size. Also, Janardhanan et al. (2019) propose a mathematical model, including worker assignment to workstations. The smaller problem instances are solved using a Mixed Integer Linear Programming (MILP) approach, whereas the larger problems are solved with a heuristic approach called the migrating birds optimization algorithm. In these mixed-model situations, the model variation is often addressed by averaging the task duration per model according to its demand ratio. These average task times can be summarized in a combined precedence graph used as input for the solution approach at hand (Bukchin, Dar-El, & Rubinovitz, 2002).

Pearce et al. (2019) propose a two-staged heuristic for the MMALB problem, including multiple workers per workstation, work zones within stations, and availability of resources required for tasks. A constructive heuristic based on the task time is used to build an initial solution. Next, two improvement heuristics are proposed to optimize the solution. The first heuristic is based on task prioritization and the second heuristic focusses on the selection of work zones within a workstation. A similar approach to the MMALB problem with some simplifications in respect to the formulation of Pearce et al. (2019) is proposed by Bukchin et al. (2002) where the solution is optimised using a local search method. Roshani et al. (2017) also propose a mathematical formulation for the multiple worker ALB type-II problem to be solved using a constructive heuristic and different variants of simulated annealing metaheuristics. Another relevant solution approach using simulated annealing while considering a U-shaped assembly line is proposed by Fathi et al. (2016).

An approach to solve the MMALB type-II with stochastic task times using a genetic algorithm is presented by Manavizadeh et al. (2012). Genetic algorithms are based on evolution using promising solution results from parents to be transferred to their child, and eventually, good solutions are found over generations utililzing mechanics from genetic inheritance and survival of the fittest. Also, Zhang et al. (2019) propose a similar solution approach using a genetic algorithm for the MMALB type-II with stochastic task times.

A solution approach to solve the multiple worker ALB problem incorporating flexible station frontiers is presented by Lopes et al. (2020). They propose a mathematical formulation to be solved by a two-stage heuristic due to the computationally intensive nature of the model. The heuristic first solves a master problem (MP) limited to assignment variables of tasks and workers. Next, the solution of the MP is used to solve the slave problem (SP), which is limited to order and schedule variables. Due to the flexible workstation lengths, the researchers were able to reduce the majority of line lengths of standard ALB problems found in the literature. Michels et al. (2019) propose a similar method with a MP and SP to be solved using MILP techniques. This model, however, incorporates some simplifications in respect to the work of Lopes et al. (2020) for example, the flexible station frontiers are not included. Both methods are based on Bender's decomposition method (Benders, 1962), who introduced the MP and SP approach.

3.3.3 OPTIMIZATION METHODS SUITABLE FOR SPECIFIC GALB PROBLEMS

In this section, we discuss 2 methods prominently present in ALB literature that are suitable to optimize GALB problems. Moreover, these methods are flexible enough to be adjusted to specific GALB problem characteristics. We consider the GALB problem because this problem class relaxes some restrictive assumptions of the SALB problem resulting in a better representation of the real world.

From the literature review, we observed that simulated annealing is a proven and popular method to solve the GALB problem (Battaïa & Dolgui, 2013). SA is a single solution based optimization method suitable to be adjusted to problem-specific elements, e.g., a combination of work zone constraints, multiple worker problem and technological constraints. It is a method able to escape local optima in search of the global optimum of the problem. Considering a GALP problem, SA finds a near-optimal solution in acceptable computation time compared to other exact methods. SA starts with an initial feasible solution which is generated using a constructive heuristic. It utilizes neighbourhoods operators, such as presented in Figure 20, to generate a solution based on the current solution. Then the objective function of this neighbourhood solution is calculated, and the outcome is accepted if it performs better than the current solution found. Alternatively, with a certain probability, the neighbourhood solution is accepted if it performs worse than the current solution found. This enables SA to escape from local optima. The probability of accepting worse solutions is controlled by a cooling scheme that determines the trade-off between the diversification and intensification search of SA.

SA does not memorize the solutions that the metaheuristic has visited so far, resulting in the possibility of revisiting solutions and thus wasting computation time. Another approach suitable for solving GALB problems and incorporating short term memory of visited solutions is Tabu search. This method is also flexible enough to incorporate specific GALB problem characteristics. Tabu search is similar to SA in that it moves from one solution to another while considering worse solutions than currently found. The main difference between the two is the criterion on accepting or rejecting a solution, which is probabilistic in SA and deterministic in Tabu search. Tabu search starts with an initial feasible solution and keeps track of recently visited solutions on a Tabu-list. Using similar operators as in SA, all neighbourhood solutions of the current solution are evaluated. The best of these neighbourhood solutions, not present on the Tabu-list, is accepted even if it is worse than the current solution. Generally, operators are stored on the Tabu-list instead of solutions. After every iteration, the Tabu-list is updated. The Tabu-list length is an important parameter in Tabu search and determines the performance of the metaheuristic (Scholl & Becker, 2006).

3.4 CONCLUSIONS

This chapter answered the following research question: "*What methods of designing a line layout and solving an assembly line balancing problem are described in the literature that can be used to improve the output of the Castor line at SPZ?*" In this section, we summarize the assembly line classifications, and we discuss the constraint types and relaxations of assumptions of the ALB problem. The design of the assembly line results from the length and layout of the workstations, given the available line space and current line setup.

In Section 3.1, we discussed assembly line types. The first important observation to note is the type of product produced on the assembly line and distinguishes the line into single-, mixed, or multi-model assembly line. Next, the setup and layout of the assembly line are important. Workstations can be arranged in series or, partly, in parallel. These workstations, in turn, can be divided into certain areas for workers to work in, e.g., the workstations can be split into two when workers are not able to cross the assembly line. Furthermore, the layout can be realized as a straight assembly line or U-shaped assembly line, where at a U-shaped assembly line, there is the possibility to operate 2 workstations by one person. The final assembly line classification concerns the driving mechanism of the line that can be paced or unpaced.

Next, in Section 3.2, we described the assembly line balancing problem. First, we discussed the core assembly line balancing problem, known as the SALB problem, and the most important simplifying assumptions. Also, the model formulations of the SALB problem are presented together with the main model inputs. The most important inputs to the SALB problem are the precedence relations and task times. Next, we discussed the SALB problem's relaxations and additional constraints of the model to arrive at GALB problems, which are a better representation of real-life problems. These GALB problems consider, e.g., parallel stations, multiple workers per station, processing alternatives, and stochastic processing times. Finally, Section 3.2.3 presents the four classical objectives of the ALB problems with two critical parameters, the number of workstations and the cycle time. Each of these four objectives all concern the two parameters, number of workstations and cycle time, where these parameters are minimized, optimized, or a bound is given on the parameters' maximum value.

The final part of this chapter, Section 3.3, provides solution approaches to ALB problems. First, more in general, we discuss combinatorial optimization problems and the distinction in the literature between exact methods and approximate methods. The exact methods are more suitable for SALB problems or small problem instances because these methods completely enumerate the solution space of the problems resulting in long computation times. These exact methods are, for example, approaches like B&B and dynamic programming. The approximate methods are not likely to find the best solution. However, for large problem instances or GALB problems, these methods provide a better trade-off between solution quality and computation time. The approximate methods consist of heuristics, algorithms, and metaheuristics. Section 3.3.2 presents solution approaches found in the literature used to solve real-life problems with practical assumptions and constraints. The methods used are dynamic programming, B&B based solutions, tabu search, simulated annealing, genetic algorithms and other metaheuristics. Section 3.3.3 presents simulated annealing and tabu search as suitable solution methods to incorporate specific GALB problem characteristics.

CHAPTER 4 ASSEMBLY LINE LAYOUT PROPOSAL

In Chapter 2, we discussed the current situation regarding long trucks. As a solution approach to mitigate long trucks' negative consequences, this research focuses on longer workstation lengths than currently deployed at the Castor assembly line. The workstation length determines the Castor line's new layout because expanding its length is not possible. This chapter presents the assembly line layout proposal. The layout determines the number of workstations used, which is an important input for the assembly line balancing model discussed in Chapter 5. First, Section 4.1 analyses the produced truck lengths within SPZ and the potential output gain of specific workstation length proposals. Next, Section 4.2 discusses bottleneck processes along the assembly line, which currently perform on their limit. Then, Section 4.3 presents the layout proposals given the findings from Sections 4.1 and 4.2. Finally, Section 4.4 summarizes and concludes on the items shown in this chapter.

4.1 ANALYSIS TRUCK AND WORKSTATION LENGTH

This section analyses the length distribution of the long trucks produced within SPZ. From this analysis, we indicate the potential output gained given a certain workstation length. Finally, this section introduces the technical difficulty of implementing longer workstations. Section 4.2 elaborates on these technical difficulties in more details.

Recall from Section 2.3.1 that a truck is a long truck when it requires a carrier distance of over 12 meters. 9.26% of the produced trucks considered in Section 2.3.1 are long trucks. We look into the length distribution of these long trucks in this section, as depicted in Figure 21. This figure presents the number of long trucks produced in a specific length group, e.g., length group 12100, of Figure 21, indicates that around 800 trucks were built with lengths between 12,001 mm and 12,100 mm. Notable is the cumulative frequency of this distribution, which is approximately linearly growing up until 3/4th of the distribution. Also noteworthy is the peak in frequency of the length group 13600 mm, consisting of roughly 20% of the long truck distribution. This higher spectrum of the long truck distribution causes more severe problems than the start of the long truck distribution on both line part 1 and line part 2. When there are multiple trucks on the assembly line from the higher end of the long truck distribution, the problems discussed in Section 2.3 aggravate. The direct output loss on line part 2 always occurs for any of the long trucks. However, the output loss for a single long truck at the higher end of the long truck distribution is more than from a truck at the start of the distribution due to the required additional carrier distance.

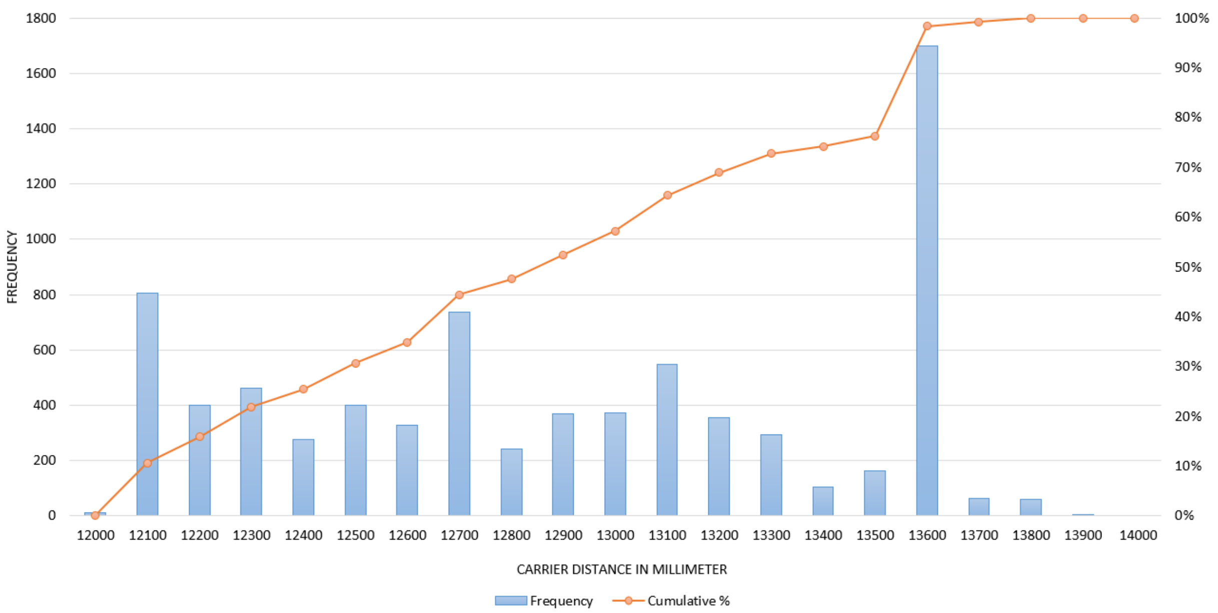


Figure 21: Long truck length distribution

This long truck distribution can be used to analyse the potential output loss reduction and the impact of the proposed workstation length. We can calculate the proportion of long trucks that fit within a certain workstation length and the proportion that does not. For the latter proportion of trucks, additional carrier distance exceeding the proposed workstation length is needed to respect the required safety distance towards successive trucks. So for the trucks still exceeding a certain workstation length, the practice of measuring the truck's length with a light screen and assigning a carrier distance accordingly, as explained in Section 2.3.1, should be kept in place. This also means that a proportion of the potential output gain is not counted, for certain workstation lengths, because direct output loss due to long trucks is still incurred.

If we assume the same daily line output while implementing longer workstations, we can calculate the output loss reduction expressed in meters of assembly line space for a specific workstation length proposal. This output loss reduction in meters can be translated to trucks saved yearly by dividing the amount of saved line space by the standard carrier distance of 12 meters. We indicate the potential output loss reduction expressed in the number of trucks yearly for each workstation length, see the left vertical axis of Figure 22. This potential gain in trucks saved yearly is calculated based on the same high demand scenario used in Table 1. Notable is the difference in potential from 370 trucks saved yearly in Table 1 and 317 trucks in Figure 22. This difference arises due to a more precise calculation of the potential output gain used in Figure 22. The carrier distances currently in practice vary from an additional 25 or 50 centimetres on top of the standard 12 meters. Whereas the potential output gain of Figure 22 uses the more precise workstation length steps of 10 centimetres. For example, if a truck just exceeds the 13-meter carrier distance class, almost 50 centimetres of additional space is taken currently in contrast to the approach used in Figure 22. We explain the secondary axis of the figure, indicating the takt time equivalent below.

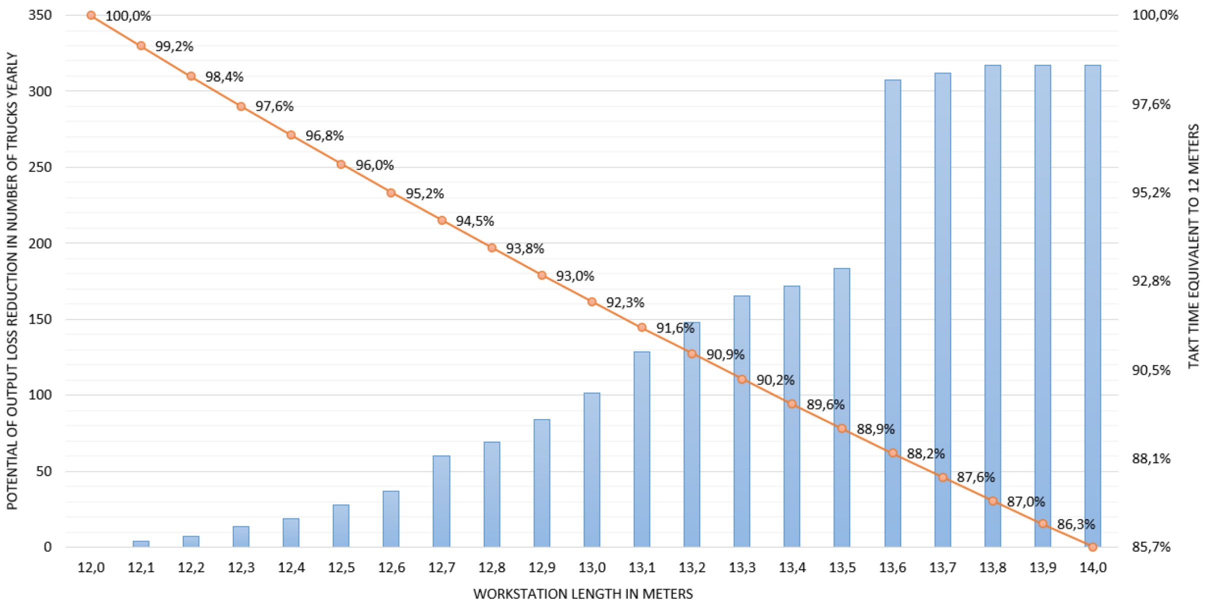


Figure 22: Potential output loss reduction and takt time equivalent

It is crucial for SPZ that this research's solution is based on the assumption of, at least, equal daily output because SPZ is always aiming to improve the plant's output. However, this does mean that the line speed should increase to maintain the same output. Because to achieve the daily output, we still need to produce a truck, e.g., every 10 minutes. So if longer workstations are implemented, a single workstation's takt time remains 10 minutes, but the distance the carrier system has to travel during this takt time is increasing, which can only be realized by increasing the line speed. Increasing the line speed can result in technical difficulties because specific equipment or processes cannot finish their task given the higher line speed and physical range limitations. For example, the process that fills the trucks cooling liquids is already performing at its maximum speed. The filling equipment's range should be extended to complete this task within the required time if the line operates at higher speeds.

Given these technical difficulties, it is useful to show when the carrier system has reached 12 meters to indicate the proposal's technical impact. Figure 23 depicts this concept for 3 station lengths: 13.0, 13.5 and 14.0 meter. The top of the figure presents the current situation at which SPZ operates. We do not report on the fastest takt time due to confidentiality reasons but normalize the current situation to 100%. So in 100% of the takt time, the carrier system reaches 12 meters. To be able to reach 13 meters in the same takt time, the carrier speeds need to increase, and we reach 12 meters in 92.3% of the current takt time. We follow the same approach for the other 2 workstation lengths of 13.5 and 14 meter in this example. The percentage of the takt time the carrier passes the 12-meter boundary, in red, is an indication of the technical feasibility of the proposal. This same concept is depicted as the “takt time equivalent” in Figure 22 on the vertical axis on the right. So when choosing an effective workstation length, there is a trade-off between output loss reduction on the one hand and investments to be made to cope with the increased line speed on the other hand.

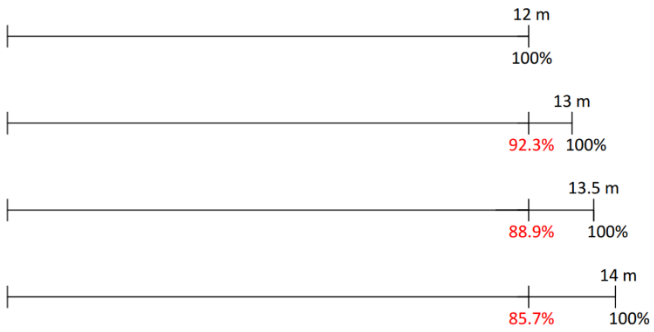


Figure 23: Takt time equivalent of workstation length to current workstation length setup

4.2 BOTTLENECK PROCESSES

This section introduces the identified bottleneck processes along the second part of the Castor assembly line. We define bottleneck processes as processes that are affected by long trucks and operate at their limit or are expensive to modify. These processes are especially relevant, given the technical difficulties we introduce by proposing higher carrier speeds when implementing longer workstations as introduced in Section 4.1.

As discussed in Chapter 2, we can subdivide the Castor assembly line into two parts, line part 1 and line part 2. At line part 1, the negative consequences of long trucks along the line mainly concern ergonomic and safety-related issues. On line part 2, long trucks mainly cause direct output loss. This output loss can be directly translated to a monetary value, whereas the potential benefits on line part 1 indirectly contribute to an increase in the plants' output. Also, at line part 1, a high task and operator density is making it more challenging to reduce the number of workstations and rebalance the task at this line part. Given the current investment climate within SPZ, the potential benefits and difficulties balancing the first line part, we focus on line part 2 of the Castor line for the remainder of this research.

SPZ is continually improving its processes to reduce takt time, aiming to improve the plant’s output. If SPZ plans on higher daily output, the workstations takt time is reduced by increasing the carrier systems' travelling speed. Therefore a considerable amount of information is available on the capabilities, possibilities, and limits of processes and equipment. There are initiatives at SPZ aiming to reduce the current lowest takt time even further and thus increase the plants' output. Increasing the line output often means that more operators along the Castor line are needed to perform the required tasks on more trucks daily. A reduction in takt time of around 5% is within reach with relatively low investments in equipment and efforts. However, further decreasing the takt time will increase the necessary investments in equipment modifications, new equipment, and efforts to introduce these modified processes. A reduction in takt time of around 14%, corresponding to 14-meter workstations, is challenging.

As mentioned, we focus on the second part of the assembly line to mitigate the direct output loss due to long trucks. The second part of the Castor line starts at station 28, see Figure 24. Processes that operate at their limit are considered bottlenecks. The limit of a process within SPZ is defined as a process having an occupancy rate of 80% or more within takt time. When checking the occupancy rate on, the current lowest takt time, the first process exceeding the 80% threshold is the cabin placement at station 36. A system called the Eagle picks a cabin from the cabin pre-assembly station, transports it to the Castor line and places it on the trucks' chassis. See Figure 24 for the pre-assembly station layout. This whole process takes 83% of takt time and is therefore considered a bottleneck. The next two processes operating over or just at their limit are the liquid filling processes of the truck's coolant and air conditioning systems. Furthermore, the tire conveyor operates over its threshold at the fastest takt time. This system supplies tires to the assembly line to be mounted on the truck.

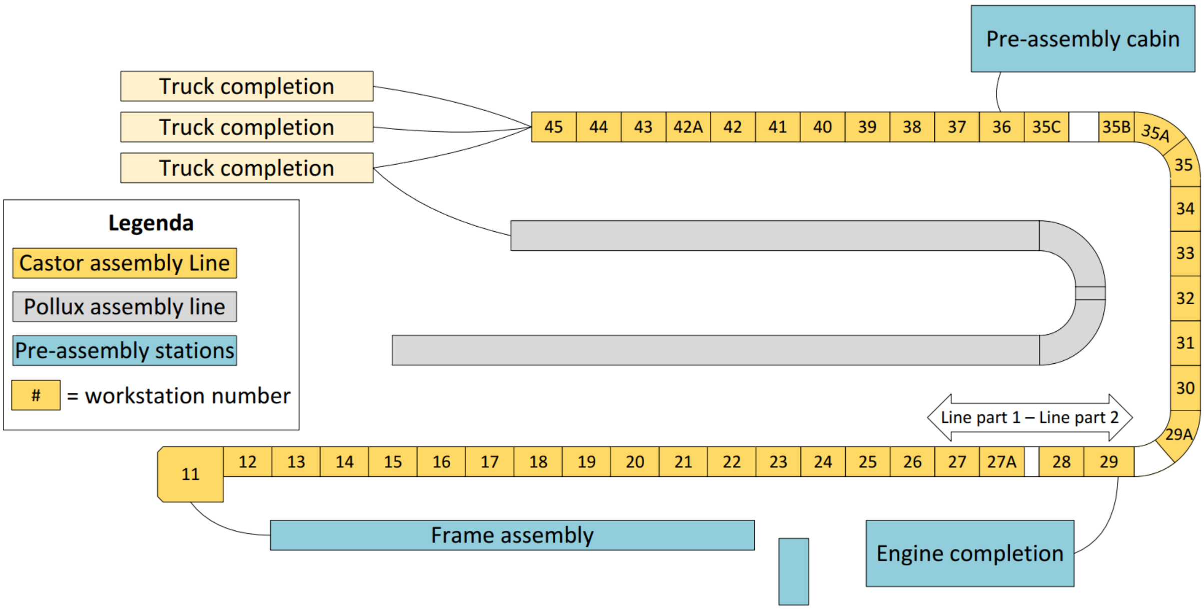


Figure 24: Assembly line layout

The processes that operate at their limit are cabin placement, liquid filling of coolant & airconditioning, and tire assembly. When implementing longer workstations, the takt time equivalent to 12 meters is shorter. This shorter takt time equivalent results in the bottleneck processes operating over their limit even further. Table 4 summarises the bottleneck processes, the occupancy rate at the current fastest takt, and the equivalent of this takt projected to 14-meter workstations. From the table, we can conclude that the occupancy rate increases when longer workstations are implemented, and investments in these processes are necessary to improve their performance and reduce their occupancy rate.

Table 4: Occupancy rate of bottleneck processes

		Occupancy rate within takt	
Station length in meters		**12**	**14**
Takt time equivalent to 12 meters		**100%**	**85.7%**
Process name	**Station #**		
Cabin placement	36	83%	96%
Liquid filling: Coolant	40	82%	95%
Liquid filling: Air conditioning	40	74%	86%
Tire assembly	43	93%	104%

Next to the large installations described above, many relatively small tools and processes are also affected by a higher line speed. The Scania Production Computer Tool (SPCT) uploads software to the cabin at station 41, 42A and, 45. This tool is designed close to the current fastest takt time, so at higher line speeds, it is possible that the software upload is not finished while the SPCT has reached the end of its physical range. This same problem also applies to other smaller tools which have a physical range along the assembly line. In general, to reduce the occupancy rate of processes, these processes' physical reach can be extended, so these processes have more time to finish their job. Alternatively, these processes can be improved to reduce their cycle time.

A different line layout could influence the ideal placement of certain processes along the assembly line. For some large installations, repositioning has considerable implications. Before the engine placement at station 29, the engine is pre-assembled. This large pre-assembly station connects seamlessly onto the Castor line at station 29. Another large installation having a connection to a pre-assembly station is the Eagle system at station 36. Furthermore, the tire conveyor installation efficiently transports the required tires to both the left and right hands side of the assembly line. The processes of placing the engine, cabin and, tires are directly connected to these large installations. When repositioning these processes, large investments have to be made to maintain these processes' cycle time. Therefore it is preferable not to adjust or reposition these installations.

4.3 LINE LAYOUT

This section describes the possible assembly line layouts considering longer workstations. As mentioned in the previous section, we focus on line part 2 of the Castor assembly line. Also, there are not many possibilities to extend the assembly line due to the factory's lack of space. Considering these constraints and the findings of Sections 4.1 and 4.2, we propose promising workstation lengths and the resulting line layouts in this section. The proposed layout, especially the number of stations to balance, is an important input parameter for the ALB model described in Section 5.2.

As one of the solution design criteria, SPZ requires that at least 2/3th of the total potential output gain is utilized to be able to make a good business case for the project. As described in Sections 4.1 and 4.2, longer workstations increase the carrier speed at which the line operates, which in turn increases the occupancy rate of installations along the assembly line. The higher the carrier speed, the more efforts and costs are required to adjust these installations to cope with the increased carrier speed. Figure 22, from Section 4.1, depicts this trade-off indicating a takt time equivalent to 12 meters and the workstation proposal's output gain. From Figure 22, we derive that a workstation length of 13.6 meters utilizes 96.8% of the total potential output gain and thus complies with the solution designs requirement, whereas 13.5 meters only utilizes 57.7% of the total potential output gain. Therefore in this section, we consider 14-meter workstations utilizing the full potential output gain and 13.6-meter stations utilizing slightly less of the full potential output gain. When implementing 13.6-meter workstations, there is still a chance of 3.2% that the truck exceeds the workstation length and therefore the light screen measure approach to ensure safety distance, as described in Section 2.3.1, should be kept in place. However, the 13.6-meter workstation length requires a lower line speed compared to the 14-meter workstation proposal making it easier to implement, see Table 5 at the end of this section for the required line speeds.

Line part 2 starts with placing the truck's chassis from a hanging position on a carrier system at station 28, Figure 24. Next, the truck moves to workstation 29, where the engine is placed and attached to the chassis. These two workstations are longer than 12 meters, and there are no issues with long trucks at these stations currently. Also, station 29 is connected to the motor pre-assembly station with a dedicated logistical motor feeding system. Therefore it is not beneficial to adjust these workstations. Thus we propose to keep the same setup for stations 28 and 29 as currently in place. Also, we propose to keep the cross-aisle between station 29 and 29A as currently deployed to reduce the impact on logistical processes. Therefore we propose not to adjust any workstation lengths before workstation 29A and consider increasing the workstation length as of station 29A towards workstation 45.

Another large installation connected to a pre-assembly station is the Eagle system placing the cabin of the truck at station 36, see Figure 24. As described in Section 4.1.2, the cabin placement process currently performs over 80% occupancy rate and is considered a bottleneck. When we propose changing the workstation boundaries significantly of station 36, this reduces the cabin placement process efficiency. The Eagle installation has an optimized logistical connection to the cabin pre-assembly station. There are considerable costs and efforts involved to adjust the current Eagle installation setup. Therefore we propose to keep the Eagle installation in place and the boundaries of station 36 as close as possible to the current setup.

We make a layout projection starting at the two constraints at station 29A and 36, see Figure 24. The current setup from station 29A until 35C, referred to as line part 2.1, are 10 stations of 12 meters. When projecting 10 workstations of 13.6- or 14-meters we require 136 meters or 140 meters where in fact 120 meters of line length are available, so we need to reduce the number of stations when proposing a layout incorporating longer workstations. Similarly, the current setup from station 36 until 45, referred to as line part 2.2, consists of 11 workstations of 12 meters. So there is 132 meters of space available on line part 2.2, but there is no space for 11 workstations of 13.6 or 14 meters.

We assessed the line layout with 13.6- and 14-meter workstations on line part 2.1, station 29A until 35C, and line part 2.2, station 36 until 45, given the current 12-meter workstation setup. When projecting 9 workstations of 13.6-meters on line part 2.1, we require 2.4 meters of additional line space. A similar projection of 9 workstations of 14-meters requires 6 meters of additional line space compared to the current setup. This space can be taken from the buffer function of station 35B where no assembly tasks are performed or partly from the cross-aisle between station 35B and 35C, see Figure 24. For line part 2.2, a projection of 10 workstations of 13.6-meters requires 4 meters of additional line space. In contrast, a projection of 10 workstations of 14-meters would require an additional 8 meters of additional line space. According to SPZ production representatives, at most 4 meters of additional line space can be made available considering the assembly track after station 45 and the tasks performed at this station. As described in Section 3.2.3, we have to choose an integer number of workstations to be used as input for the ALB model due to modelling constraints. Therefore we propose a layout of line part 2.2 with 10 workstations of 13.6-meters or 9 workstations of 14-meters. Table 5 summarizes the results of these 13.6- and 14-meter workstation layout proposals.

Table 5: Workstation length projections

Workstation length (m.)	Number of stations line part 2.1	Required length line part 2.1 (m.)	Number of stations line part 2.2	Required length line part 2.2 (m.)	Takt time equivalent to 12 meters	Potential output gain
12.0 (current)	10	120	11	132	100%	0%
13.6	9	122.4	10	136	88.2%	96.8%
14.0	9	126	9	126	85.7%	100%

To conclude on this section, the 14-meter workstation proposal utilizes the full potential output gain, operates at the highest line speed of the proposals and the workstation boundaries deviate the most compared to the current line layout. The 13.6-meter workstation proposal utilizes 3.2% less of the total potential output gain and operates at a slightly lower line speed compared to the 14-meter proposal. The 13.6-meter workstation proposal's station boundaries deviate less from the current layout than the 14-meter proposal. However, considering the 13.6-meter proposal, 3.2% of the long trucks still exceed the workstation length and therefore, the light screen measure approach to ensure safety distance should be kept in place. Section 2.3.3 presents a positive trend of the longest carrier-class type of 13.75 meters over time. This indicates that the 3.2% portion of the potential output gain that the 13.6-meter workstation proposal could not cover can increase towards the future. Considering the benefits of both the 13.6- and 14-meter workstation layouts, we propose considering both layouts in the assembly line balance to further assess the feasibility of a new line layout.

4.4 CONCLUSIONS

In this chapter, we answer the research question: *"Which workstation length and assembly line layout should be chosen to reduce the output loss regarding long trucks?"*. This section summarises the findings described in this chapter, such as potential output gain per workstation length proposal, bottleneck processes and layout proposals. Next, we draw conclusions based on these findings and propose a new workstation length and line layout.

In Section 4.1, we analysed the truck length distribution and discussed the implications of workstation lengths. The full potential of output gain can be realized when implementing 14-meter workstations as can be seen from the potential output gain distribution. Notable is the large increase in output gain from a workstation length of 13.6-meter onwards. We also discussed the trade-off between output gain and line speed, expressed as takt time equivalent. Longer workstations require an increase in carrier speed to be able to maintain the same assembly line output. Taking the highest line output as a basis, this results in passing 12 meters in 85.7% of the takt time when utilizing 14-meter workstations compared to the current setup of 12-meter workstations. This higher line speed poses challenges in processes reaching their limits or exceeding their limits even further and requiring investments to reduce the occupancy rate.

Section 4.2 focuses on these bottleneck processes. Processes operating at an occupancy rate of 80% or more are considered bottleneck processes. We focus the research on the second part of the Castor assembly line because the direct output loss is incurred at this part of the assembly line. The identified bottleneck processes on line part 2 are the cabin placement, filling of coolant, filling of air conditioning and the tire assembly process. More precise, these bottlenecks are all situated at line part 2.2, from workstation 36 until 45. Furthermore, the SPCT installations are designed on a processing time close to the current fastest takt time and together with other smaller equipment, they should be extended in their physical range to complete their process within takt time.

Section 4.3 presents two workstation length proposals constrained by a minimum potential output gain of 2/3th of the complete problem, namely 13.6- and 14-meter workstations. 14-meter stations utilize the full potential output gain. However, this concept is challenging to implement due to the higher carrier speed and practical limitations of the available line space. 13.6-meter stations yield 96.8% of the total potential output gain and, compared to the 14-meter proposal, is practically easier to implement. The total potential output gain of 96.8% can decrease slightly towards the future because there is a positive trend visible in the number of longest carrier types per month, as can be seen in Section 2.3.3. The 13.6-meter station proposal requires a smaller reduction in the number of workstations, utilizes the available line space more effectively and operates at a lower line speed.

To summarize, the 13.6-meter workstation layout is practically easier to implement. However, this 13.6-meter station proposal, in contrast to the 14-meter station proposal, does not fully utilize the potential output gain. Meaning that not all trucks fit within the 13.6-meter workstation length, and thus this proposal requires the light screen measure at the start of line part 2 to be kept in place to ensure safety distance. In both cases, the most severe bottlenecks are situated on line part 2.2, between the cabin placement and the end of the Castor assembly line. Considering both layout concepts' benefits, we propose to include both the 13.6- and 14-meter workstation layouts in the assembly line balancing analysis to further assess both concepts' feasibility.

5 ASSEMBLY LINE BALANCING MODEL

This chapter presents the assembly line balancing model used to test the layout proposals described in Section 4.3. First, Section 5.1 presents the conceptual ALB model based on literature and relevant aspects at SPZ. This is the basis of the ALB model presented in Section 5.2 used to balance the assembly line at SPZ.

5.1 ASSEMBLY LINE BALANCING CONCEPTUAL MODEL

In this section, we shape the foundation for the ALB model presented in Section 5.2. First, Section 5.1.1 presents the goal and scope of the model. Then, Section 5.1.2 presents the literature aspects relevant to the ALB problem at hand. Finally, Section 5.1.3 elaborates on the literature gap that this research fills.

5.1.1 GOAL AND SCOPE OF THE ASSEMBLY LINE BALANCE

This research focusses on reducing output loss caused by long trucks by implementing longer workstations then currently deployed at SPZ. When implemented, the proposal impacts the core of SPZ's business, building trucks, and therefore, comprises many details. However, the goal of this research is to assess the feasibility of implementing longer workstations at SPZ. Therefore, given the available time, it is important to determine the ALB model's scope given its goal carefully. Regarding balancing of tasks on the assembly line, in accordance with the detail level of the globally prescribed assembly sequence within Scania, the tasks we consider are relatively large tasks. For example, we focus on task sizes such as placing a cabin or filling coolant instead of tightening a bolt or attaching a hose. Furthermore, given the number of tasks performed at line part 2, from mounting the motor on the chassis to finalizing the complete truck, it is necessary to reduce the problem size to be able to collect detailed task data given the available time. We can partition the problem without influencing the outcome of the final solution if we choose the decoupling point smartly because, e.g., the assembly of the frame should not necessarily be considered in the same problem instance as the placement of the truck's cabin. The truck's cabin placement is such a decoupling point because before the cabin can be placed, a whole series of tasks must be completed and after the placement of the cabin, a new set of tasks becomes available to be performed. As concluded in Section 4.4, the most severe bottleneck processes are situated at line part 2.2, from the cabin placement to the end of the Castor assembly line. So if a rebalance, given a reduced number of workstations, is feasible at line part 2.2 it should also be feasible at line part 2.1. Therefore the scope of the assembly line balance is line part 2.2, consisting of workstation 36 until 45, see Figure 24, starting with the cabin placement.

5.1.2 CONCEPTUAL ALB MODEL DERIVED FROM THE LITERATURE

This section presents assembly line classifications relevant to the case at SPZ, based on the literature framework shaped in Chapter 3. Also, we discuss relevant constraint types and relaxations of assumptions of the simple assembly line balancing (SALB) problem. This section presents the building blocks for the ALB model, as described in Section 5.2.

First, we look at the classification of the assembly line and line layout. At SPZ a mixed-model assembly line (MMAL) is used without any setup times between different truck types. The line layout physically looks like a U-shaped line. However, the assembly line is large to such an extent that a straight assembly line is effectively deployed at SPZ not having the U-shaped line benefits. Two-sided assembly line jobs can be performed at SPZ, but the workstations are not split in two and workers can cross the assembly line facilitating the ability to perform multiple jobs in parallel. Furthermore, the assembly line is deployed as a paced assembly line where the workpiece's movement is bound by set times.

Linked to this problem type are the constraints of the mathematical model. Precedence and zoning constraints are of great importance due to the globally prescribed assembly sequence of trucks within Scania. This assembly sequence is determined globally to increase the company's truck assembly coherence and is used as a basis to determine the detail level of the line balance and inputs to the model.

One of the most crucial input aspects of ALB problems and also part of this research field from the introduction of the SALB problem by Salveson (1955) are the precedence relations between the tasks. Figure 16 in Section 3.2.1 shows a graphical representation of these precedence relations that determine the assembly sequence the ALB model has to take into account. Another important input aspect are the times to perform the tasks to be balanced. In the case of SPZ, the task times deviate from the SALB approach because of the extensive model mix where the SALB problem considers one homogeneous product. In the literature, such as model mix is often addressed by calculating a weighted average of the task duration based on the occurrence of a model type (Bukchin, Dar-El, & Rubinovitz, 2002). However, at SPZ, it is challenging to capture the wide model variety in a number of model types because this would result in hundreds of model types. A better approach is to look at the number of times a specific task is performed. This approach aligns with the main input for the assembly line balance, the global assembly sequence of tasks. Using this approach, we look at task time variety of a specific task, and it's occurrence. For example, placing the fuel tanks takes different times depending on the type of fuel tank assembled, where each of these tank types represents a specific demand proportion.

The task times of, for example, placing a specific fuel tank type on the truck are determined globally by performing the task several times. This average task time is distributed to all manufacturing plants of Scania, so all assembly locations have the same data source to fill a work package known as a standard, see Section 2.1.3. However, in practice, task times usually vary from cycle to cycle and are not deterministic. To address the stochastic nature of the task times, we require a distribution function. Task times can be assumed to be independent normal variates and can thus be described by a normal distribution (Becker & Scholl, 2006). So an average task time together with its standard deviation determines the distribution of the stochastic task time (Cakir, Altiparmak, & Dengiz, 2011), see Appendix 1.

Another deviation from the SALB problem is the use of multiple workers per workstation. "*Multi-manned assembly lines are often designed to produce large-sized products, such as automobiles and trucks*" (Roshani & Giglio, 2017). At SPZ, a workstation is rarely manned by only one worker due to the number of tasks that need to be performed on the truck, and certain tasks require multiple workers. Therefore, the model must incorporate multiple workers. With this approach, teams can be formed and assigned to workstations, and we can assess the worker density for specific areas at the assembly line.

Multiple workers per workstation introduce another problem, namely the possible interference of tasks performed in the same work zone (Pearce et al., 2019). As mentioned, the assembly sequence of tasks is determined globally. These tasks are assigned to 6 positions on the truck: front, left-hand front, right-hand front, left-hand rear, right-hand rear and rear. This structure is in line with the practical situation at SPZ and suitable to be used as work zone demarcation within a workstation. Using this structure, we can exclude the interference of tasks and workers physically being performed at the same place and time.

Another relevant aspect of truck assembly at SPZ is that of tasks requiring multiple workers. Especially the placement of large components such as the cabin of the truck or the 5th wheel used to attach a trailer onto the truck, are performed by multiple workers. This element can be mathematically modelled as an additional constraint of the task to worker assignment.

This research focusses on finding a new line layout within the currently available assembly line space to mitigate the output loss due to long trucks. Certain large installations perform assembly tasks along the assembly line that would require considerable efforts and resources to be repositioned. The final solution's feasibility is determined by the trade-off between output gain and investments to be made. Therefore it is essential that the ALB model incorporates these installations as technological constraints. These constraints assign specific tasks to a fixed workstation along the assembly line, which means that not all workstations are equally equipped with resources (Becker & Scholl, 2006).

Looking at the ALB problem type applicable to SPZ, minimizing the cycle time as a primary objective is the most relevant, which is described as a type-II ALB problem in the literature. Minimizing the workstation's cycle time is directly related to increasing the line output, which is one of SPZ's key objectives. Furthermore, the number of workstations is determined based on an analysis of the truck lengths distribution and available assembly line space, see Section 4.4, and is therefore considered fixed. In contrast, the type-I problem is generally chosen when an assembly line is to be designed from scratch and minimizes the number of workstations given a fixed cycle time (Fathi, Álvarez, & Rodríguez, 2016). So a type-I ALB problem would determine the workstation length in the case of SPZ given the fixed available line space, and therefore the solution is not likely to address the core problem of the mismatch between workstations and long trucks. Also, it is essential to operate at a high line efficiency to maintain SPZ's competitiveness level. This can be achieved by maximizing the line output while minimizing the number of workers on the line. Therefore, as a secondary objective, we minimize the number of workers used per workstation, as proposed by Roshani & Giglio (2017).

Other objectives are possible considering stochastic task time assignments with a lateness measure (McMullen & Frazier, 1998). However, as an objective, this would not necessarily maximize the assembly line's output and line efficiency but rather spread the workload along the assembly line evenly. The current production system at SPZ is organized by assigning more workers to bottleneck stations and using floater workers and team leaders to assist on high workload trucks, where floater workers are not assigned to a fixed workstation. This way, SPZ addresses the stochastic nature of tasks in practice, given an assembly line balance based on average task times. We consider weighted average task times, which is a prominent assumption made in ALB literature. Also, the current production system at SPZ is balanced based on weighted average task times. We address the stochastic nature of task times by assessing the robustness of an assignment of tasks to stations, using simulation practices on which we elaborate further in Section 5.2 (Fathi, Nourmohammadi, Ng, & Syberfeldt, 2019).

This section presents the important elements that the ALB model should consist of regarding balancing the assembly line at SPZ. Here we summarize the conceptual model on which the actual model is built. We present the actual ALB model in Section 5.2.1, together with the detailed modelling choices and solution approaches. Considering all the relaxations with respect to the SALB problem type, as defined in Section 3.2.1, we are optimizing a generalized assembly line balancing (GALB) problem in this research. Our conceptual model takes the SALB problem as a basis and considers the following elements:

- A mixed-model product type is considered while respecting a given production process.
- The assembly line is a paced line with a common cycle time.
- The workstations are configured serially with no parallel elements.
- The processing sequence on the assembly line is subject to precedence relations.
- Tasks cannot be partitioned among multiple workstations.
- Weighted average task times are considered
- Multiple workers can work within a single workstation.
- Tasks are assigned to work zones within a workstation to prevent tasks and workers' physical interference.
- Within a workstation, workers are allowed to switch work zones.
- Some tasks require multiple workers.
- Technological constraints assign tasks to specific locations along the assembly line representing large installations that are not meant to be replaced in a new layout.
- Not all workstations are equally equipped in terms of machines and workers.
- The objective of the model is to maximize the line output and line efficiency by minimizing the cycle time and number of active workers.

5.1.3 CONCLUSION

Section 5.1.2 presents the conceptual ALB model applicable to SPZ based on the literature framework from Chapter 3. In this section, we elaborate on the literature gap this research is filling.

Section 3.3.2 presents different solution approaches to the mixed-model assembly line balancing problem, all considering specific assembly line aspects focussing on GALB relaxations. From the GALB literature overview studies of Becker et al. (2006) and Fathi et al. (2019) we see that different researches consider different assembly line aspects. For example, Stochastic task times & zoning constraints, u-shaped assembly lines & stochastic task times and, work zone constraints & resource availability.

The GALB problem at hand is a unique combination of ALB problem elements relevant to the situation at SPZ. Taking the SALB problem as a basis, the ALB model to build combines the following GALB aspects; multiple worker assignments, work zones within workstations, multiple workers required for a single task, technological constraints and, a secondary objective minimizing the number of workers at the line. In addition, we assess the tasks' stochastic nature using simulation practices based on the system state of the found solution.

5.2 ASSEMBLY LINE BALANCING MODEL CONSIDERING THE PROBLEM AT SPZ

This section presents and explains the ALB model for the problem at hand, considering the conceptual model from Section 5.1.2. In Section 5.2.1, we present the modelling choices made and the general working of the method. Next, Section 5.2.2 explains the inputs needed for the model and how we gather this data. Then, Section 5.2.3 describes the working of the algorithm in more details. Finally, Section 5.2.4 describes the verification and validation of the model.

5.2.1 MODELLING CHOICES AND WORKING OF THE METHOD

This section presents the problems faced in modelling the relevant problem characteristics. Also, we explain the working of the proposed model with a toy problem elaborating on the modelling choices made. Section 5.1.2 presents the building blocks for the ALB model describing the problem at SPZ. When translating these building blocks into the actual ALB model, we face different problems. Here we describe the difficulties we face in the problem at hand and the general solution approach.

We start with the line layout, determining the number of workstations we consider in the problem. Given this number of workstations, we aim to assign all available tasks among these workstations. Figure 25 presents the general flowchart of assigning tasks to workstations along the assembly line. First, we need to select an unplanned task at point 2 of the flowchart. All predecessors of this unplanned task must be planned to comply with precedence relations. Also, we need a priority rule to select among the available tasks, described in more detail later. Next, we need to assign this task to a workstation, point 3 in the flowchart. This task to station assignment has to comply with the task's precedence relations as well. So we can not assign the task to an earlier station than the station to which its predecessors are assigned. Some tasks require to be performed by specific installations that have a fixed position along the assembly line. This is called a technological constraint on the task in ALB literature. If the task has a technological constraint, we must assign the task to a specific workstation. The task requires to be executed in a certain work zone within the station, point 4 of the flowchart. Only 1 task can be performed in a work zone at a certain moment. If the work zone is occupied, the task has to wait before it can be executed. Next, the task has to be assigned to a worker that is not performing another task, point 5 of the flowchart. If all workers are occupied, the task is assigned to the first available worker. Some tasks require multiple workers to be assigned to the task. This procedure is repeated until all tasks are planned, point 6 of the flowchart. When all tasks are planned, we have found a task schedule. This schedule describes the assignment of tasks along the assembly line to workstations, work zones and workers. We can calculate performance criteria such as cycle time and the number of active workers used from this task schedule. Next, we need a method to optimize this found schedule. This method should propose a different task to station assignment on which we can calculate performance data based on the structure of Figure 25.

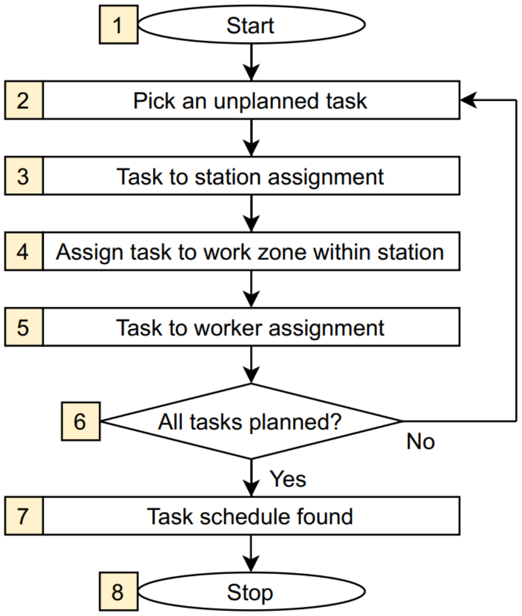


Figure 25: Flowchart of the general problem

As concluded in Section 5.1.2, we solve a generalized assembly line balancing (GALB) problem in this research. Approximate methods give a better trade-off between computational time and solution quality than exact methods on GALB problems, as concluded in Section 3.4. Given the number of tasks to balance, stations to consider, and NP-hard nature of the problem, it is not likely that we can find an exact solution in a reasonable time. Metaheuristics are suitable for finding good solutions to GALB problems and can incorporate specific ALB aspects relevant to the problem at SPZ, such as multiple worker assignments to a task assigned to a specific work zone. So metaheuristics are a suitable method to optimize the task to station assignment problem as presented in Figure 25. Section 3.3.3 presents 2 candidate methods, simulated annealing (SA) and Tabu search, proven to yield near-optimal solutions for GALB problems and are flexible methods suitable to be adjusted to the problem at hand. Tabu search requires an evaluation of the complete neighbourhood. The problem at hand considers the assignment of 90 tasks to at most 11 workstations resulting in a relatively large neighbourhood and thus large computation times. In contrast, SA considers the evaluation of 1 neighbour solution. Therefore we choose SA as an optimization method considering the large neighbourhood of our problem.

As a basis for the model, Roshani & Giglio (2017) present a suitable and proven method for the multi-manned assembly line balancing problem using SA as an optimization approach. This method primarily minimizes the cycle time and, as a secondary objective, minimizes the number of workers. These objectives are in line with the important KPI's of increasing the assembly line's output and efficiency at SPZ. This method is also flexible enough to be adjusted to the specific elements of the problem at hand. The method can incorporate mixed-model product type, multiple workers per task, work zones within workstations, and technological constraints.

In this section, we present a method to solve the conceptual model from Section 5.1.2. We elaborate on the general working of the method and the choices made by following a toy example. Due to the specific problem elements and SA optimization approach, we choose to build an algorithm to solve the problem, explained in more detail in Section 5.2.3.

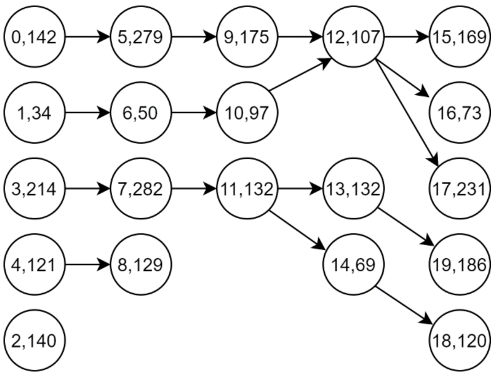


Figure 26: Precedence graph toy problem

Figure 26 presents the precedence relation graph of a 20 task toy problem representing the assembly sequence of a certain product where each node is structured as follows: task number, task time. These precedence relations and task times are essential input data to the model. As important parameter settings, the model requires the number of workstations to which tasks can be assigned to and the number of maximum available workers per station.

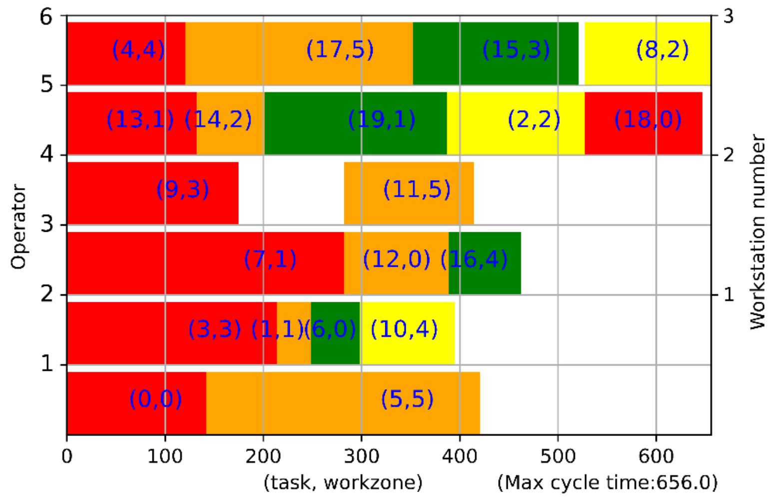


Figure 27: Assembly line balance initial solution

Figure 27 presents an initial solution to the 20 tasks toy problem, where we consider 3 workstations and 2 workers per station. The left vertical axis of the figure indicates the number of workers starting at 1 until 6. The right vertical axis indicates the number of available workstations starting at 1, e.g., worker 5 and 6 are assigned to workstation 3. The horizontal axis indicates the completion time per worker, where the cycle time is defined by the latest completion time among the workers. The annotations of the bar graph indicate the task number and work zone assignment. For example, the task in the right upper corner, task 8, is assigned to work zone 2.

Next to the precedence relations and task times, the model considers the following elements to assign tasks to workers: work zone assignment, worker availability, multiple workers required for a single task and technological constraints. The method consecutively assigns tasks to workers considering these constraints. The tasks to assign are determined according to the ranked positional weight measure. This measure sums up the task time of the task to consider together with the task times of all its followers. The ranked positional weight is a proven method widely used in ALB problems and considers the task's priority (Pearce et al., 2019). Additional tasks can be added to a specific worker if the worker completion time does not exceed the theoretical lower bound of the cycle time. The theoretical lower bound of the cycle time is defined by $L_{CT} = max\left\{t_{max}, \left\lceil\frac{t_{sum}}{n_w * M_{max}}\right\rceil\right\}$ where t_{max} is the maximum task time, t_{sum} is the total task time, n_w is the number of workstations, and M_{max} is the maximum number of workers per station (Roshani & Giglio, 2017). The final workstation considered in the problem can exceed this constraint to make sure that all tasks are planned.

Considering the initial solution example of Figure 27, we see a gap between task 9 and 11 assigned to worker 3, this is caused by the precedence relation between task 7 and 11, see Figure 26. Also, there is a small gap visible between task 15 and 8 assigned to worker 5. This gap is caused by task 2 assigned to the same work zone as task 8. Only 1 task can be assigned to a specific work zone at a time, and thus task 8 has to wait until the work zone is no longer occupied. Furthermore, we see that the final station has the longest completion time because at this station, workers may exceed the L_{CT}, to ensure that all tasks are planned.

Given this initial solution, we search for better solutions using SA utilizing neighbourhood operators. The neighbourhood operators used are swap and mutation. These are proven operators for ALB problems yielding good solutions (Scholl & Becker, 2006) (Roshani & Giglio, 2017). The swap operator randomly selects 2 tasks of different work stations considering the technological constraints and precedence relations and, if allowed, swaps the station assignment of these tasks. The mutation operator works similarly. However, it selects 1 task at random and assigns it to a different station at random if the technological constraints and precedence relations allow this station assignment. This combination of operators works well because the swap operator can make larger steps within the solution space compared to the mutation operator, where the mutation operator facilitates the assignment of a different number of tasks assigned to a certain workstation. So when a neighbour solution is created, it is checked for feasibility based on the technological constraints and precedence relations. We did investigate infeasible solutions to be accepted by implementing a penalty-term in the objective function, enabling us to explore the solution space through infeasible solutions. However, we did not manage to arrive at a feasible final solution afterwards and, due to time limitations, excluded the option of infeasible solutions.

The initial solution of Figure 27 is stored as the best solution found so far and the current solution. Utilizing the neighbourhood operators as described above, we find a neighbourhood solution consisting of a different task to station assignment. From this neighbourhood solution, we calculate the objective function. Defined as $f(Y_0) = CT + \frac{M_{active}}{n_w * M_{max} + 1}$, where CT is the cycle time, this is the largest completion time among the workstations (Roshani & Giglio, 2017). The second part of the equation is a fraction always smaller than 1, where M_{active} is the number of active workers, n_w is the number of workstations, and M_{max} is the maximum number of workers per station. This second part of the equation accounts for a small part of the objective function and therefore serves as a secondary objective. If the neighbourhood solution's objective function yields a result as good as or better than the current solution, it is accepted as the current and best solution. Alternatively, the solution is accepted as the current solution with a certain chance. See section 5.2.3 for more details on the SA mechanics.

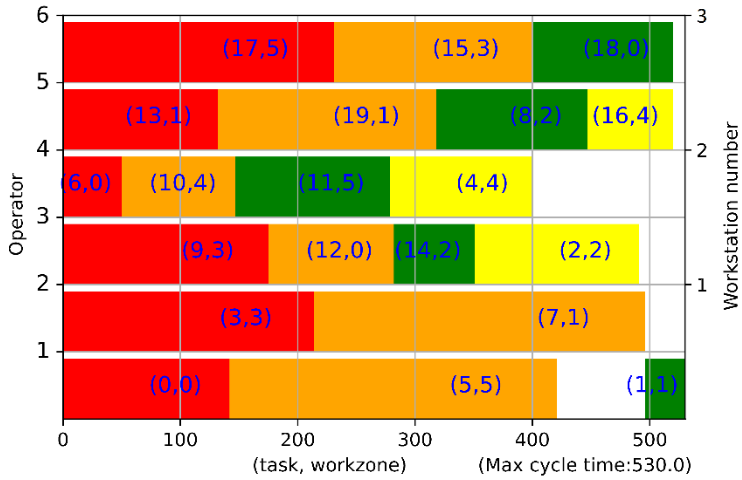


Figure 28: Assembly line balance final solution

Figure 28 presents the assembly line balance result after finalizing the SA heuristic, and we see that the cycle time is optimized from 656 to 530 seconds. In a problem instance with more available workers, the algorithm aims to activate as little workers as possible. Also, this toy problem does not consider multiple workers required for a task. In the actual problem, this is the case, and then a task is scheduled multiple times within the same workstation with the same starting time assigned to multiple workers.

Our model's result is a task to station assignment given weighted average task time based on the task's occurrence. As proposed in the paper of Juan et al. (2015), we add a stochastic system state assessment to a metaheuristic with a deterministic input. We perform a simulation run on this system state to assess the tasks' stochastic behaviour and the robustness of the found system state. Based on the normal distribution of the task time, as explained in Section 5.1.2, we draw a random task time for each task. We recalculate each workstations cycle time with these new task times while considering the task assignment constraints and priority rules as described above. This practice is repeated hundreds of times, and from each simulation run, the performance data are stored. This allows us to analyse, e.g., confidence intervals of the mean station completion time given a task to station assignment, providing insights in idle and overload times of workstations.

5.2.2 INPUT TO THE MODEL AND DATA GATHERING

This section discusses the specific input data considering the ALB model, as generally described in Section 5.2.1. The main inputs of the data are documentation on task times and expert knowledge on task constraints.

Recall from Section 5.1.1 that we focus on line part 2.2, consisting of workstation 36 until 45, for the assembly line balance. So we need to gather the data of the tasks assigned to these stations. The detail level of these tasks is in accordance with the detail level of the global assembly sequence within Scania. All the tasks a worker performs are recorded in a work package that has to be completed within takt time. This work package is a detailed description of all the small tasks a worker has to perform, including task times for each of the possible task variants. For example, the work package describes the time it takes to walk to the storage location, collect the materials, walk to the truck, prepare the part, and assemble the part. The task times are based on Scania's motion time study and distributed to all assembly locations. The collected task data is validated by supervisors and team leaders who are responsible for the performance of the specific tasks. The task times we use in our model are based on the task's occurrence using the work package as a source. For the simulation runs, we include the task's normal distribution to access the tasks' stochastic nature.

The precedence relations are another important input to the ALB model. The precedence relations determine the technical assembly sequence of the truck. The data on these precedence relations are collected using expert knowledge of supervisors and team leaders. The input data is validated several times together with the supervisors based on the ALB model's outcomes to increase the quality of the data and exclude mistakes. The task time data and precedence relations can be found in Appendix 2.

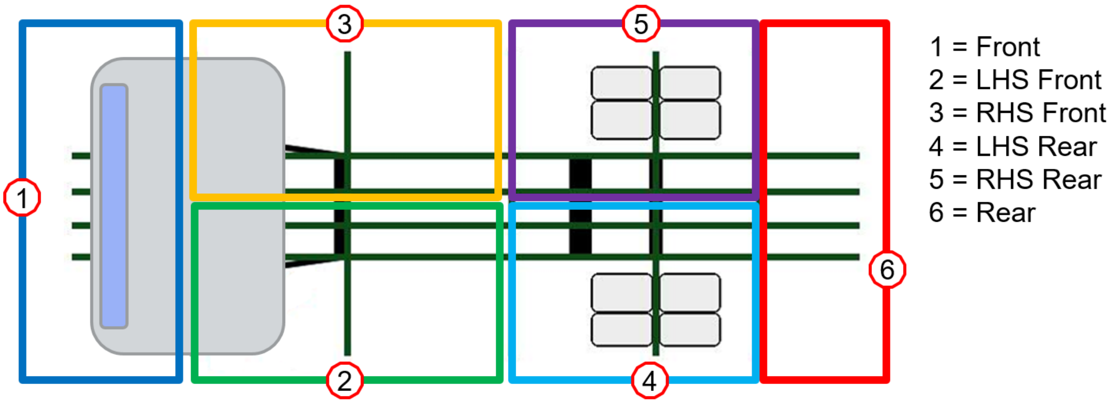


Figure 29: Work zone demarcation within a workstation

We assign tasks to different work zones within a workstation to prevent tasks and workers' physical interference. The global assembly sequence of tasks within Scania, on which we base our detail level, assigns the tasks to 6 different work zones as presented in Figure 29. We assign the tasks from line part 2.2 to work zones within a workstation in accordance with this structure. In addition, we have added a 7th work zone for tasks that mainly consist of worker waiting time. For example, loading software to the truck using the Scania Production Computer Tool (SPCT), this task requires the worker to make the connection with the truck and the SPCT, wait for the software to load during which the worker performs other tasks and finally disconnects the SPCT from the truck. If we would assign this task to, e.g., the front work zone, the SPCT task blocks all other tasks to be performed in that work zone, whereas in practices there is no interference of tasks and workers with the SPCT task. The tasks assigned to the 7th work zone can be found in Appendix 2. As validated by the supervisors, the maximum number of workers in each workstation is 6 at line part 2.2 in the current line setup. For the workstation proposals of 13.6- and 14-meter, we can allow 7 workers due to additional space within the station.

At SPZ certain tasks require multiple workers due to the placement of large components that need additional workers to guide and place the parts or ensure safe movement of parts. Also, we have combined some of the tasks from the global prescribed assembly sequence because these tasks are most efficiently performed at the same time. These tasks require common resources or due to logistical supply require to be placed at the same station. The tasks requiring multiple workers and the tasks we combined can be found in Appendix 2.

Finally, we have the technological constraints of the model. These represent installations along the assembly line that require considerable efforts and costs to be displaced and therefore should be kept in place. By assigning certain tasks to specific workstations, we achieve this result. The installations that cannot be replaced are the installations that place the cabin and supplies the assembly line with tires. If we would replace these installations, the proposed solution's business case is not likely to be feasible. In addition, the installations filling the coolant, clutch oil and air conditioning are preferably kept in place. However, the impact of moving these installations is of a lesser degree than the installations placing the cabin and supplying the tires. Therefore in some experiments, we relax the constraints on the filling installations.

5.2.3 ALGORITHM EXPLANATION

In this section, we present the ALB algorithm used to solve the assembly line balancing problem of SPZ. We explain the complete algorithm using flow charts, and we elaborate in more detail on the working of the method based on the introduction and choices provided in Section 5.2.1.

In the problem that we consider, we need to assign all available tasks to workstations and workers along the assembly line while considering precedence relations, technological constraints and work zone assignments. Figure 25 from Section 5.2.1 presents the general approach of finding an initial solution to the problem at hand. A solution to the problem is a schedule of tasks assigned to workstations, work zones and workers. From this schedule, we can calculate performance data. The approach iteratively assigns tasks to workers while considering cycle time and workstation constraints. As explained in Section 5.2.1, we use the SA optimization approach to search for better solutions, based on the initial solution, by utilizing neighbourhood operators. In this section, we explain the ALB algorithm and its mechanics in more details.

Figure 30 presents a detailed flowchart for generating an initial solution. At point 2 of this flowchart, we load the input data and define the algorithm parameters, such as the number of workstations to consider. We calculate the cycle time's theoretical lower bound at point 3 of the flowchart, based on the input data, and initialize a structure to store data. Recall from Section 5.2.1 that the theoretical lower bound is defined by $L_{CT} = max\left\{t_{max}, \left\lceil\frac{t_{sum}}{n_w * M_{max}}\right\rceil\right\}$ where t_{max} is the maximum task time, t_{sum} is the total task time, n_w is the number of workstations, and M_{max} is the maximum number of workers per station.

Next, if the number of workstations has not yet reached the maximum amount, we move to point 5 of the flowchart from Figure 30 and start another iteration. Next, we determine the set of tasks that are available to be planned. The set of available tasks $I_a \in N$, where N is the set of all tasks, contains all the tasks having no preceding task, or all their preceding tasks are already planned. Next, at point 6, we calculate the earliest start time of the available tasks based on precedence relations and the earliest available time of workers. If the task requires multiple workers the earliest starting time of the task is determined based on the earliest available time of the necessary amount of workers. This procedure also considers the work zone within the workstation and sets the earliest starting time of a task not sooner than the specific work zone to which the task is assigned to is free, i.e., not occupied by another task. This prevents tasks and workers' physical interference.

Moving to point 7 of Figure 30, if we have not reached the final station, we exclude the tasks from the set I_a that violate $S_i + t_i \leq \gamma * L_{CT}$ where S_i is the starting time of task i, t_i is the task time of task i, and γ is a parameter used to control L_{CT} (Roshani & Giglio, 2017). Tasks with technological constraints are assigned to their required station regardless of this constraint while considering the tasks precedence relations. If we have reached the final workstation, we can also violate the constraint to make sure all tasks are planned. Next, at point 8, we check if there are tasks left in I_a. If so, go to point 10 and select the task with the highest positional weight $pw_i = t_i + \sum_{h \in F_i} t_h$ where F_i is the set of all followers of task i (Scholl & Voss, 1997). Assign this task to the first available worker or workers if the task requires multiple workers. If there are no tasks left in I_a at point 8, then open a new workstation, point 9, and move to point 4 and reperform the task assignment process until we have reached the maximum number of workstations. Finally, we calculate the objective function at point 11, recall from Section 5.2.1, $f(Y_0) = CT + \frac{M_{active}}{n_w * M_{max} + 1}$, where CT is the cycle time, defined by the largest completion time among the workstations and M_{active} is the number of active workers.

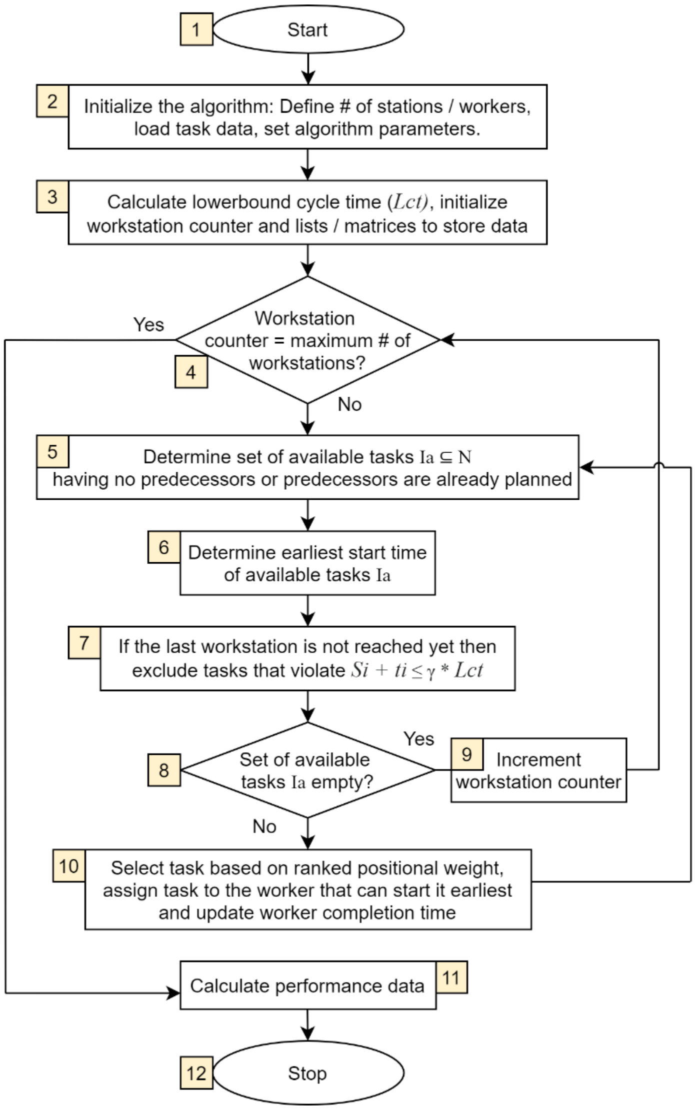


Figure 30: Initial ALB solution

Now that we have found an initial solution to the problem, we encode the task to station assignment in a solution string, based on the method of Kim, Song, & Kim (2009). This encoding structure is used to facilitate the neighbourhood operators of the simulated annealing (SA) heuristic. Each element in the solution string represents a task of the problem instance in ascending numerical order. This solution string stores the task to workstation assignment. Consider, for example, the toy problem from Section 5.2.1 (Figure 27). Then the initial solution string looks as follows: $\Pi_i = [1,1,3,1,3,1,1,2,3,2,1,2,2,3,3,3,2,3,3,3]$ where task 0 is assigned to workstation 1 and task 4 is assigned to workstation 3 (task number starts at 0). Now we can store the initial solution string as current and best solution found so far and store its performance data such as objective function, cycle time, and the number of active workers.

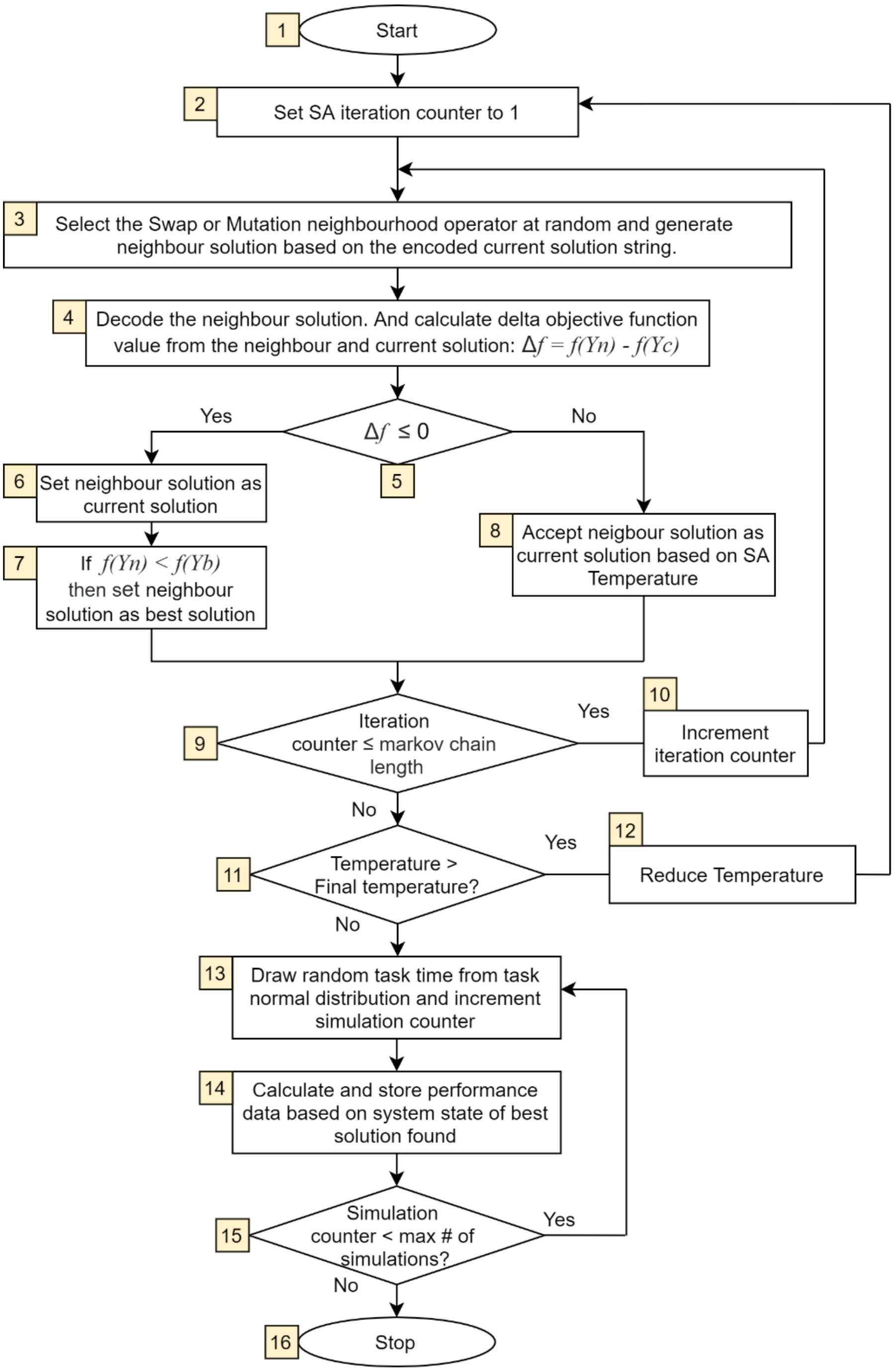


Figure 31: Simulated annealing and simulation procedure

Now that we have found an initial solution and assigned it as the current and best solution, we aim to optimize this solution by utilizing neighbourhood operators. Figure 31 presents the SA heuristic and the simulation procedure. We initialize the SA algorithm, and at point 3 of the flowchart, we randomly select the swap or mutation neighbourhood operator. We use these operators in search of a neighbour solution, as introduced in Section 5.2.1. The swap operator creates a neighbourhood solution by swapping 2 tasks from different stations. The mutation operator creates a neighbourhood solution by moving 1 task to a different station. In both cases, the precedence relations and technological constraints of the tasks must be respected. For more details on these 2 neighbourhood operators, see the flowcharts and description in Appendix 3.

Now that we have found a neighbourhood solution utilizing the neighbourhood operators, we have to decode the encoded neighbourhood solution string to calculate the performance data at point 4 of Figure 31. The decoding of the solution string is similar to generating an initial solution, as presented in Figure 30. However, now following from the neighbour solution string, we have a predetermined set of tasks assigned to each station. Like generating the initial solution, we consider the tasks precedence relations, work zone constraints and multiple worker constraints to calculate the earliest starting time of a task. In this case, however, we incrementally add an additional worker to a workstation and calculate the workstations completion time. We accept the task to worker assignment for each workstation with the lowest amount of workers able to finish their tasks below L_{CT}. If the L_{CT} constraint cannot be met, we accept the task to worker assignment with the lowest completion time for the specific workstation.

Next, from the performance data of the neighbour solution, we calculate $\Delta f = f(Y_n) - f(Y_c)$, point 4 of Figure 31 where $f(Y_n)$ is the objective function value from the neighbour solution and $f(Y_c)$ is the objective function value of the current solution. If $\Delta f \leq 0$ then we store the neighbourhood solution as the current solution, point 6. If the neighbour solution's objective is also smaller than the best solution's objective $f(Y_b)$, then store the neighbour solution as the best solution found so far, point 7. If $\Delta f > 0$ then we accept the neighbourhood solution as current solution with a certain chance, point 8 of Figure 31. The solution is accepted based on the value of $exp^{-\Delta f / T_{emperature}}$. The temperature and Markov chain length are defined by the SA cooling schedule, as explained below. After a SA iteration at point 9 of Figure 31, the algorithm checks if the Markov chain length (i.e. the maximum number of iterations) has been reached. If not, then perform another iteration using the current temperature parameter until the Markov chain length has been reached. If the final temperature has not been reached, at point 11, cool down the temperature according to the cooling schedule and move to point 2. We have reached the end of the SA meta-heuristic when we reach the final temperature.

The cooling schedule defines the trade-off between diversification and intensification of the SA heuristic. At the SA heuristic start, we explore large parts of the solution space by accepting many neighbour solutions. As the SA heuristic progresses in time, we want to intensify the search for promising solutions. The temperature parameter controls the acceptance of solutions. SA works appropriately when the acceptance ratio starts at about 1 and decreases monotonically with the temperature to around 0. The acceptance ratio is defined by the number of bad neighbour solutions accepted divided by the number of bad neighbour solutions proposed, where a bad neighbour solution is worse than the current solution. The Markov chain length determines the number of solutions to consider before cooling down the temperature. Considering our method, an appropriate cooling schedule, running in acceptable computation time, has a starting temperature of 500, cooling parameter α of 0.85, Markov chain length of 500 and a final temperature of 0.0001. Figure 32 presents the acceptance ratio and temperature decrease of these parameters considering our problem using the ALB algorithm.

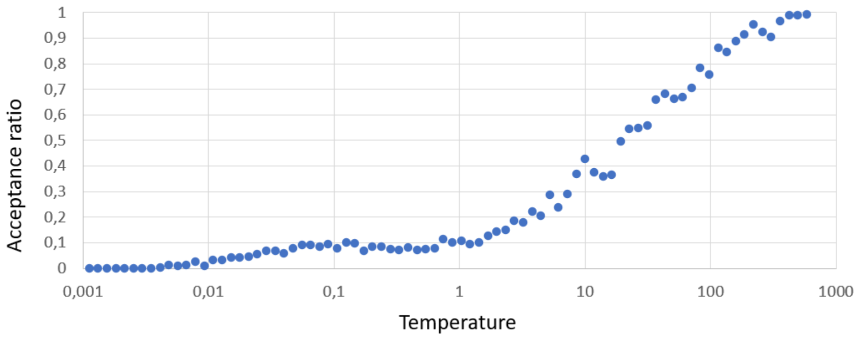


Figure 32: Acceptance ratio

Now that we found the final solution after finishing the SA heuristic, we have found a promising task to station assignment, which we call a system state. This system state is based on weighted average task times and stored in the encoded best solution string. We assess this system state's robustness by performing a Monte-Carlo simulation with random task times drawn from the tasks' normal distribution. Performing a Monte-Carlo simulation on the found solution enables us to investigate the effect of stochasticity on the system state and report on the performance data (Juan et al., 2015). We start this Monte-Carlo simulation at point 13 of Figure 31, there the simulation counter is set to 0, and random task times are drawn. Next, at point 14, we decode the best solution string and assign the tasks to workers. We use the same decoding approach as described above but now considering stochastic task times. After we have decoded the solution and a task to worker assignment is determined for each workstation, we can report on the workstation's performance data. We repeat this procedure until we reach the maximum number of simulation runs. The collected performance data of each workstation enable us to assess which stations are likely to have regular overload situations or idle times given a system state.

5.2.4 MODEL VERIFICATION AND VALIDATION

This section presents the verification and validation of the ALB model. A mathematical model that is verified and validated ensures that the model mimics real-world situations.

VERIFICATION

Verification is the process to ensure that the conceptual model is correctly translated to a mathematical model. In this case, it is the translation from the conceptual ALB model, as presented in Section 5.1.2, to a working algorithm coded in Python. To verify the correct translation from the conceptual model to a practical algorithm, we use debugging tools to check the algorithm's working. By implementing breakpoints in the code, using Spyder IDE, we can track the values of variables throughout the algorithm step by step. This approach helps to debug the code and to assess and verify the algorithm's correct working.

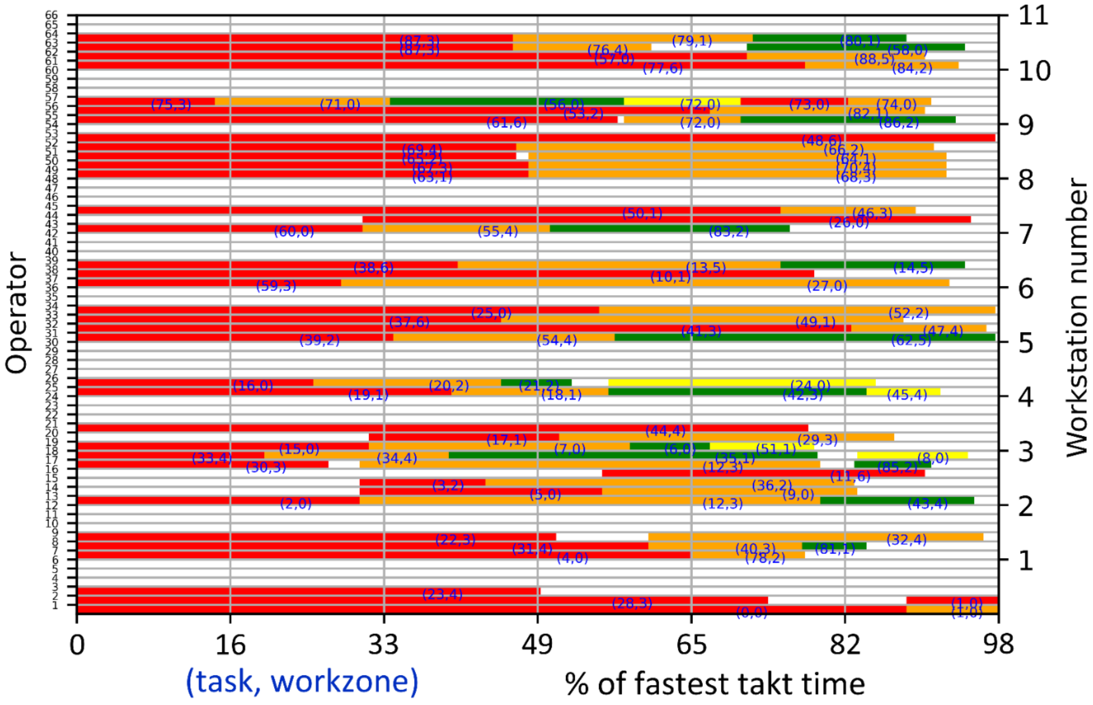
Another verification tool is the graphical output of the ALB algorithm. The program prints the ALB schedule of tasks assigned to workers and work zones within workstations. To verify the model, we check if there are any conflicts visible in the output. It is not allowed to assign multiple tasks to a single worker at the same time or plan tasks within the same work zone at the same time. Also, the task sequence should comply with precedence relations. When there is a conflict in the output visible, we know there is an error in the program. Finally, the number of tasks to plan must be equal to the number of tasks present in the ALB schedule. All tasks must be planned otherwise the truck is not completely assembled, resulting in an infeasible ALB schedule.

The SA optimization method we incorporated in the model is able to approach the theoretical lower bound of the cycle time by 1.2% on a well-known benchmark data set (Otto, Otto, & Scholl, 2013). The optimization method is able to reduce the cycle time from the initial to the final solution significantly, as presented in Appendix 4. When incorporating the specific constraints and detail level of the problem at hand, we reach the cycle time's theoretical lower bound. Recall from Section 5.2.3 that this lower bound is defined by $L_{CT} = max\left\{t_{max}, \left\lceil\frac{t_{sum}}{n_w * M_{max}}\right\rceil\right\}$. The lower bound of the cycle time in the case of our data set is defined by a specific large task.

VALIDATION

To make sure the ALB model represents reality, we need to validate the model. We start the validation by performing an experiment representing reality with the verified ALB model. Next, we validate the results using expert knowledge of SPZ representatives.

To validate the ALB algorithm, we compare its results with the actual line performance. Currently, at line part 2.2 there are 11 workstations of 12 meters. Therefore to validate the ALB model, we use the same setup. We compare the ALB algorithm results, such as the cycle time and the total number of workers assigned to the actual line performance. The current best line performance operates with 34 workers assigned to the workstations. In addition, 6 team leaders are managing these teams and assist in high workload tasks.



Workstation number current	45	44	43	42A	42	41	40	39	38	37	36
Workstation number ALB model	11	10	9	8	7	6	5	4	3	2	1

Figure 33: Validation experiment

Figure 33 shows the results and setup of the validation experiment of our ALB model. The task times are indicated on the graph's horizontal axis, the left vertical axis indicates the specific worker, and the right vertical axis shows the workstation number. Due to confidentiality, we normalize the cycle time as a percentage to the current fastest takt time. Below the graph, we indicate the workstation reference to the current layout where, e.g., workstation 8 of the ALB model is workstation 42A in practice currently. The acceptance ratio of this experiment is shown in Figure 32 in the previous section. The ALB model achieves a cycle time of 98% of the current fastest takt time with 39 workers. So the achieved cycle time is 2% better than the current fastest takt time. Due to waiting times of workers during tasks, e.g., filling of fluids or uploading software as explained in Section 5.2.2, we can deduct 2 workers from the final solution. The ALB model assigns almost 9% more workers compared to currently assigned in practice on the highest output level. This difference is explained by the relatively high level of detail on which we balance the tasks and the more restrictive model compared to practice. We consider strict station and work zone bounds, whereas these bounds are not as hard in practice. Recall from Section 5.1.1 that these assumptions are in line with the research goal, namely, to assess the feasibility of implementing longer workstations. We also assess the stochastic nature of tasks, as described in Section 5.2.3. The simulation results indicate that the highest work overload is situated at the station where the tire assembly takes place. This is in accordance with practice because the tire assembly is a known bottleneck. The team leaders assist in these overload situations.

The model is assessed by SPZ representatives, the workshop manager and supervisors responsible for the assembly tasks, and engineering representatives. Despite the assumptions made, they confirmed that reality is represented adequately given the model's goal.

5.3 CONCLUSIONS

This chapter answers the research question: *"What method can be used to balance the tasks of a new layout proposal given the specific problem?"*. In this chapter, we present the method used to balance the proposed assembly line layout, considering the problem at SPZ.

In Section 5.1, we present the goal and scope of the assembly line balancing (ALB) method. The goal of the research is to assess the feasibility of implementing longer workstations. Therefore we choose a relatively large detail level. The assembly line balance scope focuses on the line part with the most severe bottlenecks, which is line part 2.2, consisting of workstation 36 until 45. Furthermore, we present a conceptual ALB model that includes important classifications and concepts from the literature relevant to the problem at hand. Some important additions to the core ALB problem we include are considering multiple workers, mixed model product type, work zones within workstations, multiple workers required for a single task, technological constraints and an objective function aiming to increase line output and efficiency. For the full conceptual model, see Section 5.1.2.

Then in Section 5.2, we present the modelling choices made. To model the relevant aspects of the problem at SPZ, summarized in our conceptual model, we consider a generalized assembly line balancing problem that combines several relaxations of the core ALB problem. Given the NP-hard nature and large neighbourhood structure of this problem, we use the heuristic method simulated annealing to optimize the problem. We start with creating an initial solution, which is an initial task to station assignment, that we improve by utilizing the solution's neighbourhood structure. We use the neighbourhood operators swap and mutation to search for better or promising solutions and accept them based on the simulated annealing cooling schedule. This cooling schedule is determined based on the acceptance ratio of the proposed solutions. The objective function we consider minimizes the cycle time as a primary objective and as a secondary objective minimizes the number of active operators. This is in line with the important KPIs within SPZ of increasing the line output and line efficiency. The solution we find with this approach is an optimized system state, a task to workstation assignment given weighted average task times. To assess the influence of the task times' stochastic nature, we perform a Monte Carlo simulation on this optimized system state based on the normal distribution of the task time.

To include all the aspects of the problem we consider, we build an algorithm using the coding language Python. The details of this approach can be found in Section 5.2.1 in general and more in-depth in Section 5.2.3. Furthermore, we elaborate on the input to the model and how we gathered the input data in Section 5.2.2. Important inputs to our model are the task times, precedence relations of the tasks, the work zones to which the tasks are assigned and how many workers are required for a task. We also elaborate on the installations that represent technological constraints in our model: the eagle installation, filling installations, and tire assembly installation. These installations require considerable efforts and costs to be displaced, and therefore, we can choose to fix them to specific locations in the experiments we perform with the ALB model. Finally, we verify and validate the ALB model in Section 5.2.4 to indicate how well the reality is represented with our ALB model.

CHAPTER 6 SOLUTION TEST AND RESULTS

This chapter presents the results of the experiments performed with the ALB model. First, Section 6.1 describes the experiments we perform and explains why we have chosen the set of experiments. Next, Section 6.2 presents the results from the ALB model of these experiments. Finally, Section 6.3 concludes on this chapter.

6.1 EXPERIMENTS

In this section, we present the experiments performed with the ALB model, to assess the performance of adjusted workstations lengths on the assembly line.

Recall from Section 5.1.1 that we focus on assembly line part 2.2, consisting of station 36 until 45 in the current layout. Section 4.3 presents the proposed workstation lengths and layout proposals. The layout proposals define the number of workstations to consider given a certain workstation length. Recall from Section 4.3 that the current layout with 12-meter workstations corresponds with 11 workstations, 13.6-meter workstations correspond with 10 workstations and 14-meter workstations correspond with 9 workstations at line part 2.2.

These 3 line layouts are the basis for the experiments and are used to test different input data sets. The experiments differ in the technological constraints used and additional tasks added. Adding more technological constraints means less deviation in installation displacement from the current setup, enabling us to assess the layout proposals technical impact. Furthermore, adding additional tasks provides insights into the ability to introduce future truck modifications. Table 6 presents an overview of the performed experiments. The baseline experiments, 1 until 3, consider the cabin placement and tire assembly's technological constraints, i.e. the installations facilitating these tasks are kept at the current location. These technological constraints are in place for all following experiments because displacing these installations has a big impact, as explained in Section 5.2.2. Next, experiment 4 until 6 considers additional tasks. These additional tasks are based on future introductions of components and trucks in the coming years, such as the low entry cabin's city door. Then, experiment 7 until 9 considers additional technological constraints of the air conditioning pressure test and the filling of coolant, clutch oil and air conditioning fluid because the installations performing these tasks require considerable effort and cost to be displaced. Finally, experiment 10 until 12 considers a combination of additional technological constraints and additional tasks, effectively combining the data sets of experiment 4 until 9.

Table 6: Experiments overview

	Number of workstations used		
Input data considered	9	10	11
Baseline experiment	Experiment 1	Experiment 2	Experiment 3
Additional tasks	Experiment 4	Experiment 5	Experiment 6
Additional technological constraints: fluid filling	Experiment 7	Experiment 8	Experiment 9
Combination of additional technological constraints and tasks	Experiment 10	Experiment 11	Experiment 12

The experiments described above consider precedence relations based on the technical assembly sequence of tasks. Recall from Section 5.1.2. that Scania determines the assembly sequence of trucks globally. This globally prescribed assembly sequence assigns tasks to certain areas along the assembly line where an area can consist of multiple workstations. This task to area assignment is the same for different truck assembly plants within Scania and increases the assembly coherence between these assembly plants. For example, it is easier to share and implement certain assembly best practices between plants when a common assembly line setup is in place. Also, when trucks are designed within Scania, the design's manufacturability is assessed and optimized based on this prescribed assembly sequence. When deviating from the prescribed task to area assignment, future introductions of trucks become more difficult because the optimal assembly sequence is not considered.

Therefore it is relevant to include these organisational constraints coming from the globally prescribed task to area assignment. We consider a set of 12 experiments, as presented in Table 6, with and without these organisational constraints.

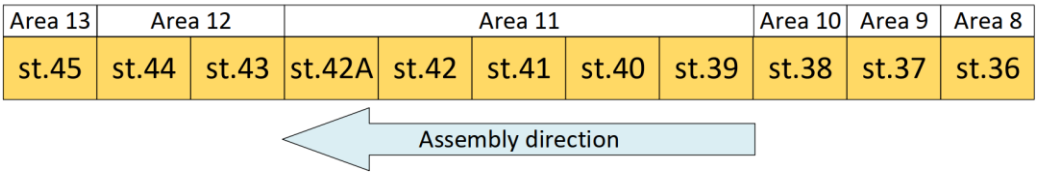


Figure 34: Line part 2.2 area assignment

The globally prescribed task to area assignment divides the assembly line part we consider into 6 areas, from area 8 until area 13, see Figure 34. Most of these areas consist of 1 workstation except area 11 and 12. Area 12 consists of 2 workstations. However, due to the technological constraint on the tire assembly tasks, assigned to station 43, the tasks within area 12 have a fixed task to station assignment. Therefore the only area at line part 2.2 without a fixed task to station assignment is area 11. Our mathematical ALB model assigns tasks to a different station in search of a better solution to the problem. So in the experiments considering the globally prescribed task to area assignment, we consider the optimization of area 11 consisting of 5 workstations.

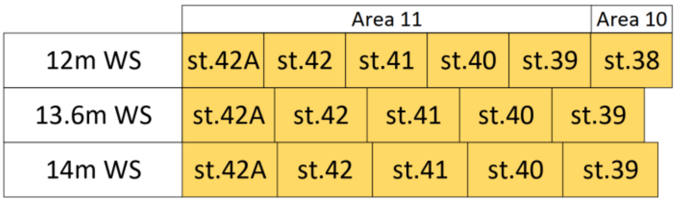


Figure 35: Projection of workstations with different lengths

The setup of the ALB model requires the number of workstations to balance, which is in line with an assembly balance for a given line length. However, if we would consider 4 or 5 workstations of 13.6- or 14-meter in our ALB model to balance area 11, we do not physically cover this complete area or exceed the area bounds by almost 17%. Therefore in the experiments where we consider the constraints of the globally prescribed task to area assignment, we consider complete line part 2.2 and adjust the input data set with a fixed task to station assignment for the tasks not assigned to area 11. We assume that the tasks with a fixed task to station assignment perform their tasks within cycle time and focus the assembly line balance on area 11.

Figure 35 presents the workstation projection of area 11 with 12-, 13.6- and 14-meter workstation lengths. At the start of area 12, we consider the tire assembly's technological constraint, and therefore this set of tasks has a fixed position assignment. We consider 5 workstations to cover area 11 and start our workstation projection from the end of area 11. To represent the 13.6- and 14-meter workstation experiments, we include tasks from area 10 based on the physical overlap station 39 has with area 10, see Figure 35. We fix the tasks we add from area 10 to the first station of area 11 when considering the assembly line balance. This way, we keep these tasks as close to their assigned area as possible.

At line part 2.2, 4 of the 6 areas consist of 1 workstation with a length of 12-meters in the current line setup. When proposing 13.6- or 14-meter workstations, the new area bounds will deviate from the current setup, and thus some tasks will cross an area bound to facilitate an efficient assembly line balance. Therefore it is not possible to exclude cross-area task assignments in the final solution. However, the experiment set, including the globally prescribed task to area assignment, minimizes the cross-area task assignments.

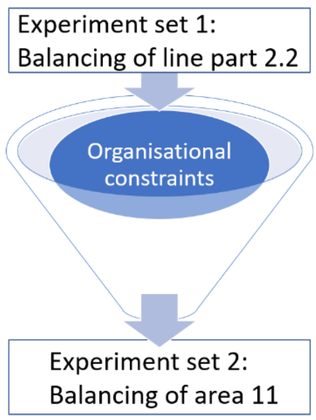


Figure 36: Experiment sets

To conclude, we consider the 12 experiments presented in Table 6 with and without the organisational constraints from the globally prescribed assembly sequence, see Figure 36. The first experiment set considers technical precedence relations and provides insights in a complete rebalance of line part 2.2. The second set of experiments considers the technical precedence relations and organisational constraints from the globally prescribed assembly sequence of tasks and focusses on area 11.

6.2 RESULTS

In this section, we discuss the results of the experiments performed with the ALB model. We use the ALB model and its settings as described in Section 5.2 and perform the experiments presented in Section 6.1 on the model. First, in Section 6.2.1, we give a general introduction on how we report on the results. Next, in Section 6.2.2, we present the results of the experiments, not considering the organisational constraints from the globally prescribed assembly sequence. In Section 6.2.3, we present the results of the experiments that do consider the additional organisational constraints.

6.2.1 INTRODUCTION

In this section, we analyze and discuss the results from the experiments as defined in Section 6.1. The result of the algorithm is a task to operator and workstation assignment. From this schedule, we can calculate performance data. We report on the cycle time, which is directly related to the output, and on the number of operators used to calculate operator efficiency. Also, we indicate the number of installation displacements requiring considerable effort and costs to be repositioned, allowing us to comment on the technical impact. Furthermore, we present the outcomes of the simulation, assessing the stochastic nature of the task duration. We report the average idle or overload time and the workstations with the highest work overload time to indicate the layout's bottleneck station and performance. This idle or overload time is calculated by taking the mean completion time per workstation from the simulation runs with stochastic task times and compare this with the cycle time result based on weighted average task times. Finally, we report on the workstations with 6 or more operators assigned to them to assess the workstations' operator density. This indicates the robustness of the outcome to future truck modifications or additional tasks because at workstations with low operator density, it is easier to assign additional operators in the future to assist on additional tasks. We perform the experiments with the SA cooling scheme, as presented in Section 5.2.3.

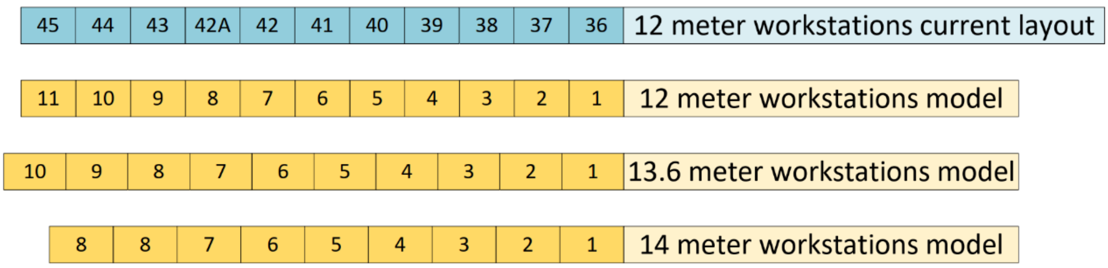


Figure 37: Workstation number reference between current layout and model layout

Figure 37 presents the reference numbers of the workstations considered in the experiments. The 12-meter workstation projection is the baseline experiment and current assembly-line setup. Workstation 1 & 11 of the 12-meter station projection corresponds to station 36 & 45 in the current setup. In Section 6.2.2 and 6.2.3, we present the experiments' results and use the station number reference from Figure 37 to indicate a specific workstation's performance.

6.2.2 EXPERIMENTS WITHOUT ADDITIONAL ORGANISATIONAL CONSTRAINTS

First, we present the results of the set of 12 experiments from Table 6, not considering the global assembly sequence organisational constraints. This section elaborates in detail on the results of these 12 experiments, see Table 7. First, we present a summary of the main results.

When reducing the number of workstations compared to the current line layout, we see some main effects. The cycle time increase when considering 9 workstations instead of 11 is considerable, an increase of 24%. This increase is not in line with the current output level. The cycle time increase when considering 10 workstations is within 1% of this current fastest takt time and therefore feasible. Due to the cycle time increase, when considering 9 workstations, the number of operators decreases. Throughout the experiments in this section, we see the following main effects when considering fewer workstations compared to the current workstation setup:

- The cycle time increases
- The operator efficiency decreases
- The operator density increases
- The average overload time increases

Table 7: Results of the experiments without organisational constraints

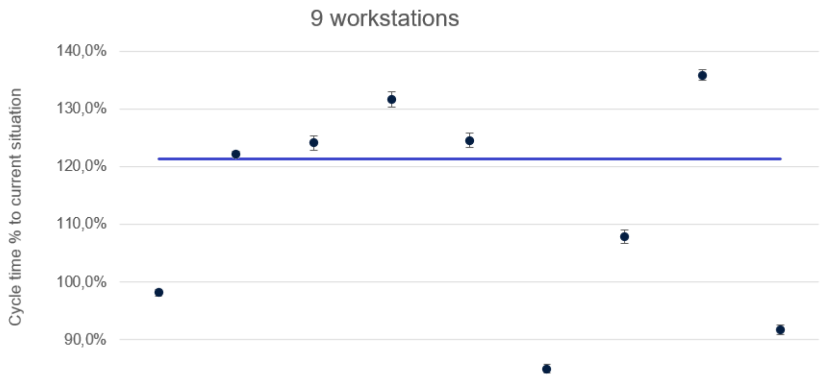
		Number of workstations used		
Input data	**Performance measure**	**9** (14 m.)	**10** (13.6 m.)	**11** (12 m.)
Baseline experiment	**Cycle time % to current situation**	120.3%	98.0%	98.0%
	Number of operators	39	40	39
	Operator efficiency	66.7%	79.7%	81.8%
	High impact task displacement	15	11	12
	Average additional time (sec.)	202	259	96
	Maximum overload cycle time	115% at st. 8	118% at st. 8	117% at st. 9
	Station number with 6 operators	3, 5, 6, 7, 8	-	3
Additional tasks	**Cycle time % to current situation**	120.3%	98.0%	98.0%
	Number of operators	38	40	40
	Operator efficiency	68.8%	80.2%	80.2%
	High impact task displacement	16	13	12
	Average additional time (sec.)	103	561	-64
	Maximum overload cycle time	114% at st. 8	117% at st. 8	108% at st. 8
	Station number with 6 operators	4, 5, 6, 7, 8	3	-
Additional technological constraints: fluid filling	**Cycle time % to current situation**	121.2%	100.7%	98.0%
	Number of operators	37	39	39
	Operator efficiency	69.7%	79.7%	81.8%
	High impact task displacement	13	14	11
	Average additional time (sec.)	-86	398	191
	Maximum overload cycle time	110% at st. 7	113% at st. 8	119% at st. 9
	Station number with 6 operators	4, 7, 8	4, 5	-
Combination of additional technological constraints and tasks	**Cycle time % to current situation**	121.2%	100.7%	98.0%
	Number of operators	40	40	40
	Operator efficiency	64.8%	78.1%	80.2%
	High impact task displacement	14	12	13
	Average additional time (sec.)	-258	506	282
	Maximum overload cycle time	112% at st. 8	120% at st. 8	115% at st. 9
	Station number with 6 operators	3, 4, 5, 8	5, 8	5

Due to confidentiality, we report on the cycle time as a percentage where 100% refers to the current fastest takt time, which is directly related to the highest output rate. The achieved cycle time percentage of the experiments considering 10 and 11 workstations is 100.7% and 98.0%. So the experiment considering 11 workstations performs 2% better than the current fastest takt time and the experiment considering 10 workstations takes 0.7% longer. This cycle time is constrained by the tasks of placing and guiding the cabin. This task set is restricted to the first workstation because of the Eagle installation. The experiments considering 9 workstations are able to achieve a cycle time percentage of 120.3% and 121.2%. This is between 20% and 24% higher than the experiments with 10 and 11 workstation. In general, the experiments considering 9 workstations have less opportunity to efficiently plan the tasks along the line where the precedence relations and constraints result in a higher cycle time. Therefore the operator efficiency reduces when considering fewer workstations. The highest operator efficiency achieved is 81.8%, considering 11 workstations, and the worst 66.7% considering 9 workstations. In the baseline experiment, the number of operators increases when considering 10 workstations instead of 11. We see a reduction in the number of operators when considering 9 workstations due to the higher cycle time. The number of high impact installation displacements, installations requiring considerable effort to be displaced, fluctuates between 11 and 16 overall. Between the baseline experiment and the experiments considering additional technological constraints, there is an increase in operator efficiency in the experiment considering 9 workstations. The number of tasks crossing an area bound see Figure 34, is around 50 throughout the experiments. The total number of tasks displaced at least 1 station is approximately 60 throughout the experiments.

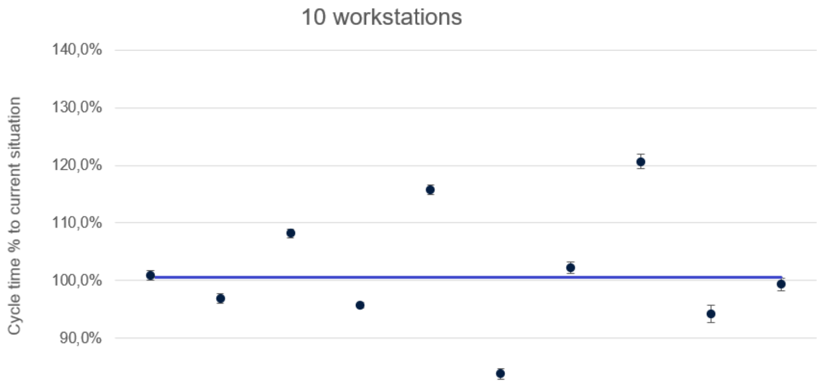
Figure 38 presents the 95% confidence interval of the completion time per station for each of the line layouts. We calculate this confidence interval from the results of the simulation runs with stochastic task times, as explained in Section 5.2.1. The experiments presented in Figure 38 consider additional tasks and constraints. This experiment is the most relevant to SPZ’s current situation, given the installation placement and additional task introductions. Recall from Section 5.2.3 that after the SA meta-heuristic finalisation, we have found a task to station assignment based on weighted average task times. The cycle time percentage of the layout based on weighted average task times is indicated as the blue horizontal line in Figure 38. The confidence intervals indicate the completion time per workstation based on stochastic task times and are generated using Monte Carlo simulation. This completion time or cycle time per workstation is expressed as a percentage of the current fastest takt time. If the confidence interval is above the average mean cycle time percentage, the station will likely have overload situations if we would run the line on this average mean cycle time. Then this station needs team leaders and floater operators' assistance more often. If the confidence interval is below the average mean cycle time percentage, the station will have idle times more often and is not fully utilized. The average results of the overload or idle times are indicated as average additional time in Table 7. The maximum overload situations are mainly situated at the station where the tires are assembled, which is station 8 in the experiments considering 9 and 10 workstations and station 9 in the experiments considering 11 workstations. The average overload situation increases when reducing the number of workstations to 10 compared to the current situation. The average overload time in the experiments considering 9 stations is less than those considering 10 and 11 workstations due to the higher cycle time. There are more stations with 6 operators assigned to them when the number of workstations decreases. Thus the operator density increases when the number of workstations decreases.

Notable from Figure 38 is that the 11 workstations experiment is the most balanced, i.e., the cycle time's confidence intervals are closer to the weighted average cycle time percentage of 98.0%. In contrast, the 9 workstations experiment has the worst balance and also the highest average cycle time. Furthermore, the highest overload times are incurred at station 8 or 9, where the tire assembly occurs. This is a known bottleneck in practice currently due to the broad model mix having 2, 3, 4 or 5 axles. This is represented in the input data by a relatively high standard deviation of the tire assembly's task time. In practice, the station bounds are not as hard as considered in the ALB model, and the task of placing the tires on a 5-axle truck starts earlier and finishes later compared to a 2-axle truck. Therefore there is no regular stop time on the tire assembly station currently.

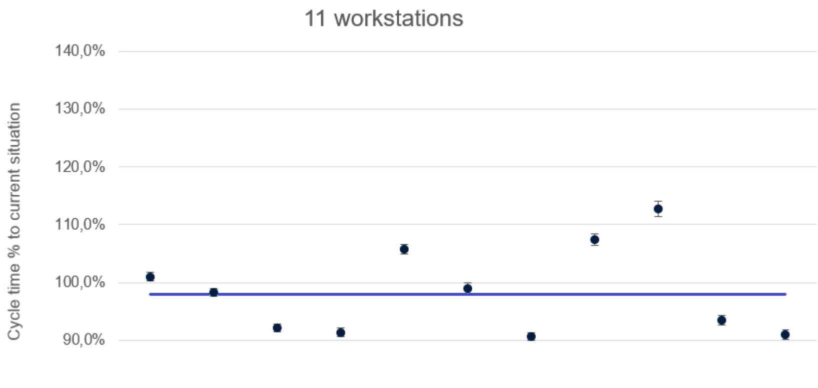
In the experiments considering 9 and 10 workstations, workstation 6 has relatively large idle times. Workstation 7 has the highest idle times in the 11 workstations experiment.



Station #	1	2	3	4	5	6	7	8	9
Mean	98,1%	122,1%	124,1%	131,6%	124,6%	84,9%	107,8%	135,9%	91,7%
Avg. mean (Det.)	121,2%	121,2%	121,2%	121,2%	121,2%	121,2%	121,2%	121,2%	121,2%



Station #	1	2	3	4	5	6	7	8	9	10
Mean	101,0%	97,0%	108,2%	95,7%	115,8%	83,8%	102,3%	120,6%	94,2%	99,3%
Avg. mean (Det.)	100,7%	100,7%	100,7%	100,7%	100,7%	100,7%	100,7%	100,7%	100,7%	100,7%



Station #	1	2	3	4	5	6	7	8	9	10	11
Mean	101,0%	98,2%	92,1%	91,4%	105,7%	98,9%	90,6%	107,5%	112,8%	93,4%	91,0%
Avg. mean (Det.)	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%

Figure 38: 95%-CI of mean cycle time considering experiments without organisational constraints

6.2.3 EXPERIMENTS WITH ADDITIONAL ORGANISATIONAL CONSTRAINTS

This section considers the additional organisational constraints on top of the 12 experiments presented in Table 6. Therefore we focus the assembly line balance on area 11 and show the detailed results below in Table 8.

We start this section with a summary of the main findings and effects. The number of operators increases when we reduce the number of workstations compared to the current line setup. Also, the cycle time percentage increases from 97.7% to 100.3% when reducing the number of workstations. Between the experiments considering 10 and 9 workstations, the cycle time percentage does not further increase. We see the following main effects throughout the experiments in this section when considering fewer workstations than the current assembly line setup:

- The cycle time increases
- The number of operators increases
- The operator efficiency decreases
- The operator density increases
- The average overload time increases

In this set of experiments, the tasks from area 8, 9, 12 and 13 are assigned to fixed stations in accordance with Figure 34. Furthermore, the tasks from area 10 are partly or fully assigned to a fixed station, as described in Section 6.1. In the experiments considering 12-meter workstations, area 11 consists of workstation 4, 5, 6, 7 and 8, corresponding to the station numbers of Figure 37. In the experiments considering 13.6- and 14-meter workstations, area 11 consists of station 3, 4, 5, 6 and 7 where workstation 3 partly covers area 10, as explained in Section 6.1. The tasks with fixed station assignments have a reduced task time to focus the assembly line balance on area 11. Therefore the achieved cycle times in the second set of experiments are lower on average than the first set of experiments. When drawing conclusions on this experiment set, considering the organisational constraints, it is important to include the findings of the experiments of Section 6.2.2.

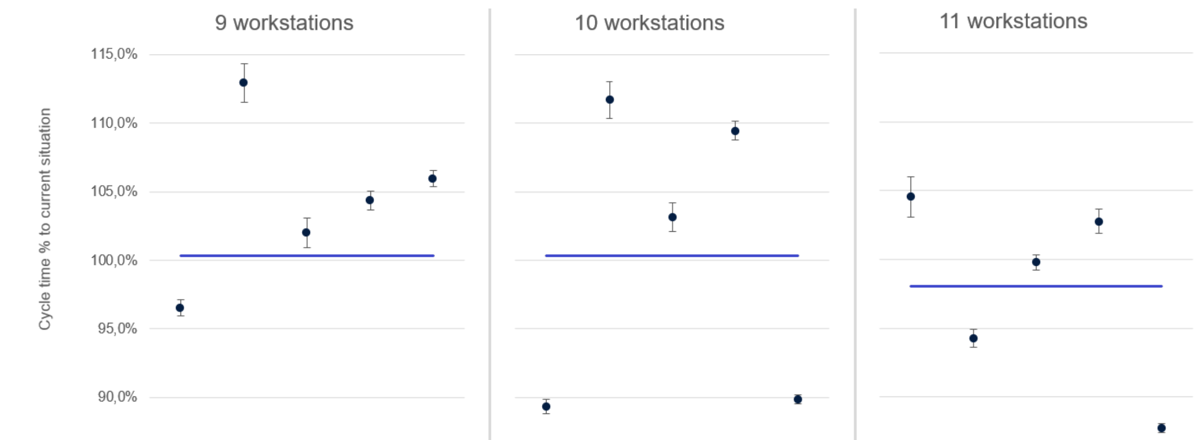
The lowest achieved cycle time percentage considering 11 workstations is 97.7%, constrained by the task that uploads software to the truck. In this set of experiments, the 9 and 10 workstation experiments are able to achieve a cycle time percentage of 100.3%. The number of active operators increases, and thus the operator efficiency decreases when the experiment considers fewer workstations. Recall from Section 6.1 that we include tasks from area 10 to the set of tasks to balance in the experiments considering 13.6- and 14-meter workstations, in line with the overlap these stations have with area 10. For these additional tasks, we need 2 more operators. To make a fair comparison with the 12-meter workstation experiment, we deduct these 2 operators from the solution. This is indicated between brackets in Table 8. Due to the experiments considering a slightly different set of tasks to schedule and the relatively small number of workstations, the results indicate a less clear efficiency reduction compared to the results of Section 6.2.2. Throughout the experiments, this operator efficiency decrease is 4.6% on average.

The model assigns more operators when fewer workstations are considered, and therefore, operator density per workstation increases in the experiments considering 10 and 9 workstations. The number of high impact tasks displacements is lower compared to the results from Section 6.2.2 due to the more restrictive model setup. The number of high impact tasks displacements fluctuate between 7 and 11. The total number of task displacements throughout the experiments is around 27, which is half of the number of total task displacements considered in the first set of experiments. Overall the average overload time and maximum overload percentage increase when the number of workstations decreases. Workstation 4 is the workstation with the highest overload time throughout the experiments. When considering additional tasks in the experiments, we see a higher operator efficiency due to a higher total task time considered in the calculation of the operator efficiency. The second set of experiments, considering organisational constraints, is constrained more than the first set of experiments. This explains the better results in the second set of experiments in achieved cycle time and operator efficiency.

Table 8: Results of the experiments with organisational constraints

		Number of workstations used (workstation length)		
Input data	**Performance measure**	**9** (14 m.)	**10** (13.6 m.)	**11** (12 m.)
Baseline experiment	**Cycle time % to current situation**	100.3%	100.3%	97.7%
	Number of operators	24 (22)	22 (20)	19
	Operator efficiency	73.8% (80.6%)	78.0% (85.8%)	84.4%
	High impact task displacement	8	7	11
	Average additional time (sec.)	274	189	9
	Maximum overload cycle time	112% at st. 4	111% at st. 4	107% at st. 4
	Station number with 6 (7) operators	5, 6	6	-
Additional tasks	**Cycle time % to current situation**	100.3%	100.3%	97.7%
	Number of operators	24 (22)	22 (20)	20
	Operator efficiency	74.6% (81.3%)	78.8% (86.7%)	81.1%
	High impact task displacement	8	6	11
	Average additional time (sec.)	370	254	97
	Maximum overload cycle time	113% at st. 4	112% at st. 4	106% at st. 4
	Station number with 6 (7) operators	6 (7 operators)	6 (7 operators)	6
Additional technological constraints: fluid filling	**Cycle time % to current situation**	100.3%	100.3%	97.7%
	Number of operators	25 (23)	23 (21)	19
	Operator efficiency	70.9% (77.1%)	74.6% (81.7%)	84.4%
	High impact task displacement	6	7	8
	Average additional time (sec.)	320	141	176
	Maximum overload cycle time	107% at st. 4	112% at st. 4	107% at st. 7
	Station number with 6 (7) operators	6	4, 6	7
Combination of additional technological constraints and tasks	**Cycle time % to current situation**	100.3%	100.3%	97.7%
	Number of operators	25 (23)	22 (20)	19
	Operator efficiency	71.6% (77.8%)	78.8% (86.7%)	85.3%
	High impact task displacement	7	6	8
	Average additional time (sec.)	317	254	74
	Maximum overload cycle time	113% at st. 4	112% at st. 4	107% at st. 4
	Station number with 6 (7) operators	6	6 (7 operators)	-

Figure 39 presents the 95% confidence interval of the completion time per station from the simulation runs with stochastic task times, as explained in Section 6.2.2. The figure considers each of the line layouts, and now we include the additional organisational constraints. The experiments we consider in Figure 39 are the experiments with additional technological constraints and tasks. Figure 39 only reports on the stations in area 11. On average, the 11 workstations experiment yields the lowest additional time. The 9 workstation experiment is more balanced than the 10 workstation experiment with the overload and idle times deviating the least from the weighted average cycle time percentage. The bottleneck station for each of the line layouts is workstation 4.



	9 workstations					10 workstations					11 workstations				
Station #	3	4	5	6	7	3	4	5	6	7	4	5	6	7	8
Mean	96,5%	112,9%	102,0%	104,4%	106,0%	89,3%	111,7%	103,1%	109,5%	89,9%	104,5%	94,3%	99,8%	102,8%	87,7%
Avg. mean (Det.)	100,3%	100,3%	100,3%	100,3%	100,3%	100,3%	100,3%	100,3%	100,3%	100,3%	98,0%	98,0%	98,0%	98,0%	98,0%

Figure 39: 95%-CI of mean cycle time considering experiments with organisational constraints

6.3 CONCLUSION

In Section 2.3.1, we presented the large potential output gain when solving the problem. Section 4.3 shows layout proposals to achieve this output gain. This chapter gives insights into the layouts' implications and answers the final sub-research question: *"What are the implications of the new assembly line layout regarding the balancing of tasks?"*. We gather the answers by analysing the results of the experiments performed on the ALB model.

Section 6.1 presents the experiments to perform with the ALB model. The experiments consist of balancing the tasks along 9, 10 or 11 workstations, corresponding with 14-, 13.6- or 12-meter workstations. All experiments consider the technological constraints of the cabin placement and tire assembly processes. We add additional technological constraints and tasks based on near-future task introductions on top of these constraints, resulting in 12 experiments in total. In addition, we consider organisational constraints from the global assembly sequence, making introductions of future modifications and trucks easier. When deviating from this global assembly sequence in a local assembly plant, such as SPZ, future introductions require more efforts to be introduced on the assembly line. So we use 2 sets of 12 experiments, an experiment set including and not including the additional organisational constraints. This gives us insights into a full and limited assembly line redesign.

Next, Section 6.2 presents the results of these experiments. The first set of experiments give a good overview of the impact of a complete line redesign useful for assessing operator efficiency and line output. The second set of experiments considers additional organisational constraints and assumptions on the stations outside area 11 performing their tasks below cycle time. Therefore it is difficult to compare both experiment sets. However, throughout both experiment sets, from Section 6.2.2 and 6.2.3, we see the following main effects when considering fewer workstations than the current setup:

- the cycle time increases
- the operator efficiency decreases
- the operator density increases
- the average overload time increases

In general, the cycle time increases when the number of workstations decreases and when more tasks and constraints are considered. Therefore, operator efficiency reduces when considering fewer workstations and more constraints. In the first set of experiments, the cycle time increases by 23.7% at most when considering 9 workstations, resulting in a cycle time of 121.2% of the current takt time. This is a considerable increase not in line with the solution design requirements of performing at the same output level of the current assembly line. The average achieved cycle time of the 10 workstation experiment is below 100% of the current takt time and therefore in line with this solution design requirement. In the second set of experiments, the cycle time increases by almost 3% on average, to 100.3% of the current takt time, when considering 9 and 10 workstations. So in this set of experiments, the cycle time is very close to the current takt time. However, in this set of experiments, the assumption is made that the stations not assigned to area 11 perform their tasks below the cycle time's theoretical lower bound to focus the balance on area 11. Fewer workstations result in increased operator density per station. The operator density per station increases by 10.7% on average when considering 1 station less. In the experiments considering additional organisational constraints, the average number of operators increases by 5.3% when considering fewer workstations. When we use this 5.3% operator increase and deduct 1 workstation, the operator density per workstation increases by 15.8%. This makes the solutions considering fewer workstations less robust to future task introductions requiring additional operator assignments because there is a limit to the number of operators we can assign to a certain workstation. Finally, we see an increase in average overload time when we consider fewer workstations due to more tasks assigned to a station on average.

Overall the 10 workstation experiments perform better than the 9 workstation experiments regarding these effects. From the experiments not considering organisational constraints, we see that approximately half of the task displacements cross an area bound of the globally prescribed assembly sequence of tasks. The high impact task displacements in this set of experiments fluctuate between 11 and 16. In the second set of experiments, we consider the full organisational constraints focussing on area 11 and do not allow cross-area task displacements. Therefore the number of high impact task displacements is lower, between 7 and 11. When leaving the filling installations in place, considering additional technological constraints in the experiments, the number of high impact installation displacements reduce by 2 on average. There is no notable efficiency decrease in the first experiment set when considering additional technological constraints. However, this decrease in efficiency is notable in the more restrictive second set of experiments, indicating a slight decrease in operator efficiency when additional technological constraints are considered. When implementing longer workstations, station boundaries have to be adjusted, and some tasks will be assigned to a different area because of areas consisting of only one workstation even when considering the full organisational constraints. The experiments without organisational constraints indicate an unacceptable increase in the cycle time of almost 24% when considering 2 workstations less compared to the current line setup. This cycle time would result in a significant output reduction. Therefore the 14-meter workstation proposal is not in accordance with the solution requirement. So we report on the average results of reducing the number of workstations by 1 in Table 9, the 13.6-meter workstation proposal. For the calculations, see Appendix 1.

Table 9: Average results of reducing the number of workstations by 1 compared to the current line setup

	Experiments without organisational constraints	Experiments with organisational constraints
Cycle time	+1.3%	+2.7%
Number of operators	+0.6%	+5.3%
Operator density	+10.7%	+15.8%
Operator efficiency	-1.6%	-6.3%
Average additional time (sec.)	+305	+121

To summarize, there is a significant output loss reduction to gain in the 13.6-meter workstation proposal. This proposal complies with the important solution design requirement of operating at the current fastest takt time. This proposal requires 5.3% additional operators at most when we considering the full organisational constraints. This can be translated to at most 2 additional operators at line part 2.2, resulting in increased operator density. The operator efficiency reduces because we consider the same task set with additional operators. The investment in additional operators regarding the assembly line balance at line part 2.2 is a fraction of the potential output gain. To conclude, there are no major concerns regarding the assembly line balance of the 13.6-meter workstation proposal, and therefore the 13.6-meter workstation proposal yields a positive result regarding the feasibility study. However, some aspects require additional analysis to build a solid business case. We will highlight these items in Section 7.2.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

In this final chapter, we draw conclusions on the research in Section 7.1. Next, in Section 7.2, we give recommendations based on the results of the research. These recommendations are relevant for SPZ to consider when implementing the solution. Finally, we present suggestions for further research in Section 7.3.

7.1 CONCLUSIONS

In this section, we draw conclusions based on the research carried out at SPZ. The central problem of this research is the output loss incurred due to long trucks at SPZ. Using a problem cluster, we found the root cause of this central problem: the mismatch between truck length and workstation length at SPZ. This research is the basis, as a preliminary study, to build and assess the feasibility of a business case to modify the line layout and address the central problem. We defined the following main research question to be answered in this research:

How should the workstation length and layout of the Castor assembly line at SPZ be redesigned to reduce the output loss caused by long trucks?

Long trucks cause problems in output loss, reduced safety levels, ergonomics and operator efficiency along the complete Castor assembly line with the current workstation length of 12 meters. There is a potential of increasing the yearly production by 278 to 370 trucks, depending on the market demand when addressing the output loss problem. This output loss is incurred on the second part of the Castor assembly line after the truck is placed on a carrier system. Long trucks require additional carrier distance on top of the standard 12-meter carrier distance resulting in output loss. Therefore we reduced the scope of this research to the second part of the Castor line.

The research focuses on longer workstations to address the current mismatch between truck length and workstation length, resulting in a new line layout. Such a new layout requires a balance of the tasks along the line to conclude on the new layout's implications. We reviewed methods of describing and solving an assembly line balancing (ALB) problem in the literature study. The core ALB problem, known as the simple ALB problem in the literature, features several simplifying assumptions, such as a single product type being produced and deterministic task times. Relaxations on the core ALB problem result in the generalized ALB problem. These generalized ALB problems consider, e.g., parallel stations, multiple workers per station and processing alternatives. The classical objectives of the mathematical ALB formulation consider the number of workstations and cycle time. Where these parameters are minimized, optimized or are bound to a maximum value. This mathematical formulation of the problem can be solved using exact or approximate methods where the exact methods are more suitable for the simpler or smaller problem instances. The approximate methods give a better trade-off between solution quality and computation time on larger or more complex problem instances. Suitable proven approximate methods are simulated annealing and Tabu-search.

It is not possible to significantly extend the assembly line. Therefore, given the available line space, the workstation length determines the layout of the assembly line. This layout is used as input to the ALB model providing the number of workstations to consider. We consider the same output level as the line can currently produce. When considering longer and thus fewer workstations along the assembly line at the current output rate, we have to increase the line speed. The full potential of the output gain regarding long trucks can be utilized when 14-meter workstations are implemented. However, this proposal increases the line speed and occupancy rate of installations along the line the most. Based on the produced truck lengths' distribution in recent years, we identified another promising workstation lengths of 13.6 meters. This proposal utilizes 96.8% of the output potential while being practically easier to implement than the 14-meter workstation proposal.

The installations with the current highest occupancy rates are situated at line part 2.2, from station 36 until 45. Therefore we focus the assembly line balancing on this part of the line. We present an ALB model based on the core ALB problem from literature with some important additions regarding the problem at hand. These additions are the use of multiple workers, mixed model product type, work zones within workstations, multiple workers required for a single task and technological constraints. Given the NP-hard nature and large neighbourhood structure of this problem, we use the heuristic method simulated annealing to optimize the problem. We utilize the neighbourhood operators mutation and swap in search of better solutions. The objective function we consider minimizes the cycle time as a primary objective and as a secondary objective minimizes the number of active workers. This is in line with the important KPIs within SPZ of increasing the line output and line efficiency. The detail level of the task data we consider is in accordance with the globally prescribed assembly sequence within Scania. Important inputs to the model are the task times, precedence relations of the tasks, the work zones to which the tasks are assigned and how many workers are required for a task. Also, we consider technological constraints representing installations requiring considerable efforts to be displaced along the assembly line. We assess the task times' stochastic nature by performing a Monte-Carlo simulation on the ALB algorithm's result, which is a task to station assignment.

The experiments we perform consist of balancing the tasks along 9, 10 or 11 workstations, corresponding with 14-, 13.6- or 12-meter workstations. All experiments consider the technological constraints of the cabin placement and tire assembly processes. We add additional technological constraints and tasks based on near-future task introductions on top of these constraints, resulting in 12 experiments in total. We perform this set of 12 experiments with and without organisational constraints from the global assembly sequence. When deviating from this global assembly sequence, future introductions require more efforts to be introduced on the assembly line and are therefore relevant to consider in the experiments. Throughout both experiment sets, we see the following main effects when reducing the number of workstations. The cycle time increases, the operator efficiency decreases, the operator density increases, and the average overload time increases.

The cycle time increases by around 21.2% when considering a 14-meter workstation layout compared to the current fastest takt time. This conflicts with the solution requirement of yielding the same output as the current line setup. In contrast, the 13.6-meter workstation proposal operates within this fastest takt time on average. Also, the 14-meter workstation layout is practically more challenging to implement and requires a higher line speed (+3.3%) compared to the 13.6-meter workstation proposal. Therefore we consider the 14-meter workstation proposal not feasible and recommend the 13.6-meter workstation proposal. This proposal utilizes 96.8% of the output potential resulting in a significant output gain of 269 to 358 trucks yearly depending on the demand scenario. The 13.6-meter workstation proposal operates at an increased line speed of 13.3%, which increases the occupancy rate of processes along the assembly line.

The experiments with additional organisational constraints consider limited task-area displacements making the solution more robust to future task introductions. However, this experiment set is more restrictive than the experiment set not considering these organisational constraints. Therefore the experiments with organisational constraints operate at increased cycle time with an increased number of operators. The 5.3% operator increase can be translated into adding 2 operators at most at line part 2.2. These 2 experiment sets give us insights into a full and limited assembly line redesign. We can reduce the effects of cyle time and operator increase of the proposal considering full organisational constraints if we would relax these organisational constraints smartly. In practice, these choices have to be made because station boundaries will change, and therefore tasks will be assigned to different workstations and areas. Table 10 below presents the study's outcomes and results from both experiment sets with and without organisational constraints of the 13.6-meter workstation layout.

Table 10: Average results 13.6-meter workstation proposal

	13.6-meter proposal without organisational constraints	13.6-meter proposal with organisational constraints
Output gain	269 to 358 trucks yearly	
Assembly line speed	+13.3%	
Cycle time % of current fastest takt time	99.4%	100.3%
Average operator increase line part 2.2	+0.6%	+5.3%
Operator density	+10.7%	+15.8%

To conclude, there is a significant output loss reduction to gain in the 13.6-meter workstation proposal of 269 to 358 trucks yearly, depending on the market demand. This proposal is in line with the requirement of operating at the same output level as the current assembly line regarding the assembly line balance. The proposal requires 2 additional operators at most when considering the full organisational constraints. This results in increased operator density per workstation and decreased operator efficiency given the fixed task set. When we relax the organisational constraints, the operator increase is lower. The 13.6-meter workstation proposal requires a relatively small investment in additional operators in contrast to the significant output gain the solution yields. Therefore, it is interesting to further investigate the 13.6-meter workstation proposal and include additional detailed information to strengthen the business case, such as investments to be made on installations. These items will be highlighted in the next section.

7.2 RECOMMENDATIONS

In the previous section, we concluded that an assembly line layout utilizing 13.6-meter workstations result in a feasible assembly line balance. In this section, we present the recommendations of the research given this conclusion.

We narrowed down the scope of the assembly line balance, due to time restrictions, to line part 2.2 from workstation 36 until 45. Because at this line part, the most severe bottleneck installations and tasks are situated. We assumed that if a balance at this line part with the most severe bottlenecks is feasible, it should also be feasible on the other part of the Castor line. We recommend performing the assembly line balance on the other part of the Castor line to validate this assumption and report on the results. The balance should be performed for the task set after the motor placement and before the cabin placement. The workstations between placing the chassis on the carrier system and motor placement currently have no issues with long trucks.

This research highlighted the output gain potential, the layout to address the problem, the resulting assembly line balance and its implications. To further assess the business case's feasibility to implement 13.6-meter workstations, the efforts and costs to realize the implementation should be detailed further. Given the 13.6-meter workstations, the line speed has to increase by 13.3% to maintain the assembly line's current output levels. Therefore there will be more installations along the assembly line performing at or over their limit. These installations require adjustments in process time or increased reach to be able to cope with the higher line speed. Also, given the new task to station assignment, certain installations have to be relocated. The impact of these adjustments should be investigated further by the project team looking at longer workstations. This analysis gives insights into the bottleneck processes along the assembly line and the efforts and costs to adjust these processes to the new layout. To further strengthen the business case, we recommend studying the effects of the new assembly line layout on the line efficiency regarding aspects we have not treated in this study. See Section 7.3 for the details on this suggestion for further research.

In line with the research goal, we looked at the impact of longer workstations with a wide scope and determined the new layout accordingly. We recommend having a detailed assessment on where to place the future workstation boundaries given the new line layout. From the analysis we performed on the new layout, it became clear that logistical cross aisles and the buffer location at station 35B have to be adjusted. In this detailed assessment, all relevant parties, such as logistics, production and engineering, should be included to establish consensus on where to place the station boundaries and cross aisles. After that, the effects of this new assembly line layout regarding material layout and material supply to the assembly line should be investigated.

Recall from Section 6.1 that respecting Scania's global assembly sequence, which assigns tasks to certain area's along the assembly line, makes the introduction of future tasks and modifications easier to implement. As concluded in Section 6.3, some tasks will be assigned to a different area than prescribed in the global assembly sequence. This is also the case when we consider the experiment set with additional organisational constraints. We recommend investigating the task assignments deviating from the global assembly sequence on the consequences of future truck modifications and introductions. Furthermore, this new task to area assignment on the Castor assembly line will deviate from the current task assignment on the secondary Pollux line. The relation between the two lines should be investigated regarding material and information supply to the assembly line. We recommend assessing the organisational consequences of this mismatch in task to area assignment between the two lines.

We concluded on a layout proposal utilizing 13.6-meter workstations. When considering this proposal, some trucks require additional carrier distance on top of the new standard carrier distance of 13.6 meters. Therefore the chassis should be measured at station 28 to check if additional carrier distance is required. We recommend adjusting the light screen distances and investigate the most effective carrier distances to use.

7.3 SUGGESTIONS FOR FURTHER RESEARCH

This final section of the report makes suggestions for further research based on the study's outcomes and findings.

Fewer workstations than currently deployed at the Castor assembly line result in higher operator and tool density per workstation. Also, an assembly line layout with fewer workstations operating at the current highest output level requires an increased line speed of over 13%. There is a feeling that this might affect operator efficiency. It might be valuable to study the impact of these aspects on operator and line efficiency because it can have an effect on the benefits of the business case.

Recall from Section 2.3.2 that we identified problems in safety, ergonomics and efficient execution of the operators' job at line part 1 of the Castor assembly line. We recommend studying the potentials of including this line part in the new line layout. Together with the option to make this line part continuous driven, as identified in the problem cluster of Section 1.2.1.

We presented an ALB model in this research regarding the problem at hand. We recommend further investigating the assignment of stochastic task times within the metaheuristic. The model now defines a task to station assignment based on deterministic task times and afterwards assesses stochasticity using Monte-Carlo simulation. It might be interesting to see if further solution optimisation is possible when considering stochastic task times while determining the task to station assignment.

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APPENDIX 1: GENERAL CALCULATIONS

Mean and standard deviation:

We calculated the mean task time using: $E(X) = \mu = \sum x * P(x)$, with x representing the task time and $P(x)$ the occurance of the task. For the variance of the normal distribution, we use the following equation: $\sigma^2 = \sum(x - \mu)^2 P(x)$ (Meijer, 2018).

Results of 1 workstation less without organisational constraints

Calculation of average results when reducing the number of workstations from 11 to 10

	Cycle time increase	Operator increase	Operator efficiency reduction	Average additional time increase
Baseline experiment	0%	2.56%	2.1%	163 (sec.)
Additional tasks	0%	0%	0%	625 (sec.)
Additional technological constraints: fluid filling	2.67%	0%	2.1%	207 (sec.)
Combination of additional technological constraints and tasks	2.67%	0%	2.1%	224 (sec.)
Average over 4 experiments	**1.33%**	**0.64%**	**1.58%**	**305 (sec.)**

Results of 1 workstation less with organisational constraints

Calculation of average results when reducing the number of workstations from 11 to 10

	Cycle time increase	Operator increase	Operator efficiency reduction	Average additional time increase
Baseline experiment	2.68%	5.26%	6.40%	180 (sec.)
Additional tasks	2.68%	0%	2.30%	157 (sec.)
Additional technological constraints: fluid filling	2.68%	10.53%	9.80%	-35 (sec.)
Combination of additional technological constraints and tasks	2.68%	5.26%	6.50%	180 (sec.)
Average over 4 experiments	**2.68%**	**5.26%**	**6.25%**	**121 (sec.)**

APPENDIX 2: TASK DATA

In this section, we present the baseline data set, not considering additional tasks. This data set is used as input data for the ALB model. Also, we present the tasks assigned to the 7th work zone, tasks that require 2 workers and the tasks we have combined.

The tasks assigned to the 7th work zone are: filling of air, coolant, clutch oil and air conditioning, the pressure test of the air conditioning and all SPCT tasks.

The tasks that require 2 workers are: guiding the truck's cabin, placing the 5th wheel, connecting the gas springs to the front hatch and mount the RAD chassis.

We have combined some of the tasks from the global prescribed assembly sequence because these tasks are most efficiently performed at the same time. These tasks require common resources or due to logistical supply require to be placed at the same station. Therefore we combined the following common tasks placed on the left hand or right hand of the truck: placement of the 5th wheel, filling AdBlue, Filling fuel, connecting the steering column, placing the spare wheel and applying torque to the tilt cylinder. Furthermore, we have combined the task of filling coolant, clutch oil and performing the air conditioning pressure test because these tasks require the same installation and therefore should not be separated.

In the table below, we present the main input data used. The table's left-hand side presents the task number, task time, the task time's standard deviation, the work zone the task is assigned to, and the number of required operators to perform the task. The right-hand side of the table presents the precedence relations between the tasks. For example, the first precedence relation indicates that task 1 has to be performed before task 2.

Task number	Task time	Standard deviation	Task work zone	Number of operators required		Precedence relations row 1	Precedence relations row 2	Precedence relations row 3
1	270	4.32	0	1		1,2	36,43	70,87
2	30	6.00	0	2		2,3	36,45	71,76
3	92	18.40	0	1		2,5	36,46	71,77
4	41	4.12	2	1		2,6	37,4	71,78
5	200	4.14	0	1		2,7	37,42	71,83
6	79	1.60	0	1		2,8	37,43	71,87
7	26	0.41	0	1		2,9	37,45	72,75
8	85	8.59	0	1		2,10	37,46	73,74
9	36	7.20	0	1		2,12	38,39	76,89
10	83	4.81	0	1		2,14	38,61	77,89
11	240	48.00	1	1		2,41	39,61	
12	105	16.18	6	1		2,44	40,47	
13	150	29.43	3	2		3,4	40,48	
14	105	16.18	5	1		3,12	40,56	
15	60	16.66	5	1		3,14	40,6	
16	95	7.54	0	1		4,12	41,5	
17	77	13.95	0	1		4,14	41,51	
18	62	12.40	1	1		5,11	42,47	
19	51	10.20	1	1		5,12	42,48	
20	122	22.40	1	1		5,14	42,6	
21	61	12.20	2	1		6,12	43,47	
22	23	2.38	2	1		6,14	43,48	
23	156	31.13	3	1		7,38	43,6	

24	151	30.13	4	1		8,38	44,53	
25	87	12.69	0	1		8,8	44,54	
26	170	41.03	0	1		8,84	45,47	
27	198	39.60	0	1		9,61	45,48	
28	198	22.00	0	1		10,61	45,6	
29	225	78.82	3	1		11,61	46,47	
30	109	21.80	3	1		12,16	46,48	
31	82	16.47	3	1		12,52	46,6	
32	186	32.00	4	1		13,4	49,62	
33	109	21.73	4	1		13,42	50,8	
34	61	12.10	4	1		13,43	51,81	
35	60	12.07	4	1		13,45	53,84	
36	120	44.29	1	1		13,46	54,85	
37	120	44.29	2	1		14,15	55,62	
38	138	8.51	6	1		16,17	56,8	
39	124	24.80	6	1		16,18	56,84	
40	103	22.50	2	1		16,19	60,61	
41	50	10.00	3	1		16,2	60,62	
42	252	26.39	3	1		16,21	61,64	
43	84	16.80	3	1		16,22	61,66	
44	50	10.00	4	1		17,25	61,68	
45	238	25.84	4	1		18,25	61,7	
46	24	4.73	4	1		19,25	61,72	
47	44	4.73	3	1		20,25	61,73	
48	44	8.80	4	1		21,25	61,81	
49	299	20.46	6	1		22,25	61,85	
50	131	26.20	1	1		23,3	61,88	
51	229	45.80	1	1		24,33	62,78	
52	34	6.80	1	1		25,26	64,65	
53	129	25.80	2	1		25,27	64,76	
54	206	41.20	2	1		25,28	64,77	
55	72	2.60	4	1		25,38	64,78	
56	61	6.40	4	1		26,49	64,83	
57	76	25.81	0	1		26,57	64,87	
58	218	25.50	0	1		26,58	65,76	
59	71	14.20	0	1		26,59	65,77	
60	86	0.98	3	1		27,49	65,78	
61	93	0.94	0	1		27,57	65,83	
62	176	11.86	6	1		27,58	65,87	
63	124	24.80	5	1		27,59	66,67	
64	147	33.89	1	1		28,49	66,76	
65	136	18.89	1	1		28,57	66,77	
66	143	37.86	2	1		28,58	66,78	
67	136	18.89	2	1		28,59	66,83	
68	147	33.89	3	1		29,36	66,87	
69	136	18.89	3	1		29,37	67,76	
70	143	37.86	4	1		29,42	67,77	
71	136	18.89	4	1		30,38	67,78	
72	57	11.40	0	1		30,47	67,83	
73	38	7.60	0	2		31,36	67,87	
74	35	7.00	0	1		31,37	68,69	
75	27	5.40	0	1		31,4	68,76	

76	45	21.79	3	1	32,36	68,77	
77	45	21.79	4	1	32,37	68,78	
78	237	61.47	6	1	32,45	68,83	
79	37	19.50	2	1	33,38	68,87	
80	78	35.77	1	1	33,48	69,76	
81	50	20.32	1	1	34,36	69,77	
82	21	11.58	1	1	34,37	69,78	
83	70	27.71	1	1	34,4	69,83	
84	78	35.77	2	1	35,36	69,87	
85	50	20.32	2	1	35,37	70,71	
86	25	7.51	2	1	35,43	70,76	
87	70	27.71	2	1	35,46	70,77	
88	142	84.42	3	2	36,4	70,78	
89	58	25.61	5	1	36,42	70,83	

APPENDIX 3: NEIGHBOURHOOD OPERATORS

In this section, we present the neighbourhood operators swap and mutation.

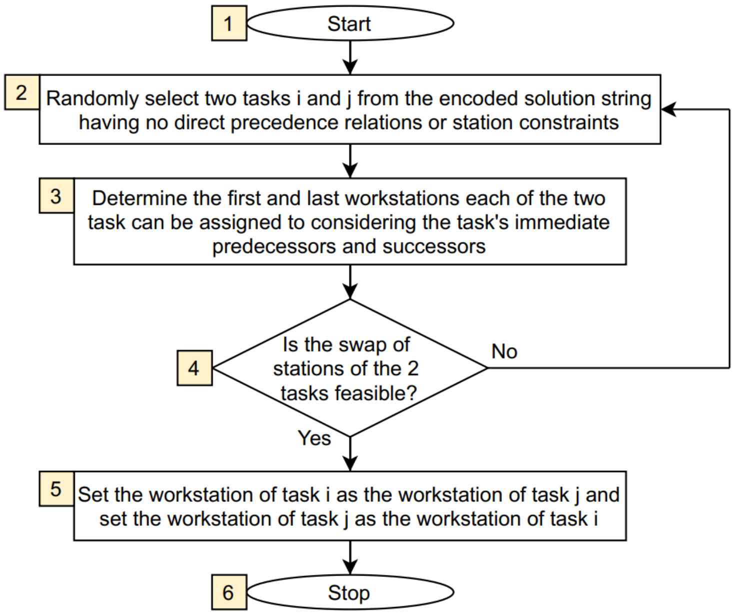

Figure 40: Swap operator

Figure 40 presents the flowchart of the swap operator. At point 2 of the flowchart we randomly select two tasks from the encoded solution string having no immediate precedence relations, e.g., task j must be directly performed after task i. If one of the selected tasks has a technological constraint and must be assigned to the current station, then select another task. Next, at point 3, specify the first and last possible workstation the tasks can be assigned to by determining the tasks immediate predecessors and successors. Next, check if a swap of both tasks is possible considering precedence relations and technological constraints at point 4. If not, then go to point 2 and start over. If the swap is possible, then set the workstation of task i as the workstation of task j and set the workstation of task j as the workstation of task i. Finally, give the found neighbourhood solution as output.

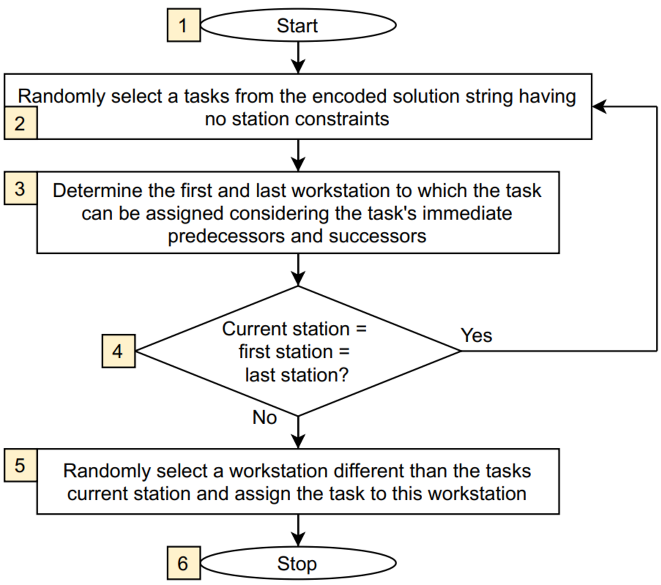

Figure 41: Mutation operator

Now we consider the mutation operator as presented in the flowchart in Figure 41. Here we randomly select a task from the encoded current solution string at point 2. If the selected task has a technological constraint and must be assigned to the current station, then select another task. Next, at point 3, specify the first and last possible workstation the task can be assigned to by determining the tasks immediate predecessors and successors. If the task cannot be assigned to a different workstation, then go to point 2 and start over. If the task can be assigned to a different workstation, then randomly select a workstation different from the current workstation and within the first and last possible stations to assign the task to, in accordance with point 3. Next, assign the task to this new station in the solution string. Finally, give the found neighbour solution as output.

APPENDIX 4: MODEL VERIFICATION

For the experiments, we consider a well-know data set in ALB theory from Otto, Otto & Scholl (2013). In the following experiment, we consider 20 operators to work on 100 tasks with a total task time of 21571 seconds. When we do not consider the precedence relations and divide the total task time by the number of operators, we find the theoretical lower bound of the problem. With this relaxation, we are able to comment on the quality of the solution. In this data set, the lower bound of the problem is: $\frac{21571}{20} = 1078.55$.

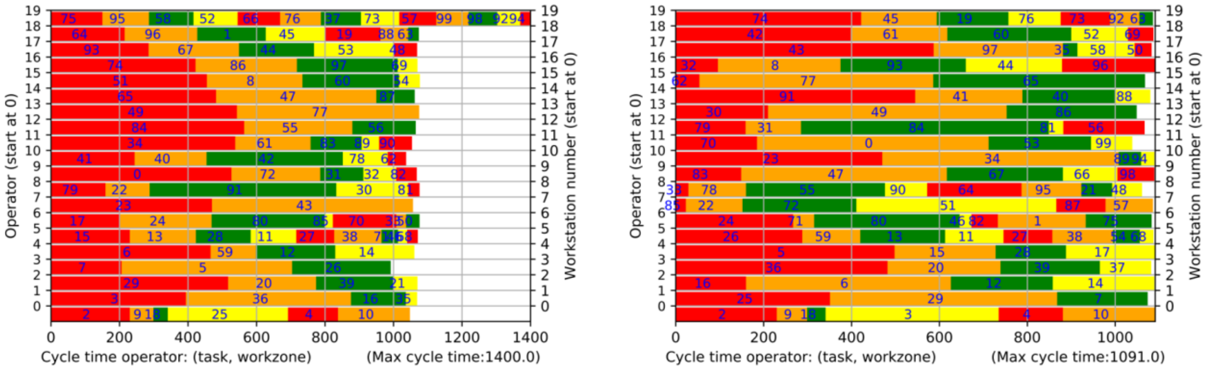

Figure 42: Benchmark data set experiment 20 workstations with 1 operator

Figure 42 presents the results of an experiment considering 20 workstations with 1 worker. The figure presents the initial task to station assignment on the left-hand side with the task times plotted horizontally, resulting in a cycle time of 1400 seconds. On the right-hand side, the task to station assignment is presented after the simulated annealing optimization procedure, resulting in a cycle time of 1091 seconds. The final result reaches the lower bound by $\frac{1091}{1078.55} - 1 = 1.2\%$.

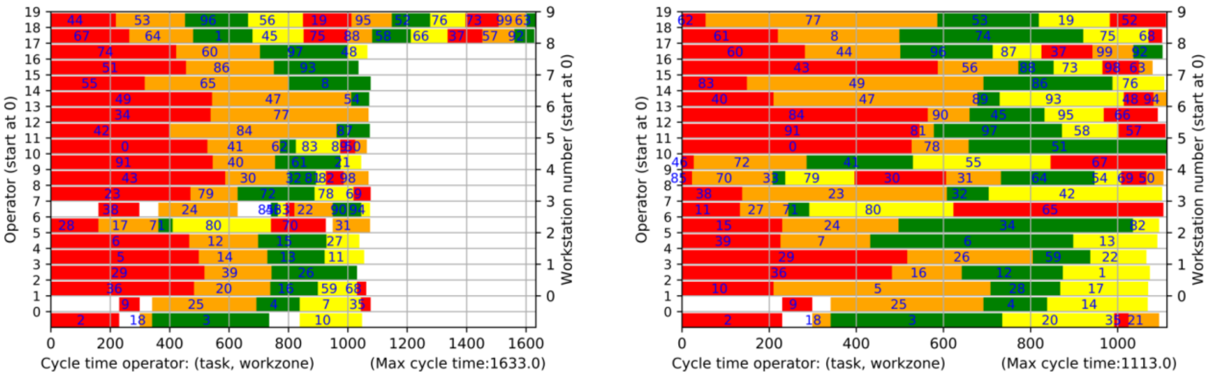

Figure 43: Benchmark data set experiment 10 workstations with 2 operators

Figure 43 presents an experiment, using the same data set, considering 10 workstations with 1 worker assigned. The initial solution results in a cycle time of 1633 seconds with a gap to the lower bound of $\frac{1633}{1078.55} - 1 = 51.4\%$. On the right-hand side of the figure, the final solution after the simulated annealing optimization is presented. This results in a cycle time of 1113 seconds with a gap to the lower bound of $\frac{1113}{1078.55} - 1 = 3.2\%$.

To conclude, the simulated annealing optimization is able to improve the initial solution significantly, resulting in a final theoretical lower bound gap of 1.2% to 3.2%.