Scania Production Zwolle

Optimizing assembly line fill rate by minimizing the losses due to discrepancy between truck and workstation lengths

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Management Summary

This study is conducted at Scania Production Zwolle (SPZ), a key site responsible for assembling approximately 60% of Scania trucks annually in Europe. At SPZ, trucks are assembled on a moving assembly line characterized by a constant pace. The focus of this research centres on the second segment of the Pollux assembly line (Pollux-2), where trucks are transported on carriers through 16 individual workstations, each with a fixed length of 12000mm. The distance required to assemble trucks on the assembly line vary in length between 6785mm and 13865mm, which is caused by the difference in length between trucks. This leads to trucks occasionally exceeding the workstation's length. To ensure optimal workflow, each truck requires 12000mm of assembly line space, allowing workers ample time to perform their tasks independent of the actual length of a truck. Yet, longer trucks cause idle time for both workers and equipment. Hence, the research question arises:

What is the effect of implementing a strategy to reduce the losses generated by long trucks on the Pollux-2 assembly line?

Currently, long trucks exceeding 12000mm contribute to 1.5% productivity loss on the Pollux line annually, resulting in a reduction of 123 trucks in output each year. SPZ currently employs mixing rules during truck planning on the assembly line to reduce the effects of long trucks. However, these rules do not fully account for the excess length of long trucks, leading to inefficiencies.

We design a strategy that involves bundling short trucks around a long truck, ensuring each truck in the bundle has the same allotted time (takt time) for completing tasks. The strategy distributes the surplus assembly reservation length from the long truck among the shorter trucks in the bundle. This concept introduces variable launching rates for trucks on the assembly line. Despite variable launching trucks, the average distance allocated to trucks on the assembly line is maintained at a minimum of 12000mm, ensuring that workers have adequate time to complete their tasks within the required timeframe.

To implement this concept, we propose the introduction of flexible workstation borders, allowing for overlap between adjacent workstations. This flexibility enables the allocation of less distance to short trucks to compensate the excess length of long trucks. Consequently, two trucks may be present at the same workstation simultaneously. However, as each workstation can only accommodate work on a single truck at a time, tooling must be reachable beyond the workstation boundaries. We assessed the limitations of tooling reachability at the workstations and determined that, with the current setup, the maximum feasible extension of tooling reachability is 1000mm. Therefore, the shift of a truck within a bundle is restricted to 1000mm forward or backward from its original position.

The assembly line at SPZ requires the categorization of truck lengths in intervals. By grouping trucks from different length categories into bundles, it becomes feasible to distribute the excess length of long trucks among shorter trucks within the same bundle. A series of 1026 experiments were performed to evaluate various bundle size configurations, employing both continuous and discrete measurement techniques for truck length assessment. The carrier system utilized by SPZ for truck transportations operates within discrete distance settings, influencing the implementation of the bundling strategy. Consequently, experiments using continuous measurement methods were used to establish an upper limit for the bundling approach. The most effective experiment, using continuous measurement of trucks, demonstrated the strategy's potential to mitigate losses attributed to long trucks by up to 99%. When the limits of the carriers system used by SPZ are integrated into the bundling strategy, the potential improvement resulted in 87.87%. Upon integration of the bundling strategy into SPZ's assembly process, an overall productivity enhancement of 1.32% is expected, translating to an annual increase in truck production by 108 units. The results of the most effective bundle experiment indicate that long trucks should be paired with two shorter trucks for optimal compensation. However, an exception applies to trucks with a length between 12000mm and 12300mm, which should be paired with a single short truck. For trucks exceeding 12300mm, a bundling approach of 'short-long-short' is recommended to minimize the additional tooling reachability required.

After implementation of the bundling strategy, we recommend that SPZ explores the feasibility of modifying the existing carrier system to incorporate continuous truck length measurement. Such integration would enhance the efficiency of implementing the bundling strategy by facilitating more accurate truck compensation based on continuous measurements. Additionally, continuous measurement could streamline assembly line operations by eliminating the need for truck categorization, thereby reducing associated inefficiencies. The bundling strategy introduces the concept of 'open' workstation borders, potentially enabling concurrent tasks across neighbouring workstations for the same trucks and therefore adequate coordination between workstations is necessary. While this study primarily focusses on the implications of bundling on the Pollux-2 assembly line, it should be investigated whether the implementation of the strategy is also beneficial to the Castor-2 line. We expect that small gains are possible, however, do to the low number of long trucks assembled on the Castor line and faster takt time, we do not expect improvements similar to the Pollux line.

One of the limitations of the research is the sensor locations for trucks, which is based on historic production data. The settings based on this data may become unsuitable for future production due to shifts in truck lengths or truck models. Second, our model assumes perfect alignment between theoretical and actual truck lengths, ignoring the deviations present at SPZ. The trucks that deviate from the theoretical length, are on average misplaced by two length categories. Moreover, assuming uniform assembly time across all trucks for all workstations overlooks variations in complexity between trucks, thus affecting efficiency. Introducing this variation in complexity, and the required assembly time into the bundle strategy results in additional parameters to take into account and can therefore result in a different outcome. We expect that this will reduce the potential improvement of the bundling strategy, since more complexity is introduced to the problem.

Preface

As I wrap up my academic journey with this thesis, it is a moment to reflect on the experiences and knowledge gained along the way. When I first set foot in Scania Production Zwolle, I knew it was where I wanted to write my theses. And now, after six months of hard work, I am proud to present the results of my graduation project.

Firstly, I want to thank Marien Damman for his invaluable guidance and mentorship throughout the duration of my graduation project. His expertise, feedback and support were instrumental in shaping the direction and outcomes of this study and helped me in my personal development.

Furthermore, I would also like to express my appreciation to Matthieu van der Heijden and Marco Schutten, my supervisors from the University of Twente. Their insightful feedback and supervision helped me a lot with the project.

Moreover, I would like to thank the entire team at Scania Production Zwolle for their collaboration, assistance and willingness to share their expertise and time. Without their support, this research would not have been possible.

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1. Introduction

This chapter outlines the main research subject of the study, which is performed at Scania Production Zwolle. The context of Scania is provided in Section 1.1, which also explains the motivation behind this research. The identified problem is then thoroughly analysed in Section 1.2, and the study design, including a set of associated research questions is presented in Section 1.3.

1.1. Company Background and Research Motivation

Section 1.1.1 provides an overview of Scania and their production location in Zwolle. Section 1.1.2 gives the motivation for the research of this project.

1.1.1. Scania Production Zwolle

Scania AB is a leading Swedish manufacturer of commercial vehicles, with their main focus being heavy trucks, buses and diesel powered engines. Scania was founded in 1891 and nowadays is part of the Volkswagen Group. Scania employs over 57,000 people in more than 100 countries. The headquarters of Scania AB is based in Sweden, where R&D is also mainly based. Scania Production Zwolle (SPZ) is the largest and most modern truck assembly plant of Scania in Europe. SPZ produces approximately 60% of the annual output of Scania trucks in Europe, which are delivered all over the world. One of Scania's unique selling points is their modular system, which gives the customer an extensive amount of customization. Currently, SPZ assembles approximately 200 trucks on a daily basis. (Scania.com, 2023)

1.1.2. Research Motivation

SPZ implements a mixed-model assembly line for trucks with diverse specifications. The aim of SPZ is to minimize the variability of the workload at each workstation while still having the flexibility to assemble different truck configurations on the same assembly line. Due to the high level of customization offered by Scania and their strategy to only build trucks after they are ordered, the trucks produced are often unique. One of the factors that affect the workload is the length of the trucks assembled, which can range from 5405 to 12485mm. The assembly line operates at a constant speed, which poses challenges for the workstations that have to deal with different truck lengths. Some trucks are longer than the length of the workstation itself, which causes a longer cycle time for long trucks at the visited workstations and therefore lead to inefficiencies. This contradicts with Scania's production strategy, as outlined in their 'Scania's Production System' handbook, which states that the workload should be balanced among each workstation and truck assembled. By reducing the inefficiencies caused by long trucks, the production output can be improved and Scania can move closer to their target of having a daily capacity of 240 trucks. Scania has already performed an extensive amount of research in overcoming the above mentioned problem, but still thinks that there is room for improvement. (Scania.com/news, 2022)

1.2. Problem Analysis and Definition

The following section gives a detailed context about the problem in 1.2.1. Next, 1.2.2 describes the core problem and 1.2.3 shows the research design, where the main research question is formulated.

1.2.1. Context

The assembly plant in Zwolle has two parallel lines, named Pollux and Castor, as shown in Figure 1-1. The inner line (Pollux) is shorter than the outer line (Castor), and has a takt time that is around 2.5 times slower for each workstation compared to the Castor line. Takt time is the time allocated for completing all the necessary tasks at a workstation. It is equal for each station on the assembly line, except for the frame and completion line. The production lines are divided into two sections. In the first section, the frame of the truck is assembled using a *'stop&go'* system. This system requires the truck to remain stationary at each station until all the activities are completed, after which it is released to the next station. This means that there is no continuous speed at this part of the assembly line. The reasoning can be explained due to components that need to be assembled on the underside of the chassis, which necessitates lifting the truck off the ground by a cable system. This system is incompatible with a continuous speed and therefore a *'stop&go'* system is used. In the second section, the truck is placed on a carrier and it travels at a constant speed through the line. The project mainly focuses on the second section of the line, as the consequences of long trucks are most severe on this part. This can be attributed to the continuous speed and the short workstations, which cause idling of workstations when long trucks are assembled. Moreover, to overcome the issues of long trucks on the *'stop&go'* section of the line, mixing rules are implemented in the planning of production, as detailed in Section 2.3.1.

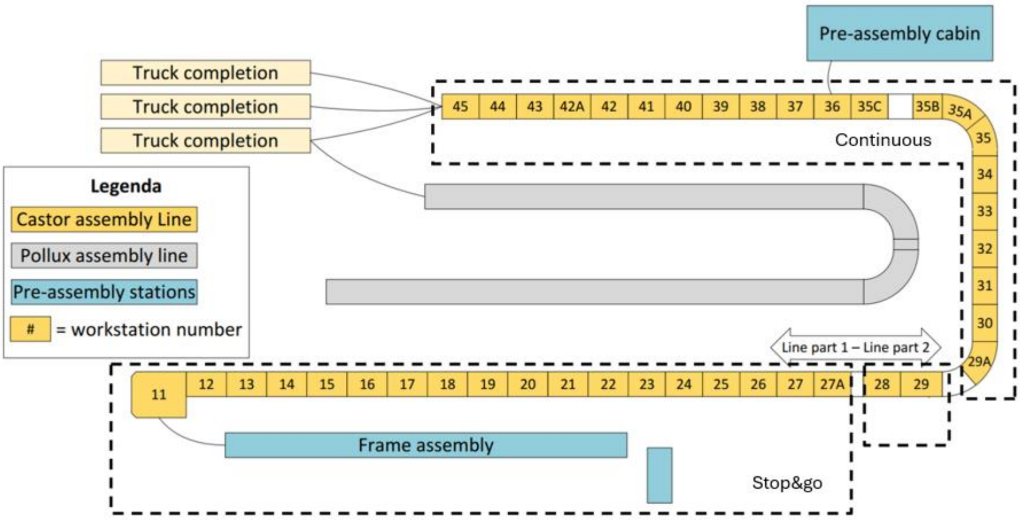


Figure 1-1, Overview production plant Zwolle

On both assembly lines, workstations with a length of 12000mm are implemented at Scania. The operators have to complete their tasks on the truck within this distance. Scania uses a takt time of 300 seconds on the Castor assembly line and 720 seconds on the Pollux assembly line, which means that all tasks to be performed on the truck should be executed within this time. Figure 1-2 illustrates this process, where the green arrow marks the beginning of the takt time and the blue arrow marks the end of the measurement at the next workstation. Ideally, the operators should have the full takt time to perform the required steps. However, this is not always feasible. Some trucks will require more process time at certain workstations. In these special cases, additional operators are added to this section of the line. Scania assembles trucks with different lengths, ranging from 5405 up to 12485. Consequently, some trucks exceed the length of the workstation when they are assembled on the line. To ensure enough space between trucks, the subsequent truck has to wait for the extra distance that the long truck occupies in its workstation. This causes losses in productivity and efficiency. On the Castor line, 6.16% of trucks assembled exceed 12000mm, while on the Pollux line a total of 21.73% of all trucks are longer than 12000mm over the past 5 years. In total, Scania loses approximately 1.5% output due to long trucks on the Pollux line, and 0.3% on the Castor line.

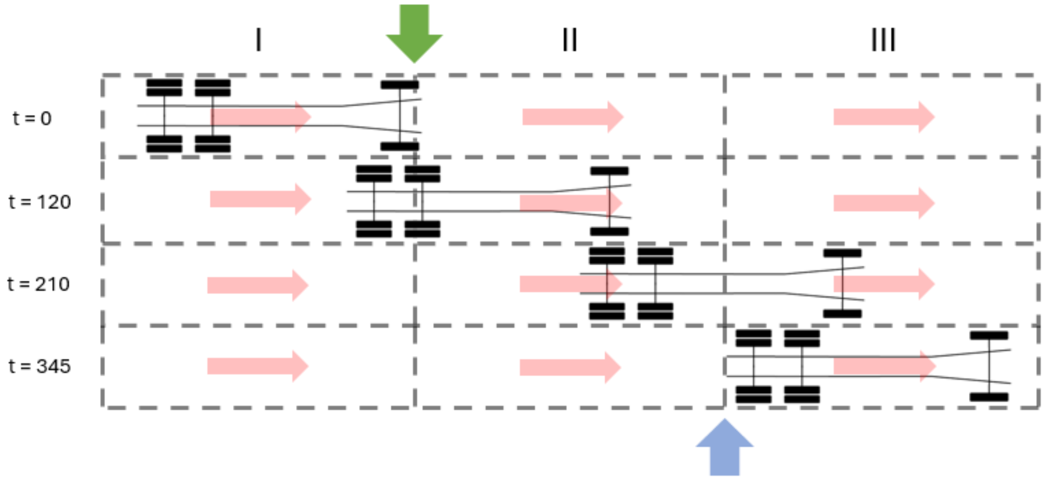


Figure 1-2, Flow of truck on line

Currently, the planning of trucks on the assembly line consists of the following steps: A truck is positioned on the assembly line, followed by a neutral zone of 1380mm. The neutral zone is used for the following measures:

- Improving the safety of workers, it reduces the risk that a worker gets stuck between two trucks.
- Provide space for equipment, for example a trolly with tools.
- Ensure that in the bends of the assembly line, two trucks do not come into contact.

If the sum of the truck's length and the neutral zone is less than 12000mm, extra distance is added. This is because each truck requires 12000mm to be assembled at each workstation, regardless of the truck's length. The vacant space on the line is essential as it enables sufficient time for the operators to execute their tasks. However, if a truck that exceeds 12000mm is positioned on the line, and the compulsory distance is added, it exceeds the station which leads to a delay of the subsequent truck. Figure 1-3 shows a diagrammatic representation of this process. Situation A illustrates the optimal situation, where each truck can be assembled within the length of the workstation. After one takt, situation B is reached. Truck 5 enters the line, with a total combined length of 14000mm. This results in an reservation of 14000mm on the assembly line, and therefore delaying the next truck by 2000mm. This truck only requires 12000mm of time to be assembled, however due to its length, it receives 14000mm, which means that operators at station I are idle for 2000mm worth of assembly time. Workers have to wait until the truck leaves the workstation on the continuously driven carrier, before they can start working on the next truck. In situation C, trucks are moved one takt, and a new truck (6) enters the assembly line. Since truck 6 cannot be positioned 12000mm after the beginning of truck 5, it is delayed by 2000mm. Situation D displays another truck entering the assembly line, which is also delayed by 2000mm. Since every truck requires 12000mm of assembly time, the delayed 2000mm is currently not recovered. One possible method of reducing this problem is by starting with a truck that is delayed before it enters the workstation. In Figure 1-3, this would mean that at situation C, operators start working on truck 6 while it has not fully reached the workstation. This method has consequences, like for example tooling access and lost time due to walking extra distances and therefore should be investigated within this project.

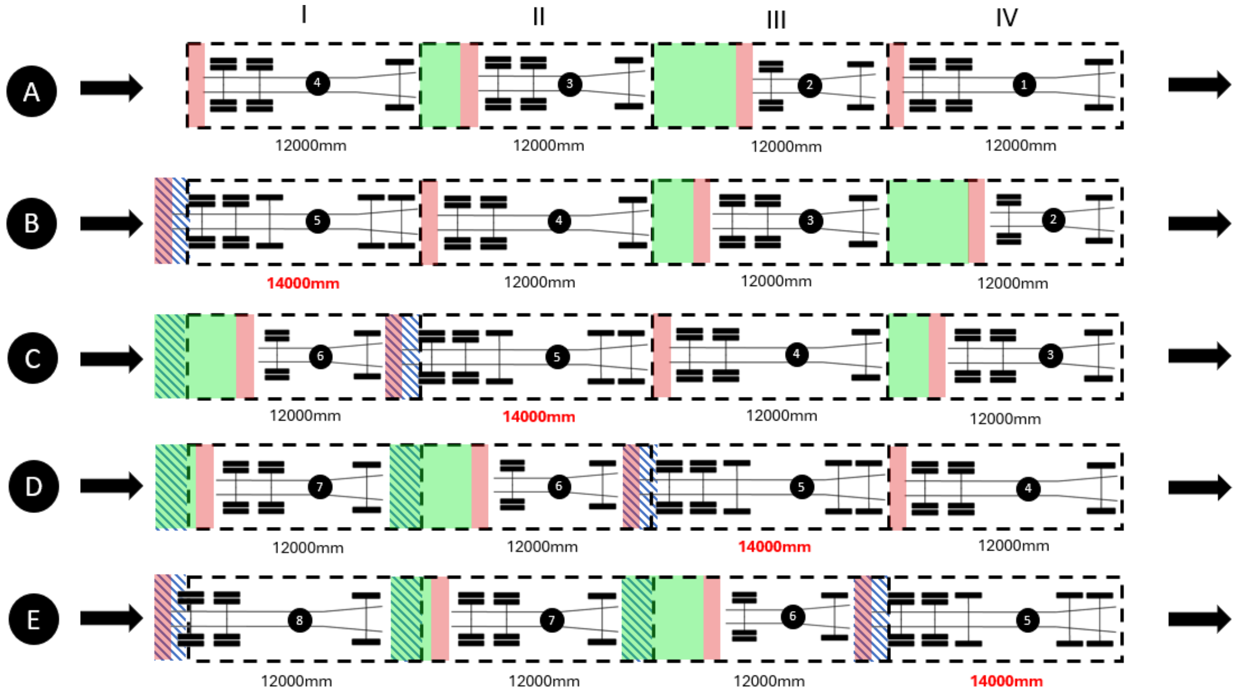


Figure 1-3, Assembly situations

Figure 1-4 shows the problem cluster containing the different problems contributing to the losses described on the previous page. The main problem is the 'Output losses due to long trucks', which is caused by a delay of trucks at workstations. Scania employs a *'mixing rule'* to mitigate the effects of long trucks on workstations. The rule specifies that a long truck should be preceded and followed by a short truck (<8000mm) in the production sequence. This rule is intended to reduce the variability of the workload and the waste caused by long trucks on the first part of the assembly line. This rule is introduced on this part of the assembly line to ensure that enough room is available to work on the truck. A long truck can overlap the preceding station, as long as it followed by a short truck. If this is not the case, and a long truck is followed by another long truck, the third truck can be shifted backwards on the workstation to an extend that equipment can no longer reach the areas where it is needed. If a long truck is followed by another long truck, either a planning mistake has been made or not sufficient short trucks are in the order pool. Planning mistakes should not occur and are therefore out of scope. The lack of short trucks available is also out of scope. It is also not possible to change the length of trucks Scania offers to their customers, therefore the problem of assembling long trucks is also taken out of the scope. This results in two problems that have potential to be improved, namely: *'Not enough reachability for tools to reach trucks'* and *'No strategy to recover lost distances*.

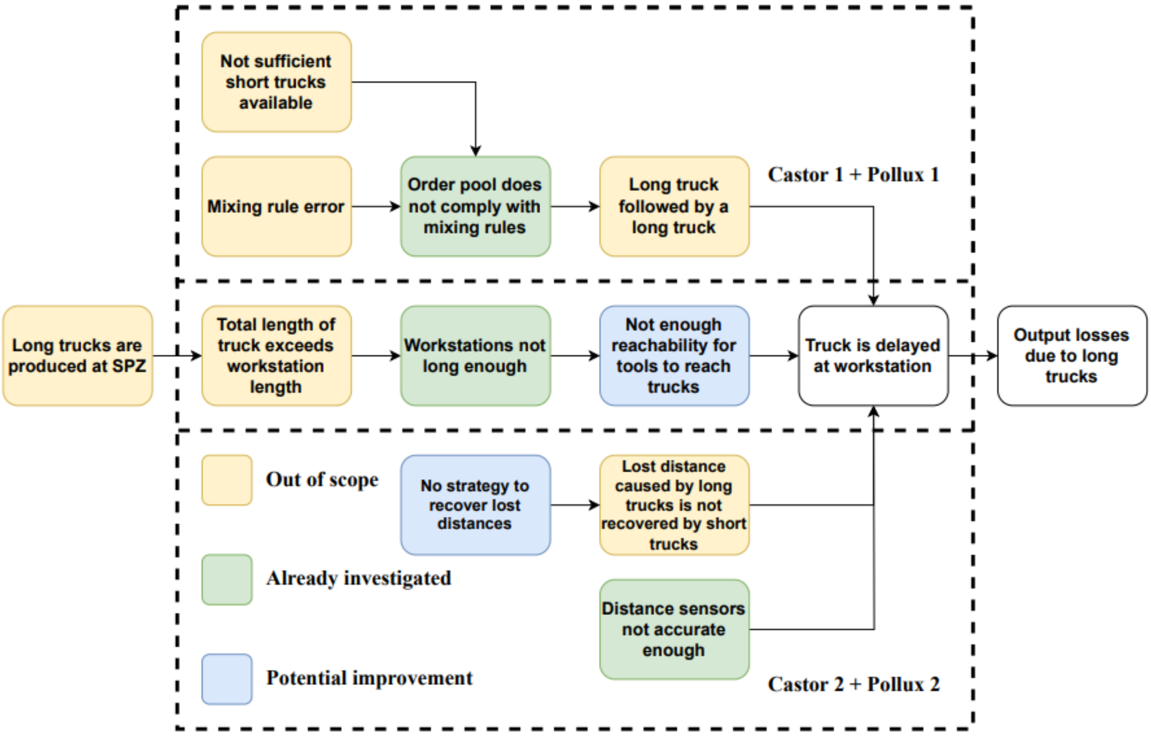


Figure 1-4, Problem cluster

1.2.2. Core Problem

The problem cluster found in Figure 1-4, reveals two main causes of inefficiency in the production line: *Not enough reachability for tools to reach trucks* and *inability to compensate for lost distance caused by long trucks*. These causes are interrelated and are examined in this project. We formulate the following core problem: ***There is no method of dealing with long trucks on a continuous production line due to limited reachability of tools and no method of recovering lost distances caused by long trucks.***

1.2.3. Scope

The scope of the project focusses on the second stage of the production line. In total, more distance is lost on the Pollux line, compared to the Castor line, and the percentage of long trucks on the Pollux line is 3.5 times higher. This makes the Pollux-line the primary target for this study.

The project does not address the issue of material supply, which is assumed to have adequate capacity. Likewise, the project does not consider the workforce availability, which is presumed to be sufficient and not affecting the project outcome.

The project aims to find solutions within the existing setup and tools at SPZ, without modifying or replacing any tools or workstations. Additionally, when applicable, recommendations for future improvements for tooling or workstations are discussed. Furthermore, assembly sequences within workstations cannot be altered.

Finally, the project adheres to the Scania Production System handbook when designing and testing different solutions. Any deviations from the current ways of working should be verified with the handbook and discussed with SPZ if any conflicts arise. (Scania, 2020)

1.3. Research Design

With the use of the core problem, objective of the project and the scope, the following main research question can be derived:

What is the effect of implementing a strategy to reduce the losses generated by long trucks on the Pollux-2 assembly line?

In order to answer above mentioned research question, we formulated the following sub-questions:

1. **How does the Pollux-2 line currently cope with the challenges posed by long trucks and what is the impact of these challenges on the production output?**
    1.1. What are the main challenges that SPZ face, caused by long trucks on the Pollux-2 line?
    1.2. How do the challenges affect the production output on the Pollux-2 line?
    1.3. What are the current strategies SPZ applies to cope with long trucks?
    1.4. What are the potential gains that can be achieved by reducing the effects of long trucks?

Firstly, we will perform a thorough analysis of the current situation at SPZ. This will help to identify the existing problems and losses caused by long trucks, and to locate the areas where improvements are possible. SPZ has access to a large amount of data, which helps create insights in the current performance of SPZ. Bottlenecks are identified with the use of this information, as well as restrictions for possible improvements. This sub-question is answered in Chapter 2.

2. **What methods described in literature address the challenges of product variation and inefficiencies on a continuous assembly line, with a focus on mitigating the impact of long trucks on the Pollux-2 line?**
    2.1. What challenges do product variations bring to a continuous assembly line?
    2.2. Which methods of solving irregular takt time problems are discussed in literature?

Chapter 3 shows the literature review that explores potential methods to handle diverse products on a continuous assembly line, which can provide possible methods to deal with long trucks on the Pollux-2 assembly line.

3. **What are possible strategies SPZ can apply to reduce the effects of long trucks?**
    3.1. What methods of reducing effects of long trucks can be derived from the literature study?
    3.2. How can the methods derived from literature be adapted to SPZ?

In order to bring possible improvements to the assembly process on the Pollux-2 line, found theory needs to be implemented and tested. To adapt and use the theory found, a computational model needs to be created to incorporate the information found, shown in Chapter 4.

4. **How do the methods found perform on the Pollux-2 line and what are the advantages and disadvantages of these methods?**
    4.1. What KPIs should be used in order to assess the effectiveness of the methods?
    4.2. How do the methods perform according to the KPIs compared to the original situation?

The solutions found and tested are analysed in order to gain insights into their impact on the assembly process of SPZ. Advantages and disadvantages with regards to implementation and effectiveness are provided in Chapter 5, in order to facilitate a clear picture of the solutions.

5. **What are the implications of the identified solutions and what recommendations can be made for SPZ?**
    5.1. How will the assembly line perform differently under the new strategy?
    5.2. What are recommendations that can be made to SPZ for future research?

After analysing the results of the solutions found, and taking into account advantages and disadvantages of these solutions, recommendations are made to SPZ about the solutions that will help them to improve the production output. The conclusion of the project, as well as the recommendations can be found in Chapter 6.

2. Current Situation

In this chapter, the current situation at SPZ is described in Section 2.1. The consequences of long trucks on the assembly line are discussed is Section 2.2. The potential gains that can be achieved by SPZ if the impact of long trucks is reduced are discussed in Section 2.3.

2.1. Main challenges

This section discusses the challenges faced at SPZ that have a contribution or impact to the losses caused by long trucks that are currently not recovered. First, the workstation sizes are discussed in 2.1.1. Next, equipment used at SPZ and their restrictions are shown in 2.1.2. In 2.1.3, the continuous line speed at SPZ is introduced, which is followed by the Jidoka tooling system used by SPZ in 2.1.4. Lastly, the carrier system used to transport trucks through the assembly line are explained in 2.1.5.

2.1.1. Workstation size

The Pollux-2 assembly line comprises of 16 workstations, excluding the completion area. Each workstation has a length of **12000mm**, except for the stations located in the bends of the assembly line. The workstations are arranged in series without any buffer zone. Figure 1-1 shows the layout of the assembly line. The Pollux-2 line commences after the engine placement station, which is located in the first turn. Before the engine placement station, a carrier is positioned below the truck to transport the truck across the workstations. The carrier follows a track in the ground and cannot deviate from this track. The carriers are electrically driven and each carrier is individually motorized. This independency facilitates different speeds between carriers, which is required for two situations on the line, both being passages for forklifts or supply of materials.

2.1.2. Equipment

The operators are required to complete their assigned tasks within the workstation's length, using the materials and tools provided at the station. Some workstations necessitate the use of 'fixed' equipment to assemble parts. A 'fixed' tool is a tool that is connected to a ceiling beam by either an aluminium beam or a steel cable. The use of 'fixed' tools at workstations can be attributed to the following reasons:

- Liftable weight; Workers are allowed to lift a maximum of 12kg, therefore additional lifting support may be required if the total weight of the tool/part exceeds this limit (Arboportaal, 2023).
- Forces on tool; Some connections require forces that are higher than an operator can handle, such as mounting wheel nuts that require certain torque. To facilitate these forces, supports are needed.

Each 'fixed' tool has a limited reach, which is either the length of the workstation or a shorter distance if there is no need or room for longer reach. This can occur if tasks can be executed in a shorter timeframe or when different tooling is placed after the tool on the same workstation, which limits its range. The reachability of the 'fixed' tooling at the workstations on the

Figure 2-1, 'fixed' tooling example

second part of the Pollux line can be found in Appendix A. Figure 2-1 shows an example of a 'fixed' tool mounted on a beam that facilitates movement of the tool across ceiling beams.

2.1.3. Continuous speed

SPZ operates with a continuous speed on the Pollux-2 line, meaning that in theory trucks move with a stable constant speed through the workstations. This speed is based on the takt time present at workstations. Takt time is the time in which operators at the workstations have to perform all the required tasks, and can be calculated with the following formula:

$$\text{Takt time} = \frac{\text{Available Production Time}}{\text{Average Customer Demand}}$$

The available production time refers to the total duration of time that is available for production during a specific period, while customer demand describes the quantity of products that the customer requires during the same period (Businessmap, 2023). At SPZ production periods of around five weeks are used. The use of takt time aligns production and logistical processes to ensure that specific parts are available at the required time. If the required tasks are not executed within the takt time at a workstation, the complete assembly line is stopped until the specific task is completed. Since almost every truck assembled at SPZ is unique, workload fluctuates for each truck at the workstations. To cope with this fluctuation, floater operators are available to assist on peak workloads. These operators are not assigned to a specific workstation but are available to assist on trucks with a workload exceeding the takt time.

2.1.4. Jidoka

Jidoka is a lean principle that aims to error-proof a process when a deviation occurs. The theory behind Jidoka is to automatically detect problems or defects at an early stage within the production process, and only proceed after resolving the problem at its root cause (Leaninfo.nl, 2023). This principle has been introduced at SPZ to reduce quality issues with regards to connections made by tooling. On the Pollux-2 line, a total of **21 tools**, which use the Jidoka philosophy, have been implemented to ensure that the connections made with these tools are reliable and deviations are eliminated and detected at an early stage within the process at the same workstation. A full list of these Jidoka's with detail can be found in Appendix A.

At SPZ, the Jidoka system is implemented as follows: A truck enters the workstation on a carrier. The Jidoka system identifies which truck has entered the workstation and what connections need to be made. The operator starts making these connections with special tooling that can send data to the Jidoka system about the connections made. If the operator has used 70% of the available distance to make the connection, a signal is given to warn the operator. If the connection is not successful before a certain distance from the end of the Jidoka, the line is automatically stopped and a signal is emitted. If all connections are successfully made before the truck reaches the end of the station, no issue exists and the Jidoka is successful. After the problem is fixed by either making the Jidoka connection or overruling the connection, the assembly line can continue again.

2.1.5. Carrier system

In the second part of the Pollux assembly line, trucks are loaded onto a carrier system. These carriers move the trucks along a set path at a constant speed through all the workstations until they reach the completion area. Here, the trucks are lifted of the carriers. Each carrier has its own power, allowing for different speeds between carriers at different parts of the assembly line. A carrier consists of two platforms, with the first one housing the electric motor. The front axle of a truck is placed on the first platform, while the rear axle goes on the second one. This design facilitates the flexibility in distances between axles on the trucks assembled. Trucks are loaded onto a carrier and then sent off to the next part of the assembly line. The timing of when a carrier is sent off depends on the distance to the previous carrier. Carriers are launched based on the distance to the previous truck, which can vary when long trucks are launched. Currently, there are six specific distances a carrier can be launched after the previous one, as the system has limitations on the number of launching distances it can handle. In total, there are ten different settings that can be programmed into the carrier system, of which four are currently not used to launch trucks.

2.2. Consequences of the current situation

Trucks assembled at SPZ exhibit varying lengths, with some exceeding the length of the workstations, thereby delaying the subsequent truck. The shortest truck configuration measures 5405mm, while the longest measures 12485mm in total length. As mentioned in Section 1.2.1, a neutral zone is necessary after each truck on the assembly line. This neutral zone has a total length of 1380mm. By adding this length to the truck length, an interval for the length of trucks can be obtained, namely: 6785 < Truck < 13865. This results in the possibility of a truck exceeding the workstation length by at most 1865mm. On the other hand, trucks can also have a total length shorter than the workstation length, resulting in a ‘vacant’ space on the assembly line. This ‘vacant’ space cannot be seen as losses since it translates to assembly time that operators need to perform necessary steps on the truck. We analysed the lengths of trucks produced over the past five years to examine the consequences of these length discrepancies.

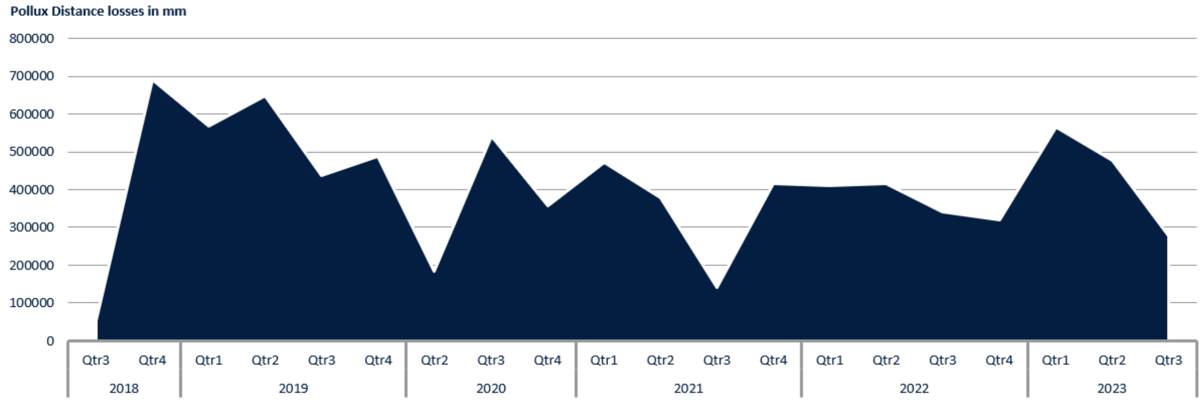


Figure 2-2, Pollux Distance Losses Quarterly

Figure 2-2 illustrates the total quarterly losses incurred due to long trucks. It is noteworthy that no data is presented for the first quarter of 2020, owing to a production stop in the line for this specific quarter and partially the subsequent quarter. Over the past five years, a total of **8.19 kilometres** or **8,186,187 mm** of production distance was lost due to long trucks, which is equivalent to **682 trucks** in total. On average, a long truck exceeds the workstation by **923.95 millimetres**. When translated to an average truck, this results in a loss of **200.77 millimetres** for each truck, independent of the truck's length characteristics. The average length of truck assembled on the Pollux line is **10315.53 millimetres**, including the neutral zone. This indicates that on average, **1684.47 millimetres** of 'empty' space is available for each truck. The use of long trucks on the Pollux line results in **a productivity loss of 1.5%.**

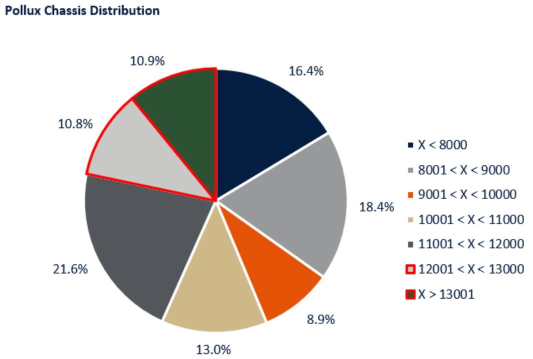


Figure 2-4, Pollux Chassis Distribution

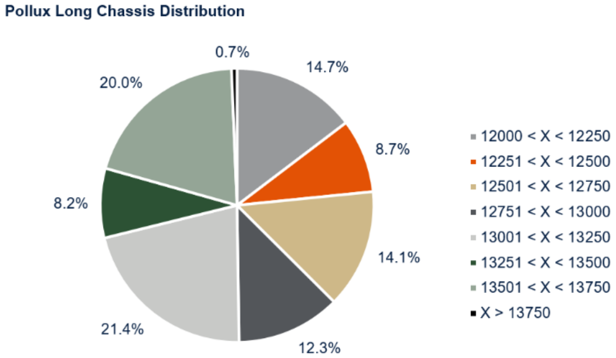


Figure 2-3, Pollux Long Chassis Distribution

Figure 2-4 illustrates the distribution of the various lengths of trucks assembled at SPZ. The sections highlighted in red denote the trucks whose total combined length exceeds that of the workstations. Over the past five years, the percentage of trucks exceeding the workstation length on the Pollux line has been 21.7%. Figure 2-3 displays the distribution of trucks longer than 12000mm, which represent the 21.7% of long trucks assembled on the Pollux line. The graph indicates that long trucks assembled exhibit fluctuations in length, and there is no significant size contributor to long trucks on the Pollux-2 line.

2.3. Current strategies

2.3.1. Planning sequences

SPZ employs mixing rules to accommodate the different characteristics of truck types. These rules outline specific conditions that must be considered when planning the truck sequence for the assembly line. The mixing rules are based on the workload and length of the trucks. The complete list of mixing rules can be found in Appendix B.

Trucks are initially divided between Castor and Pollux lines, with more complex and labour-intensive trucks typically assembled on the Pollux line due to its slower takt time. On the Pollux line, a mixing rule stipulates that at most one long truck can be sequenced for every two other trucks. Additionally, a long truck must always be preceded and followed by a short truck to ensure that no two long trucks are adjacent to each other in the first section of the assembly line. If two long trucks would follow each other, this would give additional losses on the Pollux-1 line, due to the 'stop&go' system applied on this part of the line. If two long trucks would be assembled after each other, the third truck would be delayed by up to four meters that possibly leaves too little distance for the third truck on its workstation.

2.3.2. Predetermined losses

SPZ is aware of the losses caused by long trucks, prior to the commencement of production. These losses are determined based on the length of the trucks to be assembled. Therefore, SPZ takes a predetermined loss of 1% into account during the planning stage. However, in practice, this number is higher due to issues encountered during the assembly process as shown in Section 2.2. This implies that SPZ accounts for losses caused by long trucks even before the assembly process begins. The percentage of loss is based on the combination of long trucks on both the Castor and Pollux lines, and represent the overall expected losses in total output.

2.4. Conclusion

In this chapter, we answered the first research question: *“How does the Pollux-2 line currently cope with the challenges posed by long trucks and what is the impact of these challenges on the production output?”*.

We demonstrated that various constraints exist at the workstations, such as the length, location and type of tooling. These are all factors that should be taken into account during the project. SPZ currently implements mixing rules during the planning stage to reduce the effects of long trucks on the assembly line. By compensating a long truck with two short trucks, the overall losses on the first section of the assembly line are minimized, however this rule does not affect the second part, where every truck is given a total assembly line reservation of at least 12000mm. Long trucks affect the mixing rules, making it harder for the planner to schedule every truck on the assembly line. By reducing the effects of long trucks on the assembly line, relaxations could be made on the current mixing rules, therefore reducing the limitations of mixing rules during the planning stage and increasing the number of long trucks to be assembled on the Pollux assembly line.

Currently, **two causes** can be pointed out that contribute to the losses faced by long trucks. The first cause being the fact that workstations have a maximum length of 12000mm while the longest truck + neutral zone combination equals 13865mm. The second cause is the fixed takt time implemented at SPZ. Due to this fixed takt time, every truck receives the same amount of time at each workstation, and therefore the losses faced by long trucks are currently not recovered.

The average total length of a truck assembled on the Pollux line, including the neutral zone, is 10315.53mm. The workstations span 12000mm, leaving a gap of 1684.47mm. This gap facilitates the operators on the workstations with sufficient time to execute the necessary tasks since every truck needs at least 12000mm of workstations, regardless of the actual length of the truck.

The average losses caused by long trucks in the past five years are 1.5% on the Pollux line. This implies that the annual production capacity of the Pollux line could be increased by 137 trucks if the discrepancy is eliminated. As has been noticed, the proportion of long trucks on the Pollux assembly line accounts for 21.7% of the overall production. This gives opportunity for the use of recovery tactics to make up for the lost distance from long trucks. Chapter 3 discusses in-depth research on potential theoretical approaches to reduce these losses.

3. Literature Review

This chapter discusses literature related to this project. Section 3.1 explores the challenges that product variations pose to a continuous assembly line. Section 3.2 introduces possible approaches that could be used to minimize the length discrepancy losses currently faced. Lastly, Section 3.3 provides a conclusion to the literature reviewed and formulates the choice of the direction of the solution we made.

3.1. Product variation challenges

In this section, four topics are discussed with regards to producing different product varieties on the same assembly line. 3.1.1 discusses the use of manned stations, while 3.1.2 shows the different types of assembly line variety and how to deal with these varieties. 3.1.3 explains how different products can be sequenced on the assembly line to reduce losses and 3.1.4 explains the use of takt time and the different ways of implementing takt time.

3.1.1. Manned stations

SPZ applies a Multi manned Assembly Line station philosophy (MAL). This philosophy, as the name suggests, is used in an assembly line that allows more than one worker for a workstation. This type of assembly line is suitable for products that require highly skilled collaborative operations. In Figure 3-1, a comparison between different assembly line types can be found. Factors that can influence the choice of assembly line type are product size, structure, demand rate, work in process costs and number of tasks (Kellogöz, 2016).

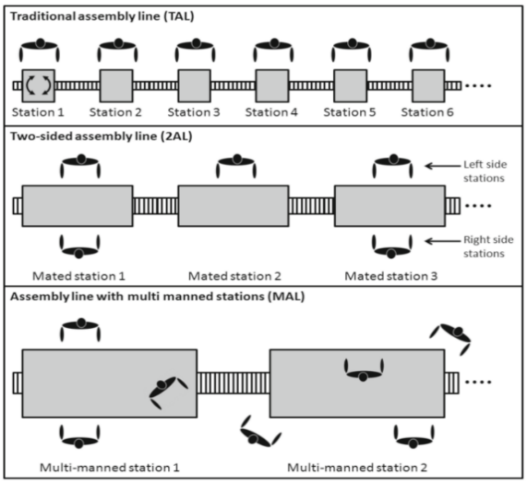


Figure 3-1, Different assembly line types (Kellogöz, 2016)

The MAL with walking workers is a variant to MAL. This variant allows workers to move between workstations, thereby introducing workforce reconfigurability. This feature can be advantageous when assembling products that differ in workload on the same assembly line. Currently, SPZ does not implement this strategy. Instead, SPZ uses mixing rules and allow workers to idle, which also results in an even distribution of workload. The reallocation of workers between stations can adjust the capacities of stations to the production sequence (Hashemi-Petrodi, Thevenin, Kovalev, & Dolgui, 2022).

3.1.2. Assembly line variety

Depending on the product variety and the setup/performance times of each workstation, different types of assembly lines can be distinguished. The three most common types are: *single-model, mixed-model* and *multi-model* assembly lines (Kazemi, Ghodsi, Rabbani, & Tavakkoli-Moghaddam, 2011). Figure 3-2 illustrates the differences between these line types. SPZ has two *Mixed-Model Assembly lines* implemented, being the Castor and Pollux line. Mixed-model assembly lines (MMALs) offer the possibility of producing different product of the same family simultaneously on the same line in order to benefit from an efficient production flow (Ebrahimi, Mahmoodjanloo, Einabadi, Baboli, & Rother, 2022). *Mixed-model assembly lines* might cause a short-term sequencing problem, where there has to be decided on the production sequence of a given number of model copies within the planning horizon, e.g., one day or shift (Boyson, Fliedner, & Scholl, 2007). This is an issue currently faced at SPZ. Mixing rules are required to ensure the continuity of the assembly line. For example, it is currently not preferred to sequence multiple long trucks after each other and therefore, a mixing rules is implemented that every long truck should be preceded and followed by a short truck.

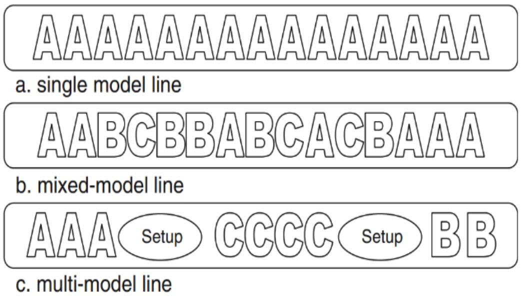


Figure 3-2, Different types of assembly lines (Kazemi, Ghodsi, Rabbani, & Tavakkoli-Moghaddam, 2011)

3.1.3. Assembly Line Sequencing

Different models of products may require different amounts of work for assembly, resulting in an uneven distribution of work along the assembly line. To design an efficient mixed-model assembly line, two interrelated problems need to be solved: **line balancing** and **model sequencing** (Thomopoulos, 1967). The model sequencing problem refers to the challenge of assembling different models on one line, with varying work requirements for each model. The goal of the sequencing procedure is to determine the optimal sequence of models in the flow that maximizes the utilization of the assembly line operators and minimizes the flexible workforce capacity needed. In order to avoid successive models with long process durations to be planned in advance at a station, sequences of products need to be selected carefully (Miltenburg, 1989). Two main sequencing problems are described in literature: *Mixed-Model Sequencing* and *Car Sequencing*. **Mixed Model Sequencing (MMS)** is a model that takes into account various manufacturing data, including processing times, workstation configurations, and operator movements. The model uses this information to determine the optimal sequence of products to manufacture on an MMAL. The model is designed to minimize work overload by explicitly considering assembly line balance when determining a car sequence. A sequence is considered MMS-feasible if no work overload occurs during its execution. The **Car Sequencing (CS)** model, on the other hand, implicitly addresses workforce and installation capacities through sequencing rules to find a sequence with minimum sequencing rule violations (Louis, Alpan, Penz, & Benichou, 2023). A sequencing rule can concern products that have a significantly greater processing time than the cycle time. With the use of *H/N* ratios the number of longer processing time products (H) is limited to N successive products. CS aims to find the best sequence to violate as little as possible sequencing rules (Boyson, Fliedner, & Scholl, 2007).

In case of SPZ, MMS is already practiced in the current way of working/planning. If a truck has a workload on a station that exceeds the predetermined takt time, it is followed by a truck that has a lower workload on the same station. This gives workers the possibility to retrieve 'lost time' caused by the first truck. However, this is only done for workload, not with regards to the length of a truck. Currently long trucks are not compensated by short trucks to 'win back' lost distances, and therefore implementing a sequencing strategy to reduce the impacts of long trucks could be beneficial to SPZ.

Line balancing involves assigning tasks to assembly operators in a way that it tries to equalize the workload among them and minimizes the number of operators needed. The assembly line balancing problem (ALBP) belongs to the class of NP-hard problems, which require an effective algorithm to produce a solution of high quality (Qidong, Xiaochuan, Jie, & Lei, 2022). There are numerous variations to the basic ALBP, one of them being the ALBP-2. This problem has the objective to minimize the cycle time given a fixed number of workstations. The cycle time acts as an upper bound for the workload of each workstation and ensures the steady pace of the line (Yuchen, 2022). Since SPZ already performed ALB to the current assembly line, no changes to the current setup are required. However, changes in the sequencing of trucks can affect on the ALB, and therefore there is a possibility that ALB should be performed when a new sequencing method is implemented.

3.1.4. Takt Time

A fixed takt time is a common method for synchronizing production units on a continuous assembly line with a constant speed and a predetermined time interval, regardless of the variation in manufacturing complexity among different models. This method requires balancing all models according to the same fixed takt time. The Weighted Average Takt Time (WATT) is an technique for adjusting a fixed takt time to the diverse processing times of different models. However, this technique entails inefficiencies: either idle time when the processing time of the current model is shorter than the WATT or utility/additional work when it is longer than the WATT. Furthermore, production planners have to alternate between models with low and high workload to prevent line stoppages, which disrupts the alignment of customer demand and the assembly line's model sequence (Huchzermeier, Mönch, & Bebersdorf, 2020). Unlike the fixed takt time method, the variable rate launching (VRL) method adopts model-specific takt times that correspond to the processing time of each model, which isolates the assembly line balancing problem for one model from the others. Moreover, operators can initiate assembly on a product without delay and complete their work without the risk of work overload. This method results in a more uniform operator workload when placing units with large workload deviations on the same line, which reduces idle time and minimizes utility work. Additionally, the constraints on the model sequence are largely removed, enabling a model mix on the line that matches current customer demand. Lastly the planning effort for introducing a new model on the line is significantly reduced, as production planners only need to modify the balance for the new model (Bebersdorf & Huchzermeier, 2022). However, the drawback of having a VRL is that workstation length equals the length needed for the longest model. Therefore, additional floorspace is needed but not fully utilized all the time.

Another possible strategy that can be incorporated in a continuous assembly line is the VarioTakt principle. By implementing the VarioTakt principle, WATT and VRL are integrated. Variable rate launching allows for a deliberate reduction of utilization losses across different products, while WATT mitigates the losses caused by option variants in terms of takt and model-mix (Bebersdorf & Huchzermeier, 2022).

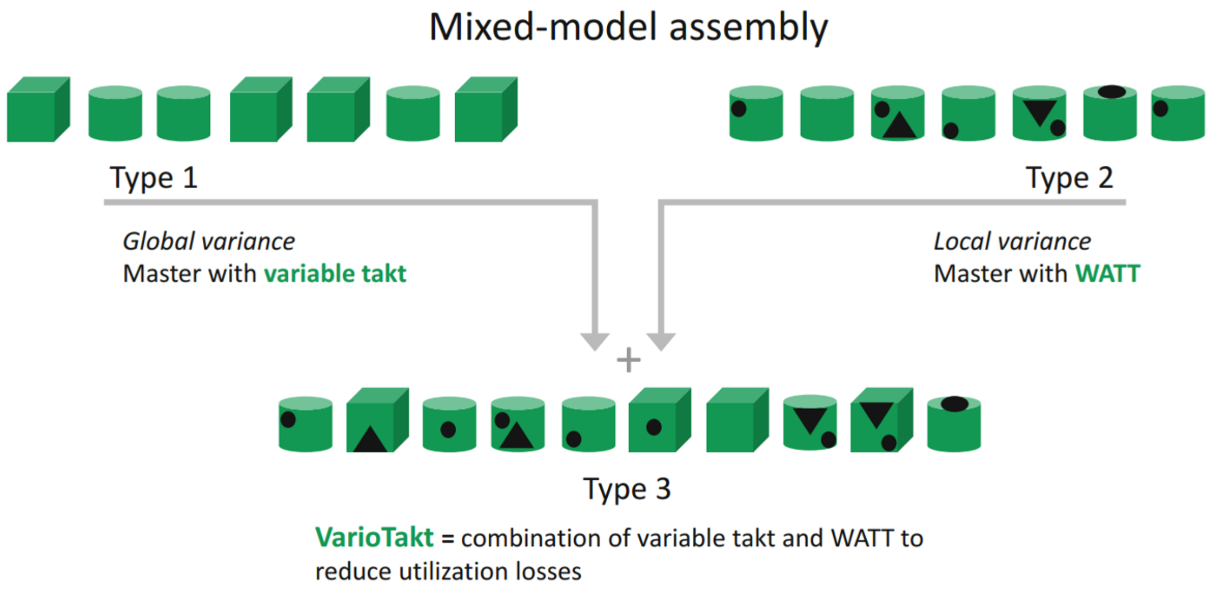


Figure 3-3, Takt-methods in a Mixed-model assembly (Bebersdorf & Huchzermeier, 2022)

The VarioTakt method was initially introduced by FENDT, a tractor manufacturing company. The company sought to incorporate a new model into their existing production line. However, the workload associated with this new model was incompatible with their current takt method. The introduction of the new tractor necessitated an extended assembly time at the workstations, creating a problem as it was integrated into the assembly line alongside tractors with considerably lower workloads. To address this issue, a new method was devised. This involved assigning a unique takt time to each tractor and augmenting the distances between them, thereby enhancing efficiency. The implementation of a variable inter-tractor distance ensured uniform workstation time for each tractor, thereby eliminating the introduction of output inefficiencies (Huchzermeier, Mönch, & Bebersdorf, 2020).

In the context of assembly line operations, when there is a discrepancy exceeding 50% in the cumulative assembly workload across products, it becomes increasingly impractical to address this issue solely through the application of variable takt. This is primarily due to the excessive enlargement of workers overlapping areas. Consequently, the implications of additional compensatory measures becomes indispensable (Bebersdorf & Huchzermeier, 2022).

SPZ currently implements the WATT principle. Every workstation receives the same takt time. With the use of mixing rules, the WATT at the workstations in maintained. If the losses caused by long trucks are recovered by shorter trucks, it would implicate that the takt time between trucks is no longer constant. In that case, SPZ would need to implement a different type of takt time, like for example the VarioTakt.

3.2.Solution Approaches

This section explores possible approaches that can be employed to address product variation challenges. It is divided into three sub-sections that examine specific approaches to these challenges, including mixed-model assembly line sequencing (3.2.1), variable launching interval (3.2.2) and VarioTakt with limited station length (3.2.3).

3.2.1. Mixed-model assembly line sequencing with variable launching interval

All stations within an MMAL are assumed to have boundaries that workers cannot cross, either a physical or an imaginary boundary. The tasks have deterministic allocated times and the conveyer belt is assumed to move at a constant speed. The interval of launching products onto the conveyer belt influences the efficiency of the system. Two main strategies can be distinguished: *Fixed rate launching* and *Variable rate launching*. Variable rate launching increases the flexibility of operating the line by dynamically adapting the launching interval to avert idle times and workloads. Figure 3-4 displays a graphical example of the model. In which different launching intervals are assigned to different products. (Parviz & Mohsen, 2008).

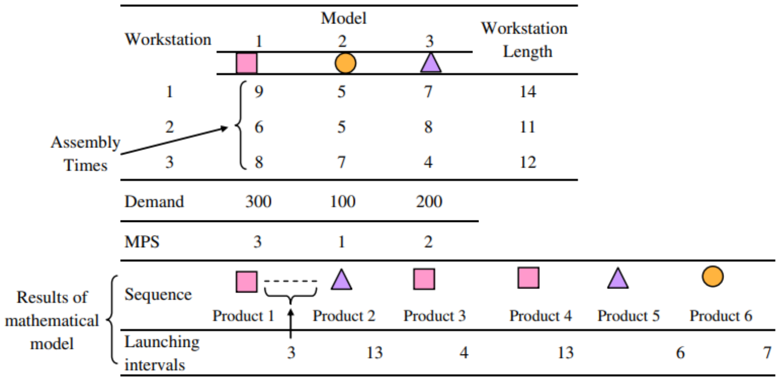


Figure 3-4, An example for the MMAL problem (Parviz & Mohsen, 2008)

The sequencing of products in an MMAL is a critical factor in achieving the efficient implementation of a just-in-time system. The sequencing problem aims to optimize two objectives: (1) balancing the workload across each station and (2) maintaining a consistent rate of utilization for every part employed by the production line (Moghaddam & Vahed, 2006). The above mentioned problem has the following formulation:

Sets:

I	$Product, i \in \{1,2, \dots I\}$
J	$Station, j \in \{1,2, \dots K\}$
M	$Model, m \in \{1,2, \dots M\}$

Input Parameters:

C_{Idl}	$Cost\ of\ idle\ (dollar/minute)$
C_U	$Cost\ of\ utility\ (dollar/minute)$
M	$Number\ of\ models$
d_m	$Minimum\ demand\ for\ model\ m$
L_j	$Length\ of\ station\ j$
K	$Number\ of\ stations$
t_{mj}	$Assembly\ time\ for\ model\ m\ at\ station\ j$
v_c	$Downstream\ speed\ of\ conveyer\ (feet/minute)$

Decision variables:

x_{im}	$1\ if\ product\ i\ in\ the\ sequence\ is\ model\ m, 0\ otherwise$
Z_{ij}	$Starting\ position\ of\ the\ work\ on\ product\ i\ in\ a\ sequence\ at\ station\ j\ (feet)$
ID_{ij}	$Idle\ time\ at\ station\ j\ for\ product\ i$
U_{ij}	$Utility\ worker\ time\ on\ product\ i\ at\ station\ j\ (minute)$
a_{i+1}	$Launching\ interval\ between\ products\ i\ and\ i+1\ in\ a\ sequence$

Model:

$$minimize \qquad \sum_{i=1}^{I}\sum_{j=1}^{K}\left(C_{Idl} \times ID_{ij} + C_U \times U_{ij}\right) \tag{1}$$

$$s.t.$$

$$\sum_{m=1}^{M} x_{im} = 1 \qquad for\ i = 1 \dots I \tag{2}$$

$$\sum_{m=1}^{I} x_{im} = d_m \qquad for\ m = M \tag{3}$$

$$Z_{1j+1} = \sum_{l=1}^{j} L_l \qquad for\ j = 1 \dots K-1 \tag{4}$$

$$Z_{i+1j} = Z_{ij} + v_c \times \left(\sum_{m=1}^{M} x_{im} \times t_{mj} - U_{ij} - a_{i+1} + ID_{i+1j}\right) \qquad for\ i = 1 \dots I-1,\ for\ j = 1 \dots K \tag{5}$$

$$U_{ij} \geq \frac{\left(Z_{ij} + v_c \sum_{m=1}^{M} x_{im} \times t_{mj} - \sum_{l=1}^{j} L_l\right)}{v_c} \qquad for\ i = 1 \dots I-1,\ for\ j = 1 \dots K \tag{6}$$

$$U_{Ij} \geq \frac{\left(Z_{Ij} + v_c \times \sum_{m=1}^{M} x_{Im} \times t_{mj} - \left(\sum_{l=1}^{j-1} L_l + v_c \times a_{I+1}\right)\right)}{v_c} \qquad for\ j = 1 \dots K \tag{7}$$

$$ID_{ij} \geq \frac{\left(\sum_{l=1}^{j-1} L_l - \left(z_{i-1j} + v_c \times \sum_{m=1}^{M} x_{i-1m} \times t_{mj} - v_c \times U_{i-1j} - v_c \times a_i\right)\right)}{v_c} \qquad for\ i = 2 \dots I-1,\ for\ j = 1 \dots K \tag{8}$$

$$x_{im} = \{0,1\}, \qquad for\ i = 1 \dots I,\ for\ m = 1 \dots M$$

$$U_{ij} \geq 0 \qquad for\ i = 1 \dots I,\ for\ j = 1 \dots K$$

$$ID_{ij} \geq 0 \qquad for\ i = 1 \dots I,\ for\ j = 1 \dots K$$

$$a_i > 0 \qquad for\ i = 1 \dots I$$

$$Z_{11} = 0$$

In the model above, seven constraint can be seen. These constraints have the following reasoning: Constraint (2) guarantees that each position in a sequence is assigned exactly one product. Constraint (3) ensures that each model's demand is met within a cycle. Constraint (4) mandates that the operation for the initial product of each cycle must commence at the leftmost boundary of the station. Constraint (5) stipulates the initial location of the worker at each station *j* for product *i+1* in a given sequence. Constraint (6) specifies the time required by an utility worker to complete product *i* at station *j* in a sequence, while constraint (7) indicates the time required by a utility worker to complete the end product *I* at this station in a sequence. The idle time caused by product *i* at station *j* is determined by constraint (8) (Parviz & Mohsen, 2008).

To use this model for this project, it is necessary to modify some of the assumptions made and incorporate the characteristics of the SPZ assembly line into the model. The following assumptions are made in the above mentioned model:

- Each station has boundaries that workers cannot cross.
- If a work-piece is not finished by the time it reaches the end of the station, an additional operator (utility worker) assists in completing the remaining work on the piece.
- The moving time of workers is not taken into account.
- The worker can only work on the work-piece when it is within the boundaries of the station.
- Products are sequenced with a common multiplier.
- Work always starts at the left boundary of the workstation.

The implementation of an MMAL with variable launching interval has several implications for SPZ. When putting this method into practice, one of the biggest obstacles is that the model concentrates on the variations in assembly times between models. Since line balancing has been carried out at SPZ, it is reasonable to assume that each product or vehicle needs the same amount of time at each workstation and, thus, the same working distance. The difficulty lies in changing the model so that the truck length, rather than the construction time, is the limiting factor. This will need to be fulfilled by substituting distance for time in the model. Nevertheless, time still needs to be considered because employees' walking distance between workstations is assessed in terms of time.

3.2.2. Production batching

Batch production is a methodological framework that has grown in relevance in manufacturing, where products are produced in distinct groups or batches. Traditional batch production can be classified into *multiproduct* and *multipurpose* . Every product in a multiproduct plant uses the same processing network. This indicates that there is only one method to create a certain product because every product needs the same set of processing tasks. Nevertheless, certain products may exclude some tasks from the sequence. The products manufactured in multipurpose plants are produced using various processing networks, and the same products may be produced in multiple ways. Generally speaking, a variety of products are manufactured at any one moment. As opposed to the multiproduct scenario, flow patterns are not linear, and certain units may be utilized to carry out non-consecutive operations for the same product (Rippin, 1993). The batch sizing and scheduling of multiple products in a single facility under deterministic conditions over an infinite planning horizon is know as the classical economic lot-scheduling problem (ELSP). It is assumed that customers receive product deliveries at continuous rates (Saglam & Banerjee, 2015). The main assumptions underlying the classical ELSP can be summarised as follows (Beck & Glock, 2018):

- Two or more products are produced on a single machine.
- Only one product can be produced by the machine at a time.
- The planning horizon is infinite.
- All parameters are deterministic, known and constant over time.
- Setup cost and setup time are independent of the production sequence.
- Shortages are not allowed.
- Inventory holding cost is directly proportional to the inventory level.

The fixed cycle time heuristic aims to gain a solution for the ELSP (Teunter, Tang, & Konstantinos, 2008). The heuristic determines the production schedule, by timing the production lots in a cycle. It uses a initial production sequence. The excess time that is initially concentrated at the end of the cycle, is redistributed among products preceding the last. Since the batching problem falls in the category of NP-hard problems, no known polynomial complexity solution techniques exist for this particular problem. The goal of most scheduling heuristics, is to test different rules for choosing sequences. As a result, they work best in processes that are variations of multiproduct processes, where the creation of a product entails a predetermined order of tasks with fixed batch sizes. It is important to note that applying heuristics to scheduling problems in the process industries is not a simple process. Since mathematical programming approaches for process scheduling and planning can capture all the intricate interconnections in such massive processing networks, this leads to high computational times (Kopanos & Puigjaner, 2019).

3.2.3. VarioTakt with limited station length

In the context of variable takt utilization, the concept of virtual station lengths emerges as a consequence of varying launch interval or distances, which are dependent on the takt time. Despite these variations, the physical boundaries of the stations should be maintained since the equipment and other facilities are based on these boundaries. The calculation of the target takt time, denoted as T_j, for product j, can be achieved through the application of the subsequent formula:

$$T_j = \frac{A_j}{W * E_{AL} * \left(1 - \left(e_{fa} + e_{pa}\right)\right)}$$

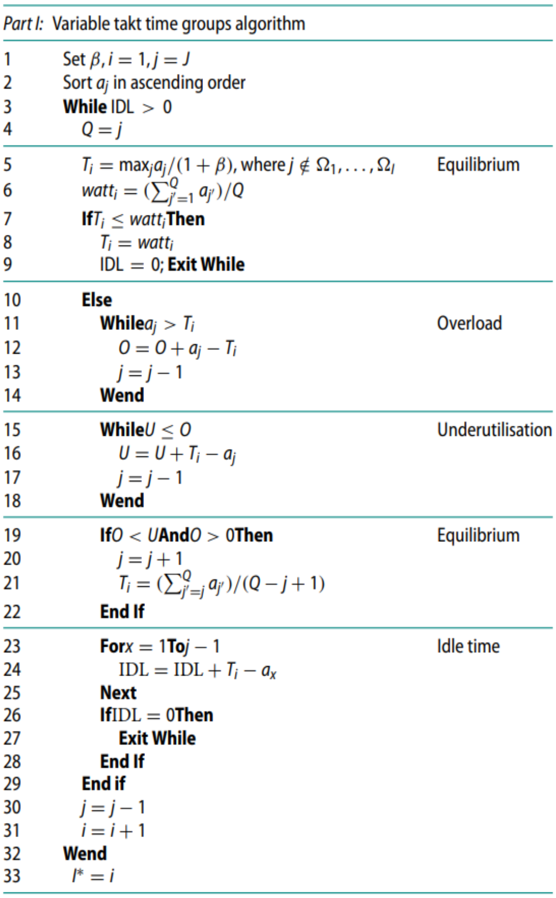
In this equation, A_j represents the total assembly workload of product j, while W denotes the total number of workers present on the assembly line. The variable E_{AL} represents the technical productivity of the assembly line. The terms e_{fa} and e_{pa} correspond to the efficiency of the workers that must be incorporated in the takt. These allowances are typically negotiated between the employee representative and the organization.

Upon determination of the takt time, it becomes possible to compute the launching distance between orders. This can be accomplished by using the following formula:

$$D_j = V_{CS} * T_j$$

Here, D_j symbolizes the distance to the next order j or launching distance of order j. The assembly line's speed is represented by V_{CS} (Bebersdorf & Huchzermeier, 2022).

The Variable Takt Time Groups Algorithm (VTGA) is a method designed to optimize assembly line efficiency by dynamically adjusting production schedules and task allocations. It is particularly suited for environments where the volume of tasks to be processed remains consistent or predictable within a given time frame. It is designed to minimize the number of different takt time settings and/or the maximum operator drift per unit. Operator drift describes the assembly times that exceed the takt time, and therefore reducing the operator idleness. The VTGA is divided into two sections, the first section starts with the product with the maximum assembly time and determines the number of Variable Takt Time Groups (VTGs) needed to eliminate idle time for a predefined operator drift. The second part determines the minimal operator drift that ensures zero idle time as a consequence of the first part. The algorithm uses a workload equilibrium condition whereby overload is equal to underutilisation. Overload is defined as the proportion of assembly time that exceeds the WATT, and underutilisation is the proportion of assembly time needed to achieve a workload equilibrium with the existing overload.



```
Part I: Variable takt time groups algorithm
Set $\beta, i = 1, j = J$
Sort $a_j$ in ascending order
While IDL $> 0$
  $Q = j$
  $T_i = \max_j a_j/(1+\beta)$, where $j \notin \Omega_1, \ldots, \Omega_I$          Equilibrium
  $watt_i = (\sum_{j'=1}^{Q} a_{j'})/Q$
  If $T_i \leq watt_i$ Then
    $T_i = watt_i$
    IDL $= 0$; Exit While
  Else
    While $a_j > T_i$                                                              Overload
      $O = O + a_j - T_i$
      $j = j - 1$
    Wend
    While $U \leq O$                                                               Underutilisation
      $U = U + T_i - a_j$
      $j = j - 1$
    Wend
    If $O < U$ And $O > 0$ Then                                                    Equilibrium
      $j = j + 1$
      $T_i = (\sum_{j'=j}^{Q} a_{j'})/(Q - j + 1)$
    End If
    For $x = 1$ To $j - 1$                                                         Idle time
      $\mathrm{IDL} = \mathrm{IDL} + T_i - a_x$
    Next
    If $\mathrm{IDL} = 0$ Then
      Exit While
    End If
  End if
  $j = j - 1$
  $i = i + 1$
Wend
$I^* = i$
```

Figure 3-5, part 1 of VTGA, (Mönch, Huchzermeier, & Bebersdorf, 2022)

In the first part of the VTGA, the number of VTGs is determined by iterating over each product for each new VTG until the WATT of unallocated unique customer configurations (UCCs) exceeds the takt time defined by the maximum assembly time and the operator drift (Mönch, Huchzermeier, & Bebersdorf, 2022)

The second part of the algorithm determines the minimal operator drift. The operator drift (β) is incrementally reduced as long as there is no operator idleness. The work content average and idle time are calculated based on the concepts of the first part of the VTGA. The process continues iteratively, adjusting the parameters to minimize idle time and ensure efficient operation (Mönch, Huchzermeier, & Bebersdorf, 2019)

3.3. Conclusion

This chapter addresses the research question: *"What methods described in literature address the challenges of product variation and inefficiencies on a continuous assembly line, with a focus on mitigating the impact of long trucks on the Pollux-2 line? "*.

Numerous techniques in the literature address issues with product variation and inefficiencies in the context of continuous assembly line optimization. The MMAL offers a thorough framework to handle workload balancing and part utilization. It is commonly employed for balancing assembly line sequences and variable launching intervals. However, when used for the Pollux-2 line, with its constant takt time, the key is to adjust the model to include truck length as a limiting variable.

With its focus on modifying takt times, VarioTakt shows promise as a solution for handling varying assembly workloads. VarioTakt's VTGA provides a methodical way to reduce operator idle time and maximize workload balance. However, in order to minimize the effect of long trucks on the Pollux-2 assembly line, the method must be adjusted for its implementation on the Pollux-2 line.

While literature offers general principles, a hybrid strategy is necessary to meet the distinctive challenges presented by long trucks on the Pollux-2 line. Combining VarioTakt's dynamic takt time modifications with the sequencing optimization techniques of MMAL and the batching heuristic may provide a more sophisticated solution. This hybrid model could potentially be able to optimize efficiency without jeopardizing the assembly line's continuous flow by balancing launching intervals and accounting for truck length restrictions.

In summary, while current approaches provide valuable information about how to deal with issues related to product variation and inefficiencies on continuous assembly lines, MMAL, batching and VarioTakt principles could possibly be combined and adapted to potentially lessen the negative effects of long trucks on the Pollux-2 line. This new approach seeks to achieve a careful balance between maximizing assembly line operator productivity, accommodating different truck lengths, and optimizing assembly sequences.

4. Model outline

In this chapter, we introduce a strategy to reduce the impact of long trucks on the Pollux-2 assembly line. Section 4.1 gives an introduction to the concept, describing the differences compared to the current working method. In Section 4.2 we present a mathematical model that formulates the bundling concept. Section 4.3 gives an overview of the heuristic created to facilitate the bundling concept and Section 4.4 summarizes the chapter and provides a conclusion.

4.1. Model Outline

Below, 4.1.1 explains the idea of the strategy we aim to introduce. 4.1.2 shows the motivation for the proposed strategy, while 4.1.3 displays the restrictions to the model. Lastly, 4.1.4 present the expectations of the strategy.

4.1.1. Truck bundling

At SPZ, a simplified version of the concept of truck bundling has been proposed, which is referred to as ‘3-takt 36m’ (Oolman, 2023). This concept involves a bundle or batch of three trucks, one of which is long and the other two are short. A bundle represent a sequence of trucks that are produced after each other on the assembly line. The aim of this concept is to introduce a new method of using takt time at SPZ. Instead of assigning a takt time for each truck, a new takt time is created for three trucks. After the takt, all three trucks are expected to be completed at their respective workstations and move to the next.

Regaining the additional planned distance for long trucks is essential to reduce the negative effects of long trucks on the assembly line. Since it is not possible to recover these distances by using long trucks, the proposed strategy requires to employ trucks shorter than 12000mm in length in order to compensate for these losses. Bundles with a long truck and several short trucks should be made in order to support this idea. In order to compensate the losses incurred by long trucks, short trucks in the bundle are launched earlier, and therefore receive less production distance on the assembly line. By introducing this concept, short trucks will receive less space on the assembly line, and therefore make up for the extra length of a long truck. However, this does not imply that a shorter truck gets less time at a workstation, even though its planned production distance is shorter. This is facilitated by introducing flexible workstation lengths, by shifting the start and end point of a station within a bundle between trucks, a constant takt time can be maintained.

This concept can be facilitated by the fact that a long truck will claim additional distance on the assembly line, caused by the physical length of the truck, even though this extra distance is not necessary to achieve the takt time for the long truck. Longer trucks do not necessary need extra assembly time, compared to a short truck. The main difference between short and long trucks, is the additional length of the frame, which does not add extra assembly time on the Pollux-2 line. Currently, with the arrival of a long truck at a workstation, assembly of parts occurs throughout the allocated takt time, resulting in the completion of all required activities at the end of the takt. When a new takt time starts, the long truck is still present at the current workstation and therefore results in a delay of the next truck. This results in idling of the workstation for the duration of the additional length of the long truck. The portion of the truck that is longer than the workstation length, and thus exceeding the takt time, are included in the assembly distance of the shorter trucks within the bundle. This implies that workstations may commence operations on a truck that is either not located at the workstation or that was already present at the workstation. The scenario as it exists now (A) and the potential results of the bundling concept (B) are illustrated in Figure 4-1. The green sections in the diagram indicate the shift of a truck's start position. In order to facilitate the bundling concept, and realizing the shift of start positions of trucks within a bundle, tooling at the workstations will require additional reachability. After analysing the tooling present at the workstations, the liquid fill station at workstation 24 was observed as the bottleneck with regards to tooling reachability. It is determined that the maximum additional reachability of tooling is limited to 1000mm, thus the maximum shift of a truck within a bundle, compared to the original starting position is limited to 1000mm.

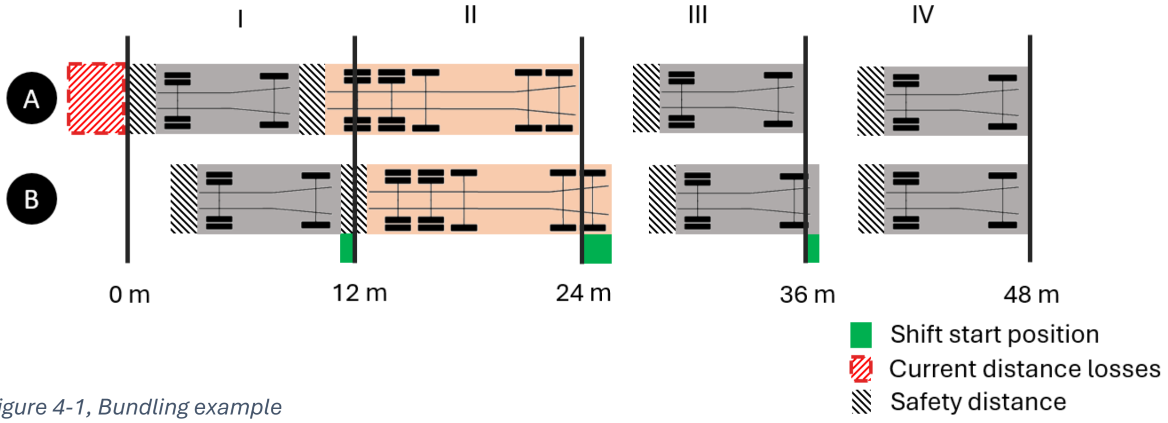


Figure 4-1, Bundling example

4.1.2. Bundle motivation

The bundle concept, as compared to alternative approaches such as the variable launching strategy discussed in Section 3.2.1, provides stability to the takt time for every truck on the assembly line. Unlike other strategies, the bundle concept does not require continuous readjustment of workload distribution among workstations. By giving every truck on the assembly line a constant takt time, the bundle strategy is expected to not introduce new line stoppages to the Pollux-2 assembly line. The bundle compensates for the additional length of a long truck by distributing it evenly among the shorter trucks within the bundle. This has the added benefit of ensuring that the start position and end position of a bundle will not shift compared to the planned position in the planning, even though the actual start position of a truck will shift within a bundle. After all trucks within a bundle have passed a workstation, the start position of the next bundle is the same as the original planned start position, providing material supply an accurate guideline for when to start delivering materials to the workstations. To limit the size of a bundle, and reduce the complexity of the optimization model, a maximum of one long truck can be available within a single bundle. If bundles would consist of multiple long trucks, more short trucks would be needed in a bundle to compensate the excess length and therefore decrease the flexibility in creating bundles. A bundle can therefore be described as a combination of a single long truck, paired with one or multiple short trucks. In essence, truck bundling is a variant on batch production. Multiple trucks are combined in a 'batch' that should be produced after each other. The difference is in the way bundles should be created. As discussed in Section 3.2.2, batch production focusses on minimizing stock and setup costs. These costs are not essential for the bundling concept, since no stock or buffers are created between workstations, and no setup changes are required to facilitate the bundling concept. However, by removing these objectives from the batch production heuristic and adding length discrepancies, a model can be designed that facilitates the bundling concept.

4.1.3. Model Restrictions

To create a bundle, a model should be created that assigns trucks to a bundle. The bundling process brings certain limitations, below four limitations to the creation of a bundle are discussed. The first two restrictions are due to SPZ's current way of working, while the last two constraints simplify the model for computational ease.

Minimum average distance. The concept of truck modelling is to match shorter trucks to a long truck to reduce the impact of the current length discrepancies of long trucks. Currently, if a truck has a total length shorter than the workstation length of 12000mm, it is still assigned a slot on the assembly line with a length of 12000mm. This is due to trucks moving with a constant speed on the assembly line, and therefore distance can be translated to time. Since every truck should be assembled within the takt time, it should receive the distance necessary to meet the takt. If a truck is given less distance on the assembly line, it would imply that it would receive less time. This would introduce new line stoppages to the process, which is not desired. Therefore, the distance reserved for a bundle on the assembly line for a bundle should be a multiple of 12000mm or more. This means that the length of the bundle, divided by the number of trucks in the bundle should always be larger or equal to 12000mm.

Maximum tooling reachability. Since tooling at SPZ on the Pollux-2 line have a limited reachability, the total shift of trucks within a bundle should be limited. After analysing the tooling present at the Pollux-2 line, we came to the conclusion that a maximum of 1000mm excess reachability, either forwards or backwards on the workstations is feasible. Therefore, the model should be limited to shifting trucks within a bundle to a maximum of 1000mm.

Sequential integrity. The idea of truck bundling is to match a number of short truck to a single long truck. Since customization is important for Scania and their customers, almost every truck assembled at SPZ is unique. This brings challenges to the assembly process, for which SPZ has applied mixing rules to mitigate these challenges, as discussed in Section 2.3.1. These mixing rules dictate the order of trucks in the production planning, to reduce the impact of the difference in workload among different trucks. In order to ensure that these rules are still applied, they should be taken into account when creating bundles. In order to reduce the complexity introduced to the production sequence of trucks, the creation of bundles is limited to the current production plan. It will not be allowed to swap or move the positions of trucks within the production planning, and the plan created before production cannot be altered.

One-to-one compensation. Lastly, it will not be possible to use the same truck in two different bundles. By limiting the use of a truck to a single bundle, no overlap or complexity is introduced. Furthermore, as discussed in Section 4.1.2, reset of the actual production position is possible, which helps material supply in aligning their delivery plan to the production plan.

The length of a long truck + safety distance lies in between the interval 12000mm and 13865mm. This suggests that a bundle can compensate up to 2000mm when the limitations above are taken into account. Scania uses a categorization for long trucks, that can be retraced to their carrier system setup. In order to incorporate this method, categorizations should be provided to the model. At SPZ, a discrete measuring technique utilizing light sensors is employed for long trucks. These sensors are placed at the final station where the 'stop&go' system is implemented, determining the launching interval of trucks on the continuous assembly line. The discrete measurement technique is vital at SPZ to validate the actual length of a truck in comparison to its theoretical length. Figure 4-2 illustrates the intervals between sensors, with sensor E placed at the 12000mm mark. Trucks are temporary in a stationary state, at the station where they are classified, where the front of the truck is positioned on a fixed place. Sensors check whether they detect a truck during this phase, if so, the system knows the categorization in which the truck should be launched on the second part of the assembly line. When a truck is for example only detected by sensor E, it is classified as longer than 12000mm and shorter than 12300mm. The truck is therefore assigned to the category 12300mm. The carrier on the continuously driven part of the assembly line accommodates a maximum of 10 different length settings, representing distinct truck length categories. This characteristic, inherent to the current system at SPZ, is a fixed limitation and cannot be modified.

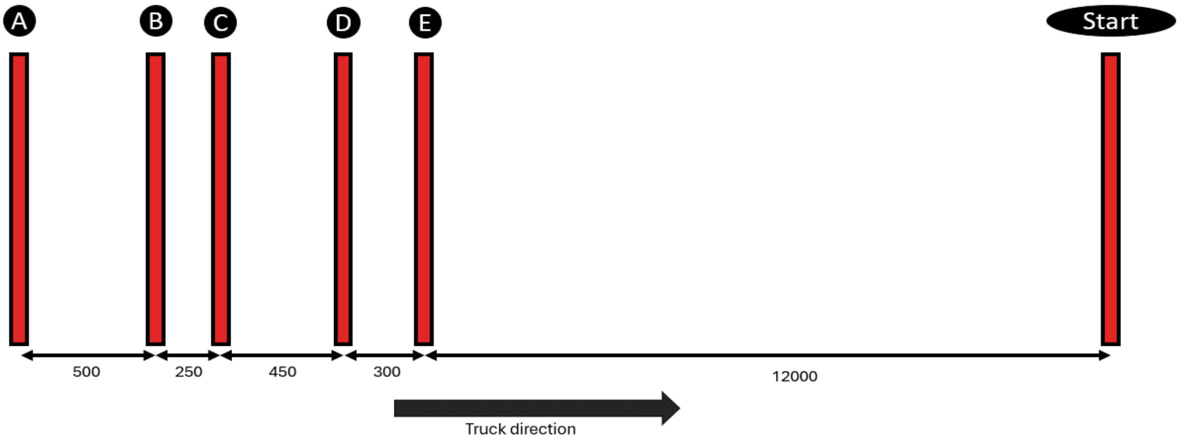


Figure 4-2, sensor interval Pollux

Despite its advantages, the discrete measurement technique incurs losses. When a truck is detected by sensors, it is automatically assigned a length equivalent to the first sensor that does not detect a truck. For example, if a truck + neutral zone is 12001mm long and thus detected by sensor E, it is assigned the length of sensor D, equal to 12300mm. This results in additional losses of 299mm. These losses have been addressed in a prior study on the positioning of light sensors and are therefore out of scope (Visser, 2022).

These categories could be used to classify the number of short trucks used in a bundle. If the bundle sizes are based on the category of long truck present in the bundle, distinctions can be made between different bundles.

4.1.4. Expectations and conclusion

With the bundle concept, we anticipate a reduction in the length discrepancy losses currently encountered. By dividing the excess length among potentially multiple shorter trucks, we expect that these losses will be mitigated. However, we also expect that the creation of bundles have some limitations. The primary consequence of the bundle strategy is the shift of the actual start position of a truck. This shift will cause the position of the front of the truck to move forward or backward relative to the front of the workstation. To enable the assembly of parts at the front of the truck, tooling will require additional reachability to facilitate this shift. The more a truck is shifted within a bundle, the more the additional reachability the tooling will need, which can become a limitation due to the maximum allowed shift of 1000mm at SPZ.

Another expectation is that when multiple long trucks are planned relatively close to each other, there may not be sufficient short trucks to recover the excess length. This could result in a not full recovery of the additional length of long trucks. However, since the planning and sequencing of trucks is outside the scope of this model, it should not be taken into account.

4.2. Mathematical model

In this section, we present the mathematical model designed to reduce the effects of long trucks by combining different truck lengths into a bundle. By bundling trucks of varying lengths into cohesive bundles, long truck losses can be reduced. The fixed takt time incorporated at SPZ can be maintained with this concept. SPZ wishes to maintain a fixed takt time to keep a smooth flow of production, which reduces disruptions and buffers. Further more, workers work in a rhythm, which increases productivity and reduces the change of human error. This is enabled through reducing the physical line reservation for short trucks in a bundle, and using this reduction to accommodate the excess length of the long trucks. This however does not imply that short trucks will receive less assembly time due to their shorter line reservation. Trucks move with a constant speed through the assembly line, and have a takt time in which all tasks should be performed at the workstations. On the Pollux-2 line, the takt time equals 720 seconds. With a workstation length of 12000mm, this can be translated to a line speed of 12000/720 = 16.67 mm/s. If a truck is assigned a line reservation of 11000mm, this would result in a takt time of 11000/16.67 = 660 seconds. This suggests that there is a discrepancy of 60 seconds between the required takt time and the received time at the workstation, which is not allowed. The concept of truck bundling eliminates this discrepancy by allowing a subsequent truck to be present at the same workstation, without work being performed on it. Below, an example is given to clarify this concept.

Four trucks are assigned into a bundle, with corresponding lengths 11000-11000-14000-11000. SPZ currently launches the trucks as followed: 12000-12000-14000-12000, resulting in losses of 2000mm since each truck only requires 12000mm worth of line reservation. The idea of truck bundling is to split the excess length of the long truck among the shorter trucks in the bundle. This could for example give the following launching interval: 11500-11500-14000-11000 which results in 0mm losses. Each truck in the bundle still requires 720 seconds of time, thus 12000mm worth of time reserved for the truck at the workstation. The given example suggests that the first two trucks receive only 11500mm worth of time, equal to 690 seconds, and the last truck 660 seconds. However, this is not the case. Truck launching distances may be shorter, but the actual start moment at the workstations, where workers can start work, remain the same. Figure 4-3 shows this idea.

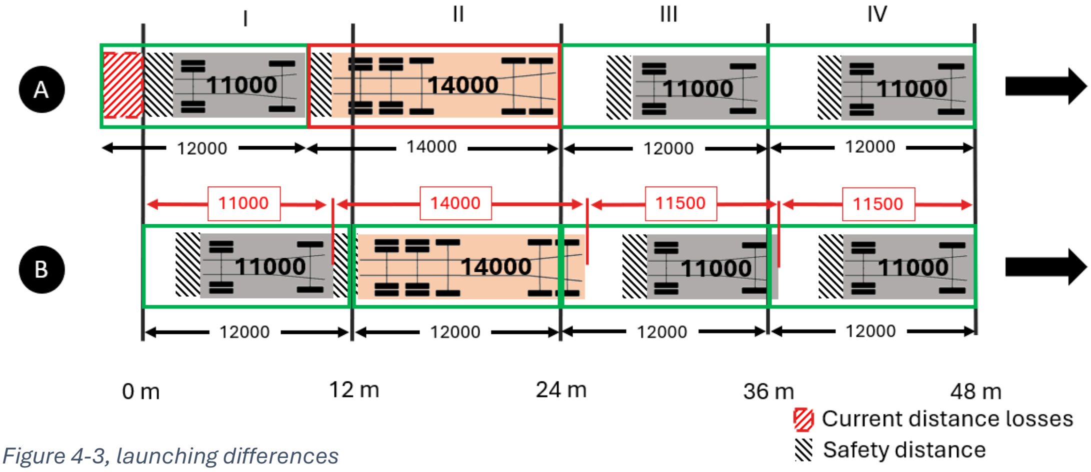


Figure 4-3, launching differences

The red section in situation A shows the issue SPZ faces, the truck with length 14000mm delays the subsequent truck. Situation B shows a possible outcome of the bundle concept. Trucks shorter than 12000mm are given less space on the line, therefore allowing the recovery of the excess length of the long truck. The green boxes show the working time in which workers are allowed to work on the truck. It can be seen that trucks can be outside of the green box, while work still needs to be performed on the truck. If we zoom in to the truck with a length of 14000mm we can see that the front part of the truck has already left the station before workers are finished with the previous truck. By introducing flexible workstations, work can be performed on the truck outside of the stations boundaries. This idea makes it possible for workers to go outside of their workstation, to work on the front side of the truck that has already left the station.

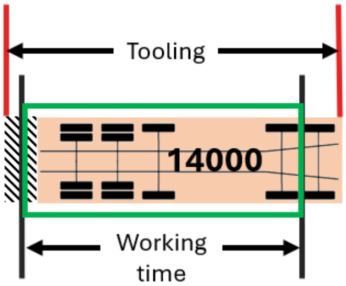


Figure 4-4, Tooling reachability

However, a limitation arises here, the reachability of the tooling at the assembly line. By introducing flexible workstations, tooling at the workstations will require to be useable in the flexible workstations part. Figure 4-4 gives a graphical representation of the tooling reachability required. Figure 4-3 also shows that when two trucks before the long truck are used to compensate a long truck, their additional tooling reachability is summed. This means that if both trucks are assigned 11500mm, the first truck requires 0 excess reachability, the second truck 500mm and the third truck 1000mm. Here, a limitation of the assembly line at SPZ arises. The additional reachability of tooling can only be increased to a maximum of 1000mm. This is due to physical constraints on the assembly line. This limitations means that for example, two consecutive trucks with an assigned length of 11000mm is not feasible since this leads to additional tooling reachability of 2000mm. However, it is possible to assigns both trucks a length of 11500mm or only one truck 11000mm. If in Figure 4-3 the trucks in station III and IV are given a reservation of 11000mm, instead of 11500mm, the tooling reachability for the long truck will increase. The start position of the long truck will shift forward by an additional 1000mm, resulting in additional tooling reachability of 2000mm. Since SPZ can only facilitate a shift of 1000mm, this will not be feasible.

With this information provided, we can formulate the mathematical model. The model uses three sets, the first being the trucks themselves $(i = 1 \dots I)$. Secondly, a set with bundles is introduced $(k = 1 \dots K)$. Lastly, a set with the different possible length classification is introduced $(n = 1 \dots N)$.

Next, four input parameters are introduced. L_i represents the length of truck i. Next, Δ denotes the maximum tooling reachability at SPZ as discussed above. M indicates the maximum allowed number of trucks in a bundle and lastly, d_n corresponds to the length associated with each truck length class n in set N.

The model uses two sets of decision variables. The first one, x_{in}, represents the length classification n given to truck $i = 1 \dots I$. If for example a truck has a length of 11000mm, it can be assigned a length class of 11000mm; however it can also be possible that it is assigned a longer class, if for example, not all 1000mm is needed for recovery or if the maximum allowable tooling range is reached and therefore making it not possible to fully utilize all the available compensation length. n_k represents the number of trucks present in bundle $k = 1 \dots I$.

The model also uses auxiliary variables, to assist in the calculation process. g_k represents the total assigned distances of all trucks in bundle k on the assembly line. N_k facilitates tracking the progression of truck allocation across bundles. It ensures that the allocation process proceeds without exceeding the total number of available trucks. As input, we have a set of I trucks, sequenced in a predetermined order. Furthermore, we have N truck length classes $d_1 \dots d_N$, where d_1 represents the shortest class and d_N the longest.

By incorporating these sets, parameters, decision variables, and auxiliary variables into our model, we get the model formulated on the following page. It should be noted that the model is not MILP formulated, caused by constraint (2), (4) and (5).

Sets:

$I = Set\ of\ trucks\ in\ a\ fixed\ order$

$K = Set\ of\ bundles$

$N = Set\ of\ truck\ length\ classifications$

Parameters:

$L_i = Length\ of\ truck\ i = 1 \dots I,\ with\ L_i \in \{d_1, \dots, d_N\}$

$\Delta = Maximum\ shift\ of\ a\ truck\ in\ a\ bundle\ allowed$

$M = Maximum\ number\ of\ trucks\ in\ a\ bundle$

$d_n = Length\ corresponding\ to\ truck\ length\ class\ n$

Decision Variables:

$$x_{in} = \begin{cases} 1, & if\ truck\ i\ is\ given\ length\ class\ d_n \\ 0, & else \end{cases}$$

$n_k = number\ of\ trucks\ in\ bundle\ k = 1 \dots K$

Auxiliary Variables:

$g_k = Length\ of\ bundle\ k$

$N_k = Total\ number\ of\ trucks\ placed\ in\ a\ bundle\ up\ to\ and\ including\ bundle\ k$

Objective function and Constraints

$$\min \sum_{k \in K} g_k \qquad (1)$$

s.t.

$$g_k \geq \sum_{i=N_{k-1}+1}^{N_k} \sum_{n \in N | d_n \geq L_i} x_{in} d_n, \qquad k = 1 \dots I \qquad (2)$$

$$g_k \geq 12000 * n_k, \qquad k = 1 \dots I \qquad (3)$$

$$\sum_{n \in N | d_n \geq L_i} x_{in} = 1, \qquad i = 1 \dots I \qquad (4)$$

$$12h - \Delta \leq \sum_{i=N_{k-1}+1}^{N_{k-1}+h} \sum_{n \in N | d_n \geq L_i} x_{in} d_n\,, \qquad k = 1 \dots I;\ \ h = 1 \dots n_k - 1 \qquad (5)$$

$$n_k \leq M, \qquad k = 1 \dots I \qquad (6)$$

$$N_k = \sum_{j=1}^{k} n_j, \qquad k = 1 \dots I \qquad (7)$$

$$x_{in} \in \{0,1\}, \qquad \forall i, n \qquad (8)$$

$$n_k \in \mathbb{N}_0, \qquad \forall k \qquad (9)$$

The presented model aims to minimize the aggregate production length required for the assembly of all truck bundles, achieved by minimizing the sum of lengths across all bundles (1). The set with bundles initially contain empty bundles, which are to be filled by the model with trucks. The total number of bundles is equal to the number of trucks in set I. Constraint (2) ensures that the length of bundle k corresponds to the summation of all trucks allocated to bundle k with assigned category n, multiplied by the length of the respective category. Constraint (3) imposes a requirement that each bundle's length must be a multiple of 12000mm or greater, thus guaranteeing that the average distance traversed by a truck within a bundle remains at or above 12000mm, thereby upholding the takt time at SPZ. Constraint (4) is employed to confine each truck to a single category. Constraint (5) restricts the total shift of any truck within a bundle to Δ. Constraint (6) limits the maximum permissible number of trucks within a bundle to M, while constraint (7) ensures that the total count of trucks placed in a bundle up to bundle k is accurately tracked, supporting the summation requirements of Constraints (2), (5), and (6). Constraints (8) and (9) represent the integrality constraints, maintaining the decision variables within integer bounds.

The model described above poses significant computational challenges due to its non-linearity, caused by constraint (5) in which a binary decision variable is multiplied with a parameter d_n, summing over the bundle size, which is also a decision variable. Furthermore, the model contains integer and binary decision variables. The presence of variable N_k, which imposes limitations on the summations of certain constraints, adds further complexity to the problem. Recognizing these challenges, we have devised a heuristic approach outlined in Section 4.3 that implements the model presented above.

4.3. Heuristic

The goal of the heuristic is to assign trucks to bundles to reduce the losses caused by length discrepancies with long trucks. The output of the heuristic is a set of bundles, which minimize the length losses. Input to the heuristic is a dataset, which is further explained in section 5.1, containing a sequence of trucks and limitations to the number of trucks used in a bundle and the intervals for categorizing short trucks. The heuristic starts by first testing the base performance of the sequence of trucks without implementing the bundling concept. This performance is stored in the dataset to be used in a later stage to determine the performance of the experiment settings tested. In order to gain insight into the base performance of the dataset, the start position of the last truck in the dataset should be calculated. By iterating through the dataset, and adding the additional length of a truck exceeding 12000mm to the start position of the next truck, the original start position of the last truck, and thus the total losses can be determined.

The next step of the heuristic is the creation of the bundles. The input to the heuristic is the length of the trucks and the sequence in which they are planned. Experiments are performed that test different number of short trucks that should be used to compensate each truck length category. With these parameters, bundles can be filled. The heuristic iterates through the production sequence, until it comes across a truck with a length exceeding 12000mm. It compares the length of the truck to the different categories which then dictates how many short trucks should be present in the bundle combined with the long truck. Next, the number of short trucks in the bundle is divided into two. The goal is to have the long truck in the centre of the bundle. This is to reduce the shift of the actual start position of the trucks, half of the short trucks, which are located in front of the long truck, will have a forwardly shifted start position, while the other half have a backwards shifted start position. The reasoning for this concept is to reduce the tooling reachability required to facilitate this shift. The heuristic will now check the short trucks before and after the long truck for two criteria; A: is the short truck already used for a different long truck, and B: is the short truck short enough to be used as a compensating truck. If a short truck, which is within the bounds of the bundle size for the long truck, meets these criteria, it is added to the bundle. After the creation of the bundles, the distance to be recovered should be divided among the short trucks in the bundle. In order to limit the additional reachability of tooling required to overcome the shift of start positions, the distance to be recovered is divided evenly among the short trucks in a bundle. This means that for example, when a distance of 1500mm should be recovered among three trucks, each truck should recover 500mm. If a short truck is not able to recover the full distance amount, the excess is divided among the other short trucks. The new planned distance of a truck is assigned to each truck, together with the new start position of a truck relative to the previous truck.

The last step of the heuristic is to calculate the new start position of the last truck in the sequence. By comparing the new planned production distance of each truck to the workstation length and adding the differences together, the total losses can be calculated and compared to the performance of the dataset if no truck bundling would be applied. This knowledge is stored and the next setting solution can be tested. Figure 4-5 shows the flow of the heuristic.

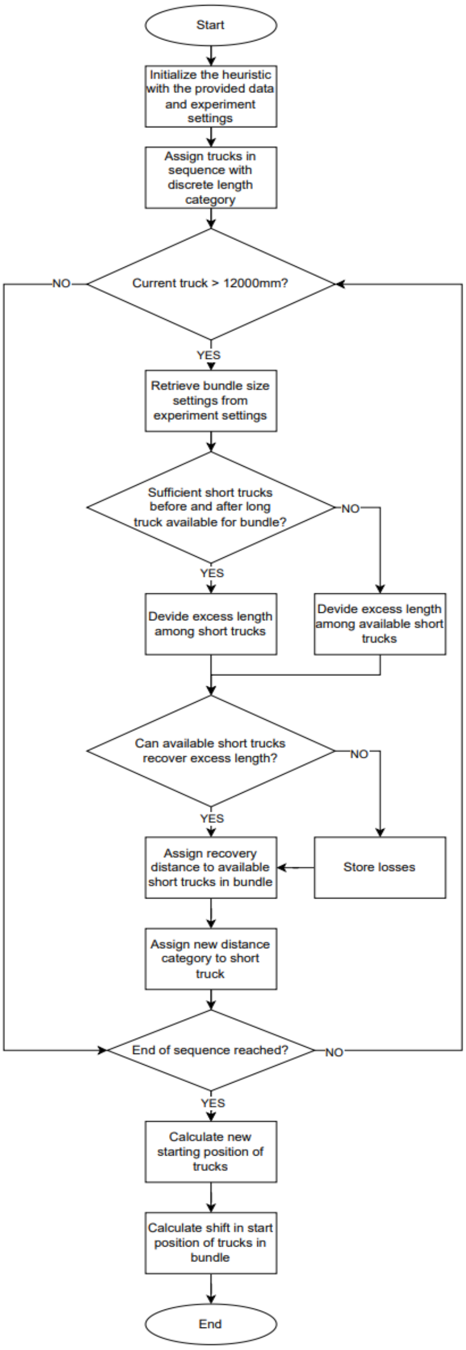


Figure 4-5, Model flowchart

4.4. Conclusion

This chapter has provided a framework for reducing the effect of long trucks on the Pollux-2 assembly line. By introducing the bundling strategy, length discrepancies of long trucks can be mitigated by assigning the additional length to short trucks. By bundling trucks together and distinguishing the number of trucks in a bundle between different truck length categories, it is expected that the losses currently faced will be reduced. Furthermore, the benefits of bundles is that the start and end of a bundle give material supply a clear signal and alignment on when to deliver parts to the workstations.

Furthermore, a framework is presented on how to bundle trucks, what choices need to be made and how these choices should be made. The heuristic describes how the model should assign trucks to bundles, and what performance should be measured. The expected limitations of the concept are also discussed.

Chapter 5 delves into the experimental design of the bundle concept, together with the results. With the help of these results, insights are created in the performance of the concept stated in this section, combined with the performance and benefits of the bundle concept.

5. Experiments / results

This chapter discusses the experimental design to test the performance of the heuristic, as well as the experiments performed and the corresponding results. First, experiments based on bundle sizes and measurement techniques are discussed in Section 5.1, after which a selection of these experiments are highlighted and discussed in Section 5.2 and followed by a conclusion in Section 5.3.

5.1. Experimental design

In order to gain insight into the performance of the heuristic discussed in chapter 4, we designed experiments with regards to bundle sizes and measurement techniques. To test different settings, a representative dataset has been selected containing all trucks assembled in the year 2022. In total, the dataset contained 8198 trucks, of which 1659 had a length exceeding 12000mm. First, experiments regarding bundle sizes are discussed in 5.1.1 after which different measurement techniques are tested in combination with multiple bundle sizes in 5.1.2. The sensitivity analysis on the placement of sensors for short trucks is discussed in 5.1.3 and a summary is provided in 5.1.4.

5.1.1. Bundle sizes

The bundling concept is based on the assignment of short trucks to a bundle containing a long truck to overcome length losses. The heuristic requires a limitation to the number of short trucks in a bundle as input. In order to determine these settings, experiments need to be designed. Currently, SPZ categorizes long trucks using a discrete measuring method. Long trucks are categorized into five categories, the intervals of these categories can be seen in Figure 4-2. This categorization is required for the carrier system SPZ uses, as discussed in 2.1.5.

The heuristic requires input with regards to the number of short trucks used to compensate a long truck. Long trucks are categorized in 5 different length categories by SPZ. Each long truck category should be provided with a number of short trucks to compensate the truck. This leaves five different bundle size settings. The experiments dictate upper and lower bounds of the number of short trucks in a bundle for each long truck category. Firstly, initial upper and lower bounds are selected, which are then tested on the dataset. With the use of these results, a narrower selection of upper and lower bounds for all experiments can be selected. In order to determine the initial bounds, a simple calculation can be made. On average, over the past 5 years, 21.7% of all trucks produced on the Pollux-2 line had a length exceeding 12000mm. This suggests that if all short trucks were used to compensate long trucks, every bundle would consists of one long truck and 3.915 short trucks. If we see this number as the average number of short trucks used to compensate a long truck, an interval can be created between 1 and (3.915-1) + 3.915 = 6.83 short trucks. Therefore, the initial bounds for all categories are determined to be 1-7 short trucks to compensate a long truck.

After running the heuristic with these initial settings , more detailed intervals are obtained regarding the minimum and maximum number of short trucks available in a bundle. The final upper and lower bounds are based on the experiments that performed the best, thus showing the best reduction of the losses caused by long trucks. After performing these experiments, and analysing the outcome, we found an interval for the number of short trucks in different bundle categories. These intervals can be found in Table 5-A.

Table 5-A, Bound settings bundle sizes

	UPPER BOUND	LOWER BOUND
A	6	2
B	3	1
C	3	1
D	3	1
E	2	1

The results of the experiments discussed above lead to the following conclusion. It is necessary to distinguish between different categories of trucks. Trucks of category B, C, D and E require fewer compensating trucks, while trucks of category A require more. These categories are based on Figure 4-2. The distinction between different truck lengths and their corresponding bundle sizes is made to improve the computational performance of the heuristic.

5.1.2. Length measurement

In order to make it possible to assign short trucks to a bundle, insights should be created into the actual length of these shorter trucks. Currently, the actual length of trucks shorter than 12000mm is not measured by SPZ. If a truck is shorter than 12000mm it is currently assigned a production distance of 12000mm. However, if short trucks are used to compensate a long truck, the actual length of these short trucks are necessary to know. To obtain these lengths, two possible length measurement techniques are tested, continuous and discrete measurement. As discussed in Section 2.1.5, SPZ currently uses a discrete measuring technique for long trucks, due to limitations of the carrier system used to transport the trucks through the second part of the assembly line. However, this discrete setup brings additional losses, and therefore within this study, the possibility of a continuous measurement system will also be taken into account. With the current setup at SPZ, the continuous measurement method is not feasible, however, it will provide insight into the performance of the discrete measurement method. The main differences between the two methods with regards to the mathematical model are the following:

Discrete

The discrete measuring method categorizes each truck based on length intervals. Trucks falling within a specific category are assigned the upper bound of that interval. This introduces losses, since the difference between the actual length and the upper bound of the interval is not used to compensate a long truck. For example, if a truck has a length of 11643mm and therefore falls in category X (11500 < Truck < 11750), it is assigned a production length of 11750. This means that it can recover up to 12000 – 11750 = 250mm. If the corresponding long truck requires compensation of 2000mm, the short truck can only compensate 250mm, resulting in 1750mm of unrecovered production distance losses.

Continuous

The continuous measuring method on the other hand, assigns the actual length of a short truck on the assembly line. For the given example, the short truck would compensate 357mm (12000 – 11643), thereby only 1643mm of losses can not be recovered and therefore result in losses. While this method provides insight into the upper bound of bundle experiments, it primarily focuses on the efficiency of discrete method intervals.

The discrete measurement of short trucks gives the possibility to introduce the same categorization method as used by SPZ for longer trucks. The position of sensor, for long and short trucks are input to the model, however, currently only the placement of the sensors for long trucks are known. To gain insights into the placement of the sensors for short trucks, we analysed the production data of the past 5 years. Figure 5-1shows the cumulative percentage of truck lengths. It is noteworthy that the minimum truck length in the x-axis is set to 11000mm. Since the max tooling reachability is limited to 1000mm, the minimum truck length allocation on the assembly line is 11000mm.

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Figure 5-1, Short truck lengths

It can be seen that there are certain lengths that are represented more often. The carrier system at SPZ limits the number of additional sensor placements to 5. With this knowledge, the positions for sensors measuring short trucks are determined. Table 5-B shows the position of the sensors to classify short trucks. These positions are based on the number of trucks with a certain length. For example, at 11770mm, we can see an increase in the number of trucks that fall below this length. It therefore makes sense to place a sensor at this position to fully utilize the recoverable distance of these trucks. These settings are input to the heuristic. The settings will also be a tested to a sensitivity analyses, to improve the categorization of shorter trucks. This sensitivity analysis is discussed in Section 5.1.3

Table 5-B, Short truck sensor settings

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5.1.3. Sensitivity analysis sensor placement short trucks

The placement of the sensors to determine the categorization of short trucks are based on data of the past 5 years. In order to gain insight into the placement of these sensors, a sensitivity analysis needs to be performed that analysis different placements of the sensors. By using the initial placement of these sensors, an interval can be created surrounding the initial placement. The bounds that are tested can be found in Table 5-C. These bounds are based on the analysis discussed in Section 5.1.2 and the lengths of short trucks assembled in the past 5 years.

Table 5-C, short truck sensor bounds

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The bounds above provide an interval in which the sensor should be positioned. Since it is computationally not possible to test every possible position for a sensor within this interval, a step-size of 10mm is determined. This means that between every tested position of a sensor, a gap of 10mm is present. With this given, a total of 216 experiments arise that are tested on the bundle size experiment that performed the best with the initial sensor settings.

5.1.4. Experiments

With the experimental factors known, a series of experiments can be designed. These experiments test different bundle size settings. The settings for short trucks in bundle creation have been discussed in Section 5.1.1. In total, when considering these settings, a comprehensive set of 270 experiments should be conducted to explore each bundle size possibility. The first set of experiments, measuring all trucks continuously, will provide an upper bound to the length losses that could be eliminated. The second set of experiments provides an upper bound to the categorization of short trucks, while incorporating the discrete measurement of long trucks used at SPZ and continuous for short trucks. The third set uses the discrete categorization of all trucks to test the best bundle sizes. The last set of experiments tests the best performing experiment of set three, with the sensor bound discussed in Section 5.1.3. This set is used to perform the sensitivity analysis on the placement of the sensors for short trucks. Table 5-D shows a summary of the experiments performed.

Table 5-D, Experiments to be tested

	NUMBER OF EXPERIMENTS	SHORT TRUCK MEASUREMENT	LONG TRUCK MEASUREMENT
SET 1	270	Continuous	Continuous
SET 2	270	Continuous	Discrete
SET 3	270	Discrete	Discrete
SET 4	216	Discrete	Discrete

5.2. Results

This section discusses the results of the bundle concept experiments. Firstly, experiments that incorporate the continuous measurement of all trucks are discussed in 5.2.1, followed by the discrete measurement of only long trucks in 5.2.2. Discrete measurement and thus categorization of all trucks is the third set discussed in 5.2.3, the last set discusses a sensitivity analysis on the placement of sensors to categorize the length of short trucks and can be found in 5.2.4. We also test the possibility to change the allocation of the number of sensors for long and short trucks in 5.2.5.

5.2.1. Continuous length measurement short and long trucks

To gain insights in the upper bound performance of the bundling concept, first experiments are performed that measure the length of all trucks continuously. By measuring the truck length continuously, no losses are incurred that are caused by the categorization of trucks, and therefore an upper bound of the performance of the heuristic can be found. The focus of this set of experiments is on evaluating the heuristic's performance under optimal conditions.

After performing 270 experiments, as discussed in section 5.1.1, results are obtained with regards to the total losses still caused by long trucks after implementing the bundling concept. Based on this KPI, the best experiment was able to recover **99.02%** of the losses, while the worst experiment was able to recover 91.14% of the losses. Figure 5-2 shows the progression of the losses, the x-axis represents the number of trucks assembled, while the y-axis represents the losses caused by long trucks. The naming of the experiments is based on the number of short trucks in a bundle. For example, 12222 means that the first category received 1 short truck, while the rest of the categories received two short trucks. This categorization is needed for the heuristic as input to assigning short trucks to a bundle. However, the actual length of a long truck is used in this set of experiments, not the upper bound of the categorization. Therefore, trucks are still measured continuously, but the assignment of short trucks to a bundle is based on categorization of long trucks. The categories of long trucks can be traced back to Figure 4-2. In Figure 5-2, six experiments are highlighted. Below, three of them are explained in more detail:

12222: This experiments incurred the lowest final losses. It recovered 99.02% of the length losses, only 14489.5mm of losses were still present at the end. The maximum single shift of a truck and thus the additional tooling reachability required was 997.5mm

12324: This experiment had the lowest single shift of a truck within a bundle. The experiment recovered 97.80% of all length losses, while having a maximum shift of 750mm.

22222: This experiment represents the 3-takt 36m concept previously studied by SPZ. This concept should recover 98.37% of the total losses while having a maximum shift of 997.5mm within a bundle.

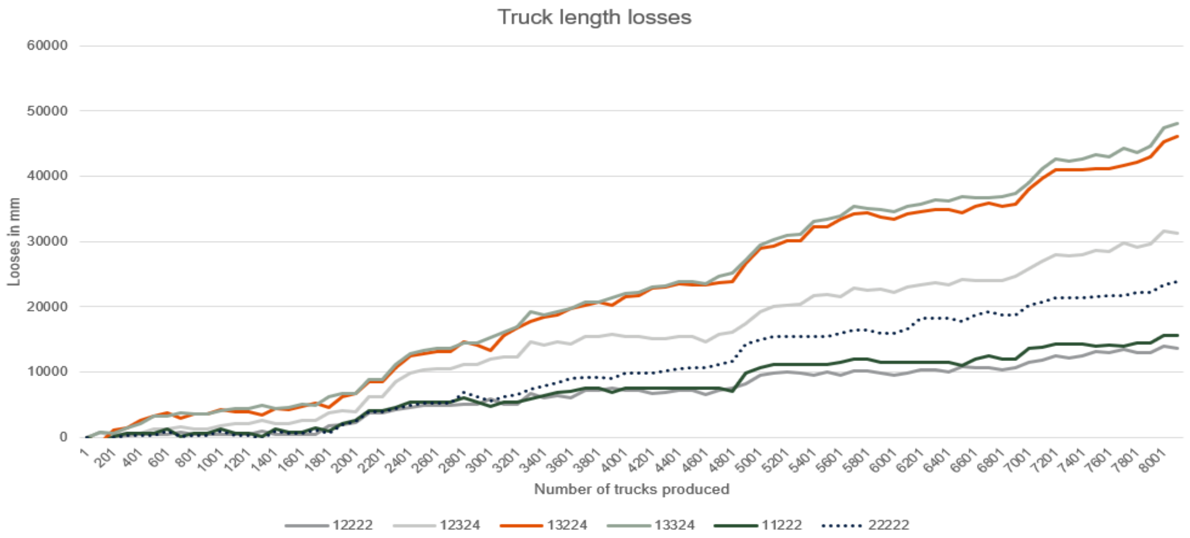

Figure 5-2, Truck length losses C-C

Figure 5-2 shows the progression of the losses that can not be recovered by the bundle heuristic. This is either caused by the lack of short trucks available to offset the excess length, or long trucks being sequenced to close to each other and therefore making it impossible to bundle sufficient short trucks in a bundle.

5.2.2. Continuous + Discrete measurement

The following set of experiments revolved around the concept that long trucks are measured and categorized using a discrete measurement system, while short trucks are measured continuously. This idea of this set of experiments is to analyse the performance of the bundle concept on the current working method at SPZ. These results have a dual purpose, the first one being analysing the performance of the bundling concept without limitations of the discrete measurement technique for short trucks. Secondly, it provides insights in the upper bound of the performance of the discrete categorization of short trucks tested in the next section. Figure 5-3 shows the evolution of the losses created by long trucks among different bundle size settings. The experiments with category settings 12223 has the best performance with regards to the maximum

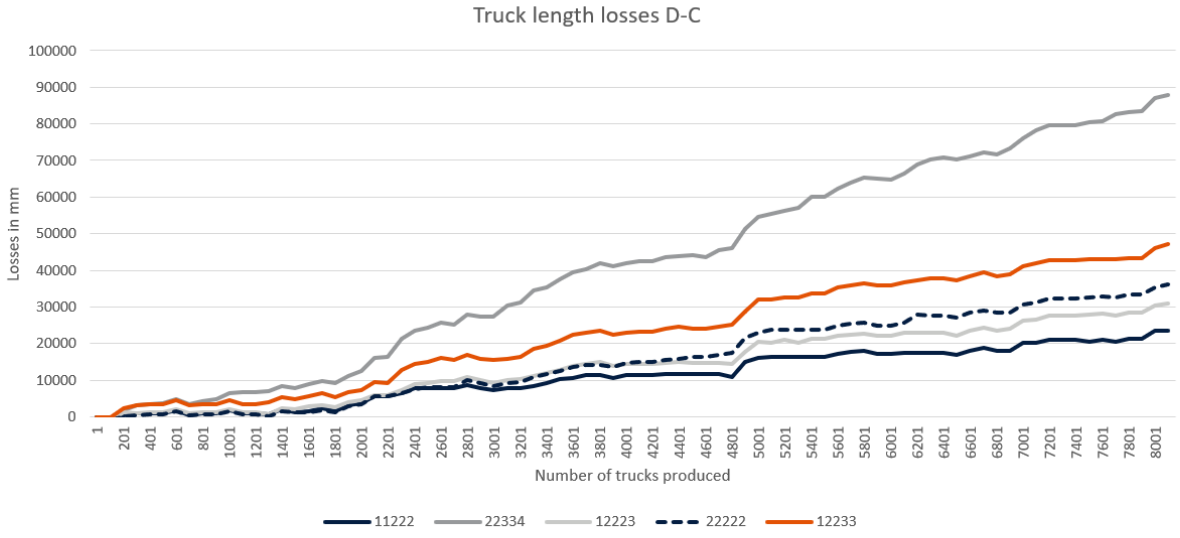

Figure 5-3, Truck length losses D-C

shift of a truck within a bundle. The experiment with settings 11222 recovered the most distance, a total of **98.41%** of all distance was recovered.

When comparing the results of the discrete measurement technique to the continuous measurement technique discussed in the previous section, it can be concluded that this measurement technique adds additional losses to the final output. On average, when comparing the performance of all experiments the discrete measurement method reduced the recoverable distance by **1.72%.** The experiments performed showed that the bundle concept has a high distance recovery potential. The best experiment was able to recover 98.41% of the total losses caused by long trucks and thus the introduction of the discrete categorization resulted to a increase of **0.61%** of length discrepancies that could not be recovered.

5.2.3. Discrete measurement trucks

The third set of experiments revolve around the measurement and categorization of all trucks in a discrete form. To operationalize the bundling concept, it is necessary to introduce a method to gain insights into the actual length of shorter trucks and their categorization, as discussed in Section 5.1.2. The 270 bundle setting experiments were all performed with a fixed position of the sensors for short trucks, which are based on the analysis discussed in section 5.1.2. The ten best performing experiments can be found in Table 5-E.

Table 5-E, Results D-D experiments

	RECOVERY PERCENTAGE	LOSSES IN MM
11222	77.79%	327,140mm
12222	86.66%	196,450mm
22222	86.36%	200,970mm
12324	83.55%	242,310mm
13224	82.54%	257,250mm
13324	81.41%	273,870mm
22334	77.81%	326,870mm
12223	84.37%	230,320mm
12234	56.44%	641,620mm
12336	79.05%	308,650mm

The best experiment (12222) showed that the bundle heuristic could decrease the losses caused by long trucks by **86.66%** when implementing the discrete categorization of all trucks. The original losses summed to 1,473,120mm, which means that the best experiment was able to recover 1,276,670mm of possible production distance, which is equal to **106.39 trucks** over the year 2022. However, when comparing the performance of the discrete categorization to the performance of the previous executed experiments, it can be noted that this way of categorizing incurred losses. Table 5-F shows the performance of the best discrete performing experiment, 12222.

Table 5-F, Performance experiment 12222

SHORT TRUCK MEASUREMENT	CONTINUOUS	CONTINUOUS	DISCRETE
LONG TRUCK MEASUREMENT	CONTINUOUS	DISCREET	DISCRETE
RECOVERY PERCENTAGE	**99.02%**	**98.40%**	**86,66%**

The discrete categorization of short trucks reduces the possible improvements of the bundle concept by **11.74%** compared to only categorizing long trucks discrete. These losses can be explained by the excess length that is lost when trucks are categorized. For example, if a truck has a length of 11126mm, it is categorized as 11190 mm, according to Table 5-B. This means that the truck is given a distance reservation of 11190mm on the assembly line, while 11126mm is the minimum required. The difference, 64mm, is not used to compensate a long truck, and therefore adds to the 11.74% of inefficiency. To improve these losses, the following section discusses a sensitivity analyses performed.

5.2.4. Short Truck Sensor Sensitivity Analysis

In order to accurately categorize short trucks and effectively implement the bundling concept, precise measurements of truck lengths are essential. As discusses in Section 5.1.2, the placement of sensors plays a crucial role in determining the actual length of shorter trucks on the assembly line. To ensure optimal performance of the heuristic model, it is imperative to investigate the sensitivity of sensor placement and its impact on the categorization of short trucks.

This section presents a sensitivity analysis for the sensor placement for short trucks, aiming to assess the robustness of the heuristic under varying sensor configurations. By systematically evaluating different sensor positions within predefined bound, we can gain insights into the sensitivity of the heuristic with regard to the sensor placement and corresponding performance. The analysis seeks to optimize sensor positions to enhance the accuracy of truck length measurements and improve the effectiveness of the bundling strategy.

The best performing experiment with continuous measurement categorization (12222) has been tested with a total of 216 unique experiments that each differ in sensor placements. The best performing setting resulted in a new compensation percentage of **87.87%**, adding **1.21%** to the total excess length recovered by long trucks. The settings of this experiment can be found in Table 5-G.

Table 5-G, Short truck sensor placement

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Since the initial chosen positions for the sensors for short trucks are based on the lengths of short trucks of the past five years, it can be explained that the improvement of the sensitivity analysis is minimal. However, when performing the same analysis in the future, when data has been updated with new truck lengths, the improvement of the analysis could become more significant.

5.2.5. Number of short truck categories

The carrier system used by SPZ to transport trucks through the second part of the assembly line is limited to a maximum of 10 different length settings. Currently, SPZ reserves 5 of these settings to categorize long trucks. Therefore, in the heuristic, we used the 5 empty settings to categorize short trucks. Since the number of sensors used for long trucks and the corresponding positions have already been analysed and optimized in a previous study, we assumed that there will not be any benefit to increasing the number of sensors used for long trucks. However, in order to validate that the number of sensors used for both long and short truck categorization are optimal, we performed experiments to test different allocations, based on decreasing the number of sensor reserved for long trucks. If we use 4 sensors for long truck categorization, and therefore use 6 sensors for short truck categorization, the losses incurred by short truck categorization are reduced. However, since long trucks will incur more losses due to the larger intervals between categorization, we found that the best performing experiment (12222) performed significantly worse than when a 5 short, 5 long allocation is used. To determine the positions of the long truck sensors, we used the model designed in a previous study (Visser, 2022). The total losses still incurred with the 4 long - 6 short allocation were 552,310mm which is an increase of 281%. We can therefore say that, within the limitations of the carrier setup at SPZ, an optimal allocation of the 10 sensors between long and short trucks is made.

5.3. Conclusion

With the experiments performed, we demonstrated that the implementation of the truck bundling concept results in a significant reduction of losses currently caused by long trucks. The experiments show, without taking the discrete measurement method currently used at SPZ, that the bundling concept can recover up to 99.02% of all losses. However, the discrete measurement experiments also showed that using a discrete measurement method results in a less efficient solution.

6. Conclusion, Recommendations & Discussion

In the final chapter of this report, we draw conclusion on the research in Section 6.1. Next, in Section 6.2, we give recommendations to SPZ which are based on the research we performed. Lastly, in Section 6.3, we argue the limitations of our study and suggest further research directions.

6.1. Conclusion

In Chapter 1, we formulated the research question: ***"What is the effect of implementing a strategy to reduce the losses generated by long trucks on the Pollux-2 assembly line?*** To give an answer to this question, our research commenced with the conceptualization and design of a comprehensive strategy aimed at reducing the effect of long trucks on the assembly line's efficiency. This strategy merges the principles of batch production with variable rate launching, all while ensuring adherence to the assembly line's limitations.

The strategy we developed groups short trucks around a long truck into a bundle. Each truck in the bundle has the same amount of time to complete its tasks (takt time), but the distance assigned to each truck on the assembly line varies. Despite this variation, the average distance allotted to trucks on the assembly line is at least 12000mm, ensuring workers have enough time to complete their tasks within the required time frame.

The initial implementation of the strategy exhibited a potential saving percentage of 99.02% of the total losses attributed to long trucks. However, the limitations of the Pollux-2 assembly line were not factored into this calculation. Two main limitations must be integrated into the model: the maximum shift of the truck's start position within the bundle due to limited tooling reachability, and the constraint of the carrier system used for transporting trucks on the assembly line.

While SPZ already categorizes trucks exceeding 12000mm, short trucks are currently categorized as 12000mm. Hence the introduction of short truck categorization is imperative. An analysis of short trucks assembled over the past 5 year resulted in the identification of five short truck categories. Upon implementing this categorization, the recoverability of excess length from long trucks decreased to 86.66%. To test the optimality of short truck categorization, a sensitivity analysis was conducted, yielding and increase in recoverability of 1.21%. Overall, after conducting all experiments, a theoretical reduction of losses caused by long trucks of 87.87% was achieved. This increase in potential output at SPZ amount to 1.32%, equivalent to 108 trucks on a yearly base.

6.2. Recommendations

The first recommendation we make to SPZ is to investigate the possibility to adapt the current carrier system to adopt continuous measurement of all trucks. By measuring truck lengths continuously, and thus being able to launch trucks based on this continuous measurement method, compensation of a long truck by using the bundling method becomes more efficient. Furthermore, continuous measurement will also improve the efficiency of the assembly line if the bundling strategy is not implemented since long trucks will no longer need to be categorized and therefore the inefficiencies in this categorization are removed.

The bundling approach introduces the concept of 'open' workstation borders, allowing workers to overlap neighbouring workstations. Consequently, this scenario can potentially lead to situations where employees are concurrently engaged in tasks across different workstations for the same truck. Such situations necessitate coordination among the various workstations to uphold the flow of assembly process. Moreover, the adoption of bundling may evoke a perception among workers that they have less allocated time to complete tasks on short trucks used to compensate a long truck. This makes it important to communicate and train employees about the new strategy. We therefore recommend additional training of the workers to introduce the concept of open workstation borders.

This study primarily concentrates on analysing the implications of the bundling strategy within the context of the Pollux-2 assembly line. The Pollux line operates at a slower takt time and handles a higher proportion of long trucks compared to other assembly lines. While the bundling strategy holds potential for adaptation to the Castor-2 assembly line, it is imperative to acknowledge the unique challenges posed by its faster takt time. The expedited pace of operations on the Castor-2 line may introduce additional complexities and constraints. Specifically, the introduction of truck shifts could potentially alleviate concerns regarding tooling reachability, as long truck occupancy durations may lead to reduced assembly time due to increased worker transit periods. It is essential to conduct thorough research to validate this presumption before contemplating the integration of the bundling concept into the Castor-2 line.

6.3. Discussion

In our study, we extensively explored the optimization of short truck measurement and categorization within the bundling strategy framework. However, limitations pose challenges to our approach. Firstly, the placement of sensors for truck measurement, based on past production data, introduces uncertainty regarding their suitability for future production. While historical data offer insights into truck lengths, shifts in manufacturing trends or the introduction of new truck models may render the sensor positions suboptimal for future production. This limitation underscores the need for adaptive sensor placement strategies that account for evolving production dynamics, ensuring continued accuracy and efficiency in truck measurement processes.

Secondly, our model assumes that the theoretical length of short trucks aligns perfectly with their actual length. However, data reveal that measured trucks deviate from their theoretical lengths. This discrepancy poses a significant challenge as it can lead to inefficiencies and losses within the bundling strategy. Our current approach relies on the theoretical length of trucks being equal to the actual length. However, when implementing the bundling strategy at SPZ, this is not feasible. To address this limitation, advancements in measurement technologies or additional sensor systems capable of accurately determining the actual length of short trucks before they enter a bundle with a long truck may be necessary.

Another limitation of our study lies in the assumption of uniform assembly time across all trucks, regardless of their complexity. In reality, trucks vary in complexity, leading to differences in assembly time requirements. Complex trucks often require more time for assembly due to intricate design and specialized assembly processes, while simpler trucks have shorter assembly times. To address this limitation, future iterations of the bundling strategy could incorporate truck complexity and assembly time as parameter in bundle creation.

The predetermined sequence of trucks in the production plan, dictated by mixing rules, constrained our exploration of alternative sequencing strategies. While this approach ensured compliance with operational guidelines, it may have limited our ability to optimize bundle creation. There may be potential benefits in reordering trucks within the production plan to enhance efficiency and productivity of the bundling concept. By incorporating mixing rules into the bundle concept, it may be possible to create bundles that not only reduce losses caused by long trucks, but also caused by the difference in complexity between trucks.

At the end of the study, we wanted to test the idea of dynamic programming to solve the bundling problem. The heuristic we designed is limited by the constraint that only one long truck can be present in a bundle, therefore limiting a short truck to only being used to compensate a single long truck. Dynamic programming would remove this constraint and allow a short truck to be used for multiple long trucks, since bundles can now contain more than one long trucks. This idea can provide an upper bound to the performance of the heuristic, and show the potential of the bundling concept at SPZ. We have performed 20 iterations of the dynamic programming model by hand to show it’s working and performance, which can be found in Appendix C. After performing 20 iterations, we found out that the performance was slightly better than that of the heuristic. However, since bundles no longer have predetermined sizes, and short trucks can be used for compensating multiple long trucks, the implementation of the bundling concept becomes less feasible at SPZ. The aim at SPZ is to have a fixed takt time, the bundling strategy, when using a fixed bundle size, can still be seen as a fixed takt time. With dynamic programming, bundle sizes will no longer be based on the length of the long truck in the bundle. However, these restrictions could be added to the dynamic programming model, therefore making it suitable for application at SPZ. Given that our heuristic can ideally recover up to 99.02% of losses, substantial efforts were not directed towards dynamic programming implementation. However, employing dynamic programming for the bundling strategy holds promise for enhancing model speed and recovery percentage.

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Appendix A

Appendix table A, Jidoka tool information

JIDOKA	STATION	STARTING POSITION ON LINE	70% OF RANGE	END POSITION ON LINE
TOOL 1	24	477	486	488
TOOL 2	24	477	486	488
TOOL 3	24	477	486	488
TOOL 4	24	477	486	488
TOOL 1	24a	482	491	493
TOOL 2	24a	482	491	493
TOOL 1	26	508	516	519
TOOL 1	28	527	534	536
TOOL 2	28	527	535	536
TOOL 3	28	527	535	536
TOOL 1	29	543	551	554
TOOL 2	29	543	548	552
TOOL 3	29	543	551	554
TOOL 4	29	541	544	547
TOOL 1	30	552	559	563
TOOL 2	30	552	558	561
TOOL 3	30	557	565	568
TOOL 4	30	557	565	568
TOOL 5	30	552	559	563
TOOL 1	35	612	620	623
TOOL 2	35	612	620	623

Appendix B

Appendix table B, Mixing Rules

MIXING RULES

TYPE	Line	Rule
LONG CHASSIS	Pollux	1:4, preceding and followed by a short truck
ALLISON	Pollux	Not before or after a Gryphus
LOW ENTRY	Pollux	Not before or after a Gryphus
GRYPHUS	Pollux	Special arrangement
8X8	Pollux	Always Pollux
CREWCAB	Pollux	Always Pollux
10X4*6	Pollux	Always Pollux
6X6	Pollux	Always Pollux
8X6A/B	Pollux	Always Pollux
8X* ; 8X/ ; 8X/*	Pollux	Always Pollux
8X4B; 8X2B	Pollux	Always Pollux
8X2/8X4 2 KR	Pollux	Always Pollux
10X4/6	Pollux	Always Pollux
CUSTOMER COLOUR	Castor	Max 10 per day

HEAVY TIPPER	Castor	1:6
6X4*4	Castor	Always Castor
TAG AXLE	Castor	Always Castor
8X6Z	Castor	Always Castor
10X4/6 BT400	Castor	Always Castor
AIRSUSPENSION FRONT	Both	1:2
ROOF AIR DEFLECTOR	Both	1:10
16L ENGINE	Both	Leveling
HIDDEN TANKS	Both	1:2
ASLA	Both	1:10
FOU	Both	1:2

Appendix C

Dynamic programming

$V(i) = Minimum\ total\ used\ distance\ for\ all\ trucks\ up\ to\ i$

$g(i,k) = truck\ i\ placed\ in\ a\ bundle\ with\ size\ k\ starting\ from\ bundle\ i$

$M = maximum\ number\ of\ trucks\ in\ a\ bundle = 6$

$V(i) = \min_{k=1..M}\{g(i,k) + V(i-k)\}$

V(0)				= 0
V(1)				= 12000
V(2)				= 24000
V(3)				= 36000
V(4)				= 48500
V(5)				= 60000
V(6)				= 72000
V(7)	= min	g(7,1) + V(6)	= 12000 + 72000	= 84000
		g(7,2) + V(5)	= 24000 + 60000	= 84000
		g(7,3) + V(4)	= 36000 + 48500	= 84500
		g(7,4) + V(3)	= 48500 + 36000	= 84500
		g(7,5) + V(2)	= 60500 + 24000	= 84500
		g(7,6) + V(1)	= 72000 + 12000	= 84000
V(8)	= min	g(8,1) + V(7)	= 13500 + 84000	= 97500
		g(8,2) + V(6)	= 24500 + 72000	= 96500
		g(8,3) + V(5)	= 36500 + 60000	= 96500
		g(8,4) + V(4)	= 48500 + 48500	= 97000
		g(8,5) + V(3)	= 61000 + 36000	= 97000
		g(8,6) + V(2)	= 73000 + 24000	= 97000
V(9)	= min	g(9,1) + V(8)	= 12000 + 96500	= 108500
		g(9,2) + V(7)	= 24500 + 84000	= 108500
		g(9,3) + V(6)	= 36000 + 72000	= 108000
		g(9,4) + V(5)	= 48000 + 60000	= 108000
		g(9,5) + V(4)	= 60000 + 48500	= 108500
		g(9,6) + V(3)	= 72500 + 36000	= 108500
V(10)	= min	g(10,1) + V(9)	= 12000 + 108000	= 120000
		g(10,2) + V(8)	= 24000 + 96500	= 120500
		g(10,3) + V(7)	= 36500 + 84000	= 120500

		g(10,4) + V(6)	= 48000 + 72000	= 120000
		g(10,5) + V(5)	= 60000 + 60000	= 120000
		g(10,6) + V(4)	= 72000 + 48500	= 120500
V(11)	= min	g(11,1) + V(10)	= 12000 + 120000	= 132000
		g(11,2) + V(9)	= 24000 + 108000	= 132000
		g(11,3) + V(8)	= 36000 + 96500	= 132500
		g(11,4) + V(7)	= 48500 + 84000	= 132500
		g(11,5) + V(6)	= 60000 + 72000	= 132000
		g(11,6) + V(5)	= 72000 + 60000	= 132000
V(12)	= min	g(12,1) + V(11)	= 13500 + 132000	= 145500
		g(12,2) + V(10)	= 24500 + 120000	= 144500
		g(12,3) + V(9)	= 36500 + 108000	= 144500
		g(12,4) + V(8)	= 48500 + 96500	= 145000
		g(12,5) + V(7)	= 61000 + 84000	= 145000
		g(12,6) + V(6)	= 72500 + 72000	= 144500
V(13)	= min	g(13,1) + V(12)	= 12000 + 144500	= 156500
		g(13,2) + V(11)	= 24500 + 132000	= 156500
		g(13,3) + V(10)	= 36000 + 120000	= 156000
		g(13,4) + V(9)	= 48000 + 108000	= 156000
		g(13,5) + V(8)	= 60000 + 96500	= 156500
		g(13,6) + V(7)	= 72500 + 84000	= 156500
V(14)	= min	g(14,1) + V(13)	= 12000 + 156000	= 168000
		g(14,2) + V(12)	= 24000 + 144500	= 168500
		g(14,3) + V(11)	= 36500 + 132000	= 168500
		g(14,4) + V(10)	= 48000 + 120000	= 168000
		g(14,5) + V(9)	= 60000 + 108000	= 168000
		g(14,6) + V(8)	= 72000 + 96500	= 168500
V(15)	= min	g(15,1) + V(14)	= 12000 + 168000	= 180000
		g(15,2) + V(13)	= 24000 + 156000	= 180000
		g(15,3) + V(12)	= 36000 + 144500	= 180500
		g(15,4) + V(11)	= 48500 + 132000	= 180500
		g(15,5) + V(10)	= 60000 + 120000	= 180000
		g(15,6) + V(9)	= 72000 + 108000	= 180000
V(16)	= min	g(16,1) + V(15)	= 12000 + 180000	= 192000
		g(16,2) + V(14)	= 24000 + 168000	= 192000
		g(16,3) + V(13)	= 36000 + 156000	= 192000
		g(16,4) + V(12)	= 48000 + 144500	= 192500
		g(16,5) + V(11)	= 60500 + 132000	= 192500
		g(16,6) + V(10)	= 72000 + 120000	= 192000
V(17)	= min	g(17,1) + V(16)	= 13500 + 192000	= 205500
		g(17,2) + V(15)	= 25000 + 180000	= 205000
		g(17,3) + V(14)	= 36500 + 168000	= 204500
		g(17,4) + V(13)	= 48500 + 156000	= 204500
		g(17,5) + V(12)	= 60500 + 144500	= 205000
		g(17,6) + V(11)	= 73000 + 132000	= 205000
V(18)	= min	g(18,1) + V(17)	= 12000 + 204500	= 216500
		g(18,2) + V(16)	= 24500 + 192000	= 216500
		g(18,3) + V(15)	= 36000 + 180000	= 216000
		g(18,4) + V(14)	= 48000 + 168000	= 216000
		g(18,5) + V(13)	= 60000 + 156000	= 216000
		g(18,6) + V(12)	= 72000 + 144500	= 216500

V(19)	= min	g(19,1) + V(18)	= 12000 + 216000	= 228000
		g(19,2) + V(17)	= 24000 + 204500	= 228500
		g(19,3) + V(16)	= 36500 + 192000	= 228500
		g(19,4) + V(15)	= 48000 + 180000	= 228000
		g(19,5) + V(14)	= 60000 + 168000	= 228000
		g(19,6) + V(13)	= 72000 + 156000	= 228000
V(20)	= min	g(20,1) + V(19)	= 12000 + 228000	= 240000
		g(20,2) + V(18)	= 24000 + 216000	= 240000
		g(20,3) + V(17)	= 36000 + 204500	= 240500
		g(20,4) + V(16)	= 48500 + 192000	= 240500
		g(20,5) + V(15)	= 60000 + 180000	= 240000
		g(20,6) + V(14)	= 72000 + 168000	= 240000