A simulation study; modelling Ubbink's tugger train replenishment system, in a Kanban controlled environment

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Author: Steven Kraaijvanger

University of Twente
Master program: Industrial Engineering and Management
Specialization: Production and Logistics Management

University supervisors:
Dr. I. Seyran Topan
Dr. E. Topan

Company supervisors:
Benno Onderwaater (Senior Process Engineer)
Erik Thijssen (Process Engineer)

Preface

Every good thing has to come to an end, which was no different for the period that I was doing an internship project at Ubbink. So hereby, I present the report of my thesis assignment, in which I built a simulation model with which I modelled Ubbink's (future) material supply system.

Before the start of my assignment, I expected that I could encounter some difficulties during the assignment, as I recall some occurrences of when I was executing my Bachelor assignment.
However, I feel like the whole process went rather smoothly. I started every working day with enthusiasm and a willingness to deliver. Encouraged by the steps I made I kept in the flow until the end of the project, making my internship at Ubbink really enjoyable.

Logically, most important for this assignment was the input of Benno and Erik, as my company supervisors. However, I have spoken with many people at the company from various departments and learnt from all of them. I want to thank everybody at Ubbink for being accessible for questions and their openness to help me further.

The people that got to know me the best were the Ubbink employees working at the quality department, where I had a place to work. I enjoyed working there and the chit chats I had with the people there.

Lastly, I want to thank Ipek and Engin for being my supervisors from the university. Especially, the structure of report has improved because of the feedback. And although most of our meetings were online, I still got to know you as very friendly people.

Management summary

We started this thesis assignment with the idea that **Ubbink wants to implement a new material supply system** for the new assembly lines, that are designed according to the Low-Cost Intelligent Automation (LCIA) concept. LCIA lines include bin storage racks at the line. These bins are filled with components, whose are used as input for the assembly process. Tugger train transportation is used to replenish the lines with full bins and to transport empty bins from the assembly line to a storage place. Full component bins are picked from one of the three Kanban supermarkets. Supermarket 1 contains tube components, Supermarket 2 contains stickers/labels and Supermarket 3 contains the rest of the assortment.

Although the strategic decision (long-term) to implement a new material supply system has already been made, there are many things unclear at a tactical planning level (mid-term), which affects day-to-day operations as well (operational level). We formulate the following main research question:

> *How should the material supply for Ubbink's LCIA lines be arranged at a tactical level?*

In the future, at least 10 LCIA lines are expected to be operational. These assembly lines will all be part of the new material supply system. Because of the extent of innovation, it is difficult for Ubbink to foresee how many tugger trains it should possess or how much buffer space needs to be reserved for bin racks. In order to maintain a sufficient average line utilization at an operational level, trade-offs between costs and average line utilization need to be considered. The costs incurred depend on the material supply setting, consisting of eleven decision variables *(Number of tugger trains* and *10 buffer levels (one buffer level per assembly line, ten assembly lines are considered))*.
Furthermore, there are other undecided tactical factors that affect the average line utilization of a material supply setting at an operational level. These are schedule rules, the target average line utilization and the plant layout.

In order to provide answers on how to arrange the tactical planning, we develop a material supply model. The model is implemented in Plant Simulation.
The model is constructed to include operational aspects, e.g. a single working day is simulated each run. One can observe tugger trains driving tours and making stops at stations to perform handling actions. Using the model, we solve various scenarios considering different inputs. The scenarios consider three different input factors: input schedule (abbreviation is IS, 7 possible IS), target average line utilization (97% and 99%) and layout (2 layouts). The difference between layout 1 and layout 2 relates to the positioning of the LCIA lines. In layout 1, the LCIA lines are positioned where currently the assembly lines are positioned. In layout 2, the LCIA lines are placed closer to the supermarkets. Combing all input factors, this gives a total of 28 regular scenarios

Considering that the job sequence of a schedule has an influence on the solution, we develop another model, called a level scheduling model, to level the required tugger train capacity during the day by changing job sequences. We run the regular scenarios with both level schedules as well as unlevelled schedules as input schedules.

All 28 regular scenarios run to determine the (near-) optimal solutions (material supply settings), with the objective to minimize costs while maintaining a certain target average line utilization. Additionally, we perform a sensitivity analysis. Here, we change parameters that are considered fixed for one of our regular scenarios.

These additional scenarios are also solved to near optimality. Lastly, we perform a component-based analysis, in which we identify components that have a high stockout risk.

Based on an analysis of all our results and comparisons between the results of similar scenarios, we are able to give Ubbink the following recommendations.

1. Level scheduling is cost-efficient in comparison to random scheduling. Therefore, we recommend Ubbink to create level schedules when multiple LCIA lines are operational. The Excel tool could be used for this purpose. It should be noted that level scheduling could be used more effectively when it is applied to level the time induced by handling actions as opposed to levelling the required tugger train capacity during the day. This is explained more extensively in chapter 7.1, paragraph *Level Scheduling.*
2. We recommend layout 2 over layout 1, as buffer space and tugger train driver salary can be saved if layout 2 is adopted.
3. We recommend Ubbink, to put *container* bin components with a Kanban size (amounts of components in a bin) of below 20, in a bin that is twice as large (*Quarter meter box* format). This way, stockouts can be prevented.
4. We estimate that Ubbink should possess a number of tugger trains in the region of 6 or 7. In our estimation, we have also accounted for expected component (un)availability, line breakdowns, tugger train breakdowns and peak demand. However, the accuracy of this estimation is debatable. Future research should be done about component availability, line breakdowns and tugger train breakdowns.
5. It differs per scenario, which buffer level we find per assembly line. To this end, we recommend investigating how much bin places there should be in a rack at a component level. It is recommended to choose to choose a number of bin places per component, that guarantees a high component availability for a large majority of possible scenarios. In case certain scenarios happen regularly, Ubbink could determine the required number of bin places per component, for each of these scenarios.
6. We recommend the introduction of scannable bar codes instead of physical Kanban cards, which can be scanned by an electronical device. This electronical device can register all the components bins that are picked and make an overview of this information. This should yield significant time savings, as the tugger train driver can much easier check what needs to be picked from the supermarkets.
7. For lines that have many components as input, we expect it to be difficult for the tugger train driver to know where empty bins are located at assembly lines. To this end, I recommend an electronical board at the line, which contains an overview of empty bins and available Kanban cards.
8. Tugger trains need space to manoeuvre and to pass each other. Hence, we recommend making changes to either wagon design or the width of paths in the plant.
9. When multiple LCIA lines are operating, there will be occurrences in which multiple tugger trains queue behind each other. However, there needs to be space for this. To this end, we recommend widening the paths in the busiest supermarket, Supermarket 3, such that multiple tugger trains can queue here or can have access to the supermarket at the same time. If multiple tugger trains can be served at the same time in supermarket 3, large cost savings can be accomplished.
10. The more unnecessary movements are executed by the tugger train driver, the more tugger trains, and buffer space Ubbink will need. Hence, we recommend minimizing the execution of unnecessary movements for the tugger train driver.
11. We highly recommend making the bin racks as accessible as possible, so the tugger train driver can get close to it. In other words, it would be smart to place the bin racks as close to the driving paths as possible.

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Before reading this report, note that…

People working at Ubbink generalize assembly and production as production. They do not make a distinction. In this thesis, when we write about production, we only refer to injection moulding and thermo forming. Assembly refers to the assembly processes.

We refer to every area that is dedicated to assembling as an assembly line. So, in our references we do not make a differentiation between different assembly concepts. We simply call everything an assembly line. In reality however, Ubbink does have different assembly concepts such as stations, carrousels, single-person workplaces etc.

When I talk about Ubbink, I refer only to Ubbink's facility in Doesburg; the plant where this Master Thesis is conducted.

Key words and abbreviations

Key words

Low-Cost Intelligent Automation (LCIA): New assembly concept adopted by Ubbink. LCIA lines are designed in such a way that unnecessary handling and movements are minimized, enabling the LCIA line to facilitate a fluid assembly process.
Kanban: Internal communication system adopted by Ubbink to facilitate material replenishments.
Lean supermarket / Kanban supermarket: Dedicated storage location in the warehouse where components are picked from
Tugger train: Train-like vehicle that is going to going to be used to pick components and supply the assembly lines.
Bin: General name for a *container*, *quarter meter box*, half meter box, one meter box or *end box*.
Kanban size: The number of components that fit within a component bin.
Tactical planning: Planning level that a company takes to break a strategic plan (long-term) into smaller goals.
Part / component: One single unit, which has been manufactured but not connected to other parts yet, is what we call a **part.**
Neighbourhood operator: Part of the SA algorithm. The neighbourhood operator performs an operation (e.g. SWAP) on the current solution to construct a neighbourhood solution.
Conceptual model: Conceptual representation of the model (including a general model description, assumptions, simplifications, model inputs and model outputs)
Level scheduling model: Model that needs an input schedule as input and changes it into a "levelled" schedule, in which the variation in supply capacity needed during the day is minimized.
(Future) material supply system: Ubbink's future replenishment system, in which LCIA lines (assembly lines) are replenished by tugger trains in a Kanban controlled environment.
Material supply system model: Simulation model which imitates Ubbink's future material supply system.
Material supply setting: A setting of decision variables *Number of tugger trains* and *Buffer levels*.
Average line utilization: The average line utilization, considering ten LCIA lines. Every assembly line as the same weight.
Tugger rain driver behaviour: Percentage of time the tugger train driver is executing a certain action.
Tugger train capacity usage: Percentage of wagon capacity occupied with full component bins after supermarket 3 has been visited.

Abbreviations

LCIA	Low-Cost Intelligent Automation
SM	Lean supermarket
BOM	Bill of materials
LSP	Level Scheduling Problem
ORVP	Output Rate Variation Problem
DP	Dynamic Programming
SA	Simulated Annealing
SA1	Simulated Annealing algorithm of level scheduling model
SA2	Simulated Annealing algorithm of material supply system model
CORVP	Constrained Output Rate Variation Problem

1. Introduction

This thesis assignment is performed at Ubbink's plant in Doesburg. This is Ubbink's only location in The Netherlands, hence this plant is also called Ubbink Nederland. For the remainder of this thesis, we only write Ubbink when we refer to Ubbink's plant in Doesburg.
In chapter 1.1, we introduce Ubbink as well as the reason this assignment came about. The goal of this chapter is to give the reader an understanding of the company and the situation the company was in at the start of the assignment.
In chapter 1.2, we introduce the problem, after which we identify the core problem, and we discuss the research design of this assignment.
In this chapter's last section, chapter 1.3, we explain the methodology we follow in order to come up with answers for the research questions that were proposed in the research design.

1.1 About Ubbink

Ubbink was founded in the Netherlands in 1896. In Ubbink's 125 year existence, it has become a household name in the construction industry. Ubbink manufactures products within the following categories: flue gas discharge, ventilation, airtight and watertight construction. The products are sold on the Dutch market as well as to export customers.

Ubbink's products are known to be **reliable and of high quality**. In addition to its high-quality standard, Ubbink's **product assortment is varied**. In 2020, Ubbink manufactured about ? different articles. Ubbink may offer a rather simple product in varying colours and different dimensions. Competitors may not be willing to differentiate to this extent and prefer to offer standardized products. The variation in its article assortment and its high-quality standard differentiates Ubbink from its competitors.

Ubbink is doing very well in terms of profit and growth. Looking back at the previous years, Ubbink's revenue has grown every year. This growth is expected to continue; Ubbink's sales revenue is expected to grow by **a%** (confidential) over the next five years (Ubbink, 2020).

Ubbink is part of the Ubbink Centrotherm Group. Ubbink forms together with sister companies Centrotherm, IVT and Sonnenstromfabrik the Gas Flue Systems division of Centrotec SE; a global organization that has specialized in energy efficient technology for buildings. Centrotec is represented in over 50 countries (Ubbink, 2021). The Ubbink Centrotherm Group has subsidiaries in the United States, United Kingdom, France, Italy, Belgium, The Netherlands, Germany and China.(Centrotherm, 2021). Figure 1 shows where the Ubbink Centrotherm Group companies are located.

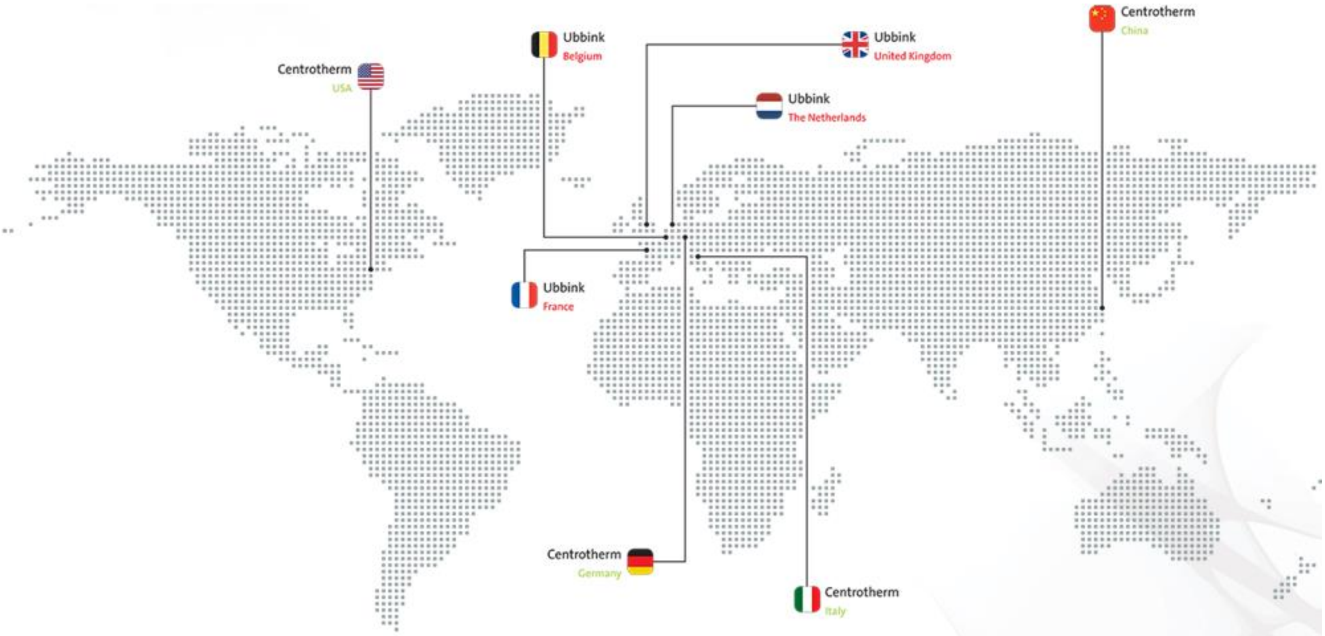


Figure 1: Ubbink Centrotherm Group companies around the globe

At Ubbink, plastic parts are produced, whose may be used in a follow-up assembly process as well. Most of the plastic parts are produced by means of injection moulding, but Ubbink also has a thermo forming machines which produce plastics.

External parts, coming from suppliers, can also be used as input for assembly. These external parts are typically made out of different material than plastic. External parts can also be resold directly. Chapter 2.2 provides extensive information about the different flows a part could follow through the plant.

1.2 Problem introduction

In order to be able to compete with producers in the far east, Ubbink aims to lower the cost prices of its products. To this end, Ubbink wants to use its plant surface more efficiently and thus increase its output per m^2.

1.2.1 Lean manufacturing

In order to increase its output per square meter, Ubbink has adopted a new manufacturing philosophy. **Lean manufacturing** aims at creating maximum value for the customer, while waste is minimized. The pursuit is to reduce costs and to improve the operating result.

The newly adopted Lean manufacturing philosophy has an impact on many processes at Ubbink. Two of these processes are assembly and the material supply to the assembly lines.
Due to the current line designs, assembly lines rely on large component buffers close to the line to have access to components. In addition, the current line designs take up a lot of space as well.

In the future, the current assembly lines will be replaced by **Low Cost Intelligent Manufacturing (LCIA)** lines. LCIA can be regarded as a general line concept that considers a number of fundamentals that fit within the domain of LCIA.

At Ubbink, LCIA lines take up (about) twice as little space as opposed to the current line designs. Hence, the LCIA lines are compact. The LCIA lines at Ubbink incorporate small bin racks (figures 2 & 3) to store full bins with components, that stand within reach of the workers. It depends on the bin type, component type and the cycle time how fast a component bin is emptied. For most component types, multiple component bin replenishments need to be carried out in order to prevent the line from stockouts.

The introduction of a **Kanban controlled replenishment system** should help to replenish components just-in-time, reducing on-line inventories. Kanban as a concept is part of the Lean manufacturing philosophy. The aim of Lean is to minimize waste, such as inventories at the assembly line. The aim with Kanban controlled replenishments is to deliver the components just-in-time, reducing on-line inventories.

Figure 2: A bin rack with container bins

Figure 3: A bin rack with one meter box bins

The Kanban controlled replenishment system is operated by a tugger train driver, or "milk man". A tugger train consists out of a front part (locomotive) and three wagons (Figure 4). The milk man drives around the assembly lines to replenish the lines with new parts.

The wagons of the train can be loaded with full and empty component bins. After replenishing a line with new component bins, the milk man loads empty bins from the line onto the tugger train. He brings the bins to a place dedicated for bin storage. Attached to an empty bin is a Kanban card, which shows which component bin needs to be picked again from any of the three Lean supermarkets, to replenish the line again. A supermarket is a dedicated storage location in the warehouse where full component bins are stored. The supermarkets are replenished by the warehouse. After the train is loaded with newly picked components a new tour starts. Figure 5 presents simple a visual representation of the material supply concept. In chapter 2.5.5, we provide a more thorough explanation of the material supply concept and its aspects.

Figure 5: Example of a tugger train (STILL, 2021)

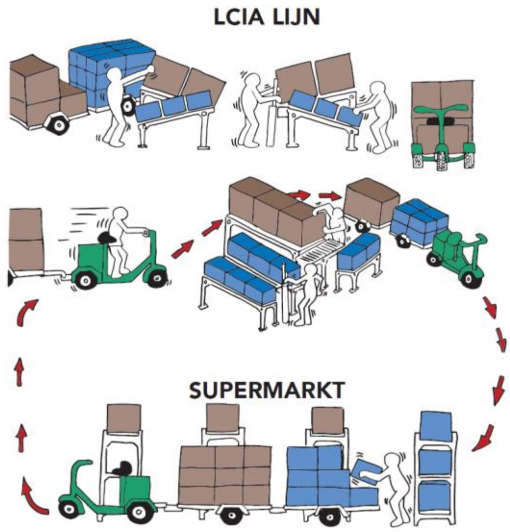


Figure 4: Tugger train line replenishment concept (Ubbink, 2020)

Usually, Ubbink would do minor analysis before the implementation of new systems/processes. Ubbink would learn and make changes accordingly after implementation. However, because of its complexity and importance, Ubbink desires to be well-informed before the new material supply system is launched. As of now, no analysis been done about how the new material supply system should be arranged and implemented for multiple assembly lines.

1.2.2 Problem identification

In the coming years, it is expected that **ten assembly lines will be replaced by assembly lines incorporating the LCIA concept**.
Every assembly line will have a set of jobs (products) scheduled on an assembly day, that need to be executed. Jobs differ from each other with respect to their cycle times and the components that are needed as input to execute the job. The cycle time and the number of components in the job's component bins influence how much supply capacity is needed to fulfil the job demand; some jobs require a lot of tugger train capacity (jobs with high cycle times and low quantity component bins) and some jobs do not require much capacity (jobs with low cycle times and high quantity component bins). Hence, it depends on which jobs are scheduled how much tugger trains are needed to fulfil line demand.

In addition, the limited buffer space of the LCIA lines and the just-in-time functioning of the system, which is desired, make replenishing extra challenging. There is a need for a constant reliable supply to the assembly lines, in order to maintain a high line utilization.

For the LCIA lines to have a high utilization, component stockouts need to be mitigated. After all, one component out of stock at an assembly line, means that the complete assembly line stands still. Hence, the number of component bins in the buffer and the number of tugger trains driving around needs to be sufficient. However, Ubbink also wants to keep costs low by keeping the number of tugger trains driving around low and by keeping the space reserved for line buffers small.

Strategic plans regard decisions defining the organization's direction in the long run. The strategic decision to implement a new material supply system has been made. **A tactical plan should be made to support the implementation of a strategic plan**.

Many important tactical decisions that affect day-to-day operations (operational level), have not been made yet. **Tactical decisions regarding how many tugger trains to possess or how much buffer space needs to be reserved for bin rack placement are still open.**
Furthermore, **there are other undecided tactical factors that affect the average line utilization of a material supply setting (number of tugger trains and buffer levels) at an operational level: way of constructing a schedule, the standard average line utilization target and the plant layout.**
The lack of a tactical plan leads to the identification of one core problem:

There is no tactical plan on how the future material supply system should be arranged

The complexity of the implementation of the new material supply system can be summarized in the problem cluster below (Figure 6).

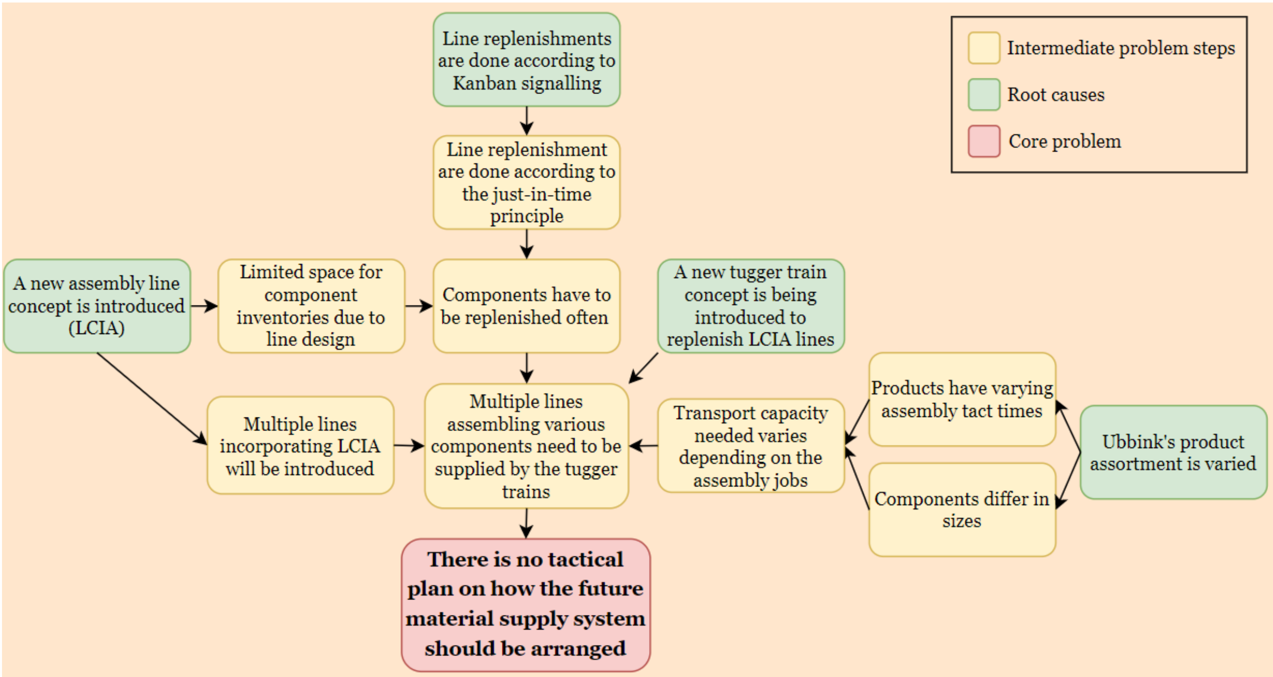


Figure 6: Problem cluster (Heerkens & van Winden, 2012)

1.2.3 Research design

In the previous section, we discussed that the number of tugger trains to purchase and the amount of space to reserve for buffers are tactical planning decisions. In this section, we elaborate more on these decisions, and we explain why these decisions are complex in this case. Finally, we propose our research design.

Research goal

Purchasing tugger trains and increasing buffer levels (or reserving buffer space) comes with a cost. The more trains are purchased, and the more space is reserved for buffers, the higher the cost.

In our research, we want to develop a model which emulates Ubbink's future material supply system, at an operational level. In the model, we include a cost function that depends on decision variables *number of tugger*

trains and *buffer level per line*. We want to solve the model to find **settings of decision variables such that costs are (close to) minimal, all the while we still maintain a target average line utilization, for every scenario**.
The scenarios we consider differ with respect to input factors **input schedule**, **the plant layout,** and the threshold value that Ubbink takes as **target average line utilization.**

The input schedule contains for every line information about the jobs that need to be carried out and their corresponding durations. It is expected that the job content of daily assembly schedules has considerable influence on the average line utilization. Hence, **we want to get an understanding what the effect of a schedule is on the decision variables**. This also includes assessing the effect of job sequencing on the average line utilization. To this end, we introduce a level scheduling model, which helps us to create schedules with minimal variation in supply capacity needed during the day.

At Ubbink, the position of the assembly department is not fixed. To this end, **we want to examine how the different plant layouts impact the decision variables**.
Lastly, **it is unknown to which extent the chosen target average line utilization impacts decision variables.**

Model development

We propose the development of two models, in order to fulfil our research goal. A **level scheduling model** and a **material supply system model**. The material supply system model can be regarded as the main model of this assignment, in which we imitate the functioning of the future material supply system (Table 1).

Table 1: Models to be constructed in this thesis project; level scheduling model and material supply model

Model	Input	Model purpose
Level scheduling model	- Assembly jobs to be executed (unlevelled input schedule) - Cycle times of assembly jobs - Bill of materials (components per job, quantities etc.) - Component bins - Tugger train capacity per hour, for every job	1. Processing (Excel) input 2. Create a level schedule in terms of tugger train transport capacity needed

Material supply model	- Scenario settings
	  - Input schedule
	  - Plant layout
	  - Target average line utilization
	- Tugger train wagon types and capacity
	- Tugger train speed
	- Human handling times
	- Costs of a driving tugger train
	- Costs of adding an extra buffer level per line
	- Bill of materials
	- Component bin per component
		Experimenting; finding a good material supply setting (decision variables) for different scenarios, while keeping the line utilization acceptable

Level scheduling model

Hypothetically, we expect that considerably less tugger trains are needed if we keep the “tugger train capacity” needed during the day level. To this end, we propose the development of **a level scheduling model**; a model that levels the material supply capacity demanded from the lines. So, it needs an (random) input schedule as input and gives a more levelled schedule as output. Basically, if some jobs demand an above average **tugger**

train capacity at a certain time during the day, we would like to compensate this by scheduling jobs on other lines that demand an under average tugger train capacity.

The output of the level scheduling model can be used as input to the main model, the **material supply system model**. To this end, we could evaluate unlevelled schedules and level schedules with the same job content as input for the material supply system and compare their outcomes.

Material supply system model

Secondly, we develop our main model, the material supply system model. In this model, we run the material supply system for various settings of decision variables (material supply settings).

A single run of the model runs one working day and gives the costs and average line utilization as output. Eventually, we want to experiment with material supply settings to find settings with an acceptable average line utilization for (close to) minimal costs for various scenarios. Hence, a solving method should be incorporated in the model.

Running only one working day indicates that the simulation model considers an operational level, which is correct. However, our research goal was to give recommendations on a tactical level. We think that when we consider all the found solutions together, it gives information about the decisions that should be taken on a tactical level.

Research questions

We propose a main research question that guides our research. The answer on this question should provide a solution for our core problem (There is no tactical plan on how the future material supply system should be arranged). Our main research question is formulated as follows:

> *How should the material supply for Ubbink's LCIA lines be arranged at a tactical level?*

The main research question is divided into sub research questions. The sub research questions are divided into more specific research questions on their part.

By answering all the research questions, we get the knowledge we need to answer the main research question. The sequence in which we answer our research questions serves a structural purpose as well, as they guide the research.

In **chapter 3**, we address the literature that considers similar models and their model properties. The aim is to get inspiration and information on how we could construct our models.
In **chapter 4 and chapter 5**, we discuss respectively the design of the level scheduling model and the material supply model. In **chapter 6** we present the result of our models, and we discuss the model results. In the last chapter, **chapter 7**, we conclude the research by giving a conclusion and recommendations.

Chapter 2: Problem context

In the first part of this chapter, we want to learn about the current processes that concern material supply within Ubbink. This part is covered in research question *1.1* to *1.3*. We get our knowledge by interviewing Ubbink employees, and we may review literature or use books to see how Ubbink's processes relate to theory.
In research question 2, we dive into the design of the future material supply system. This is the situation that is the most important for this project, as we model the future material supply system.

Research question 1: What is the current situation with regards to material supply within Ubbink?
1.1 What is the current layout of the plant?
1.2 Which different ways can a part flow through Ubbink's plant?
1.3 How is the material supply process to assembly lines currently arranged?

Research question 2: What is the future situation with regards to material supply within Ubbink?
2.1 How does the newly adopted Lean philosophy impact Ubbink?
2.2 How is Ubbink going to integrate Kanban, LCIA, Lean supermarkets and tugger trains into the new material supply system?
2.3 What could be the future layout of the plant?

Chapter 3: Literature study

In chapter 3, we do a literature study. The aim of this literature study is to answer two research questions, which focus each on one of the two models that we want to construct: the level scheduling model and the material supply model.

Basically, we want to get an impression of similar problem instances that have been considered and how those instances were modelled. Based on our findings, we want to come up with our own modelling approach which suits our situation.

Research question 3: How can we model an application that produces a level assembly schedule?
3.1 What objective is most suitable to minimize the amount of variation of supply capacity needed in a schedule?
3.2 What solving approach is most suitable for our application?

Research question 4: How can we model the material supply system?
4.1 How are the key concepts of the material supply system treated in the literature?
4.2 Which modelling approach is most suitable to model our material supply system (considering Kanban controlled replenishments using tugger trains)?
4.3 How can we include a solving approach in the model, with the aim to minimize costs against a predefined average line utilization?

Chapter 4&5: Model design - Level scheduling model and the simulation model

In chapter 4 and 5, discuss the design of our models. Research question 5 and its sub research question guides us in describing the design of the model. However, it does depend on the model which sub research questions are relevant, but most sub research questions can be answered for either model.

Research question 5: How are we going to design our models?
5.1 How can we describe the model conceptually?
5.2 How can we formulate the model mathematically?
5.3 How can we describe processes and solving approaches with flow charts?
5.4 How correct is the implementation of the model?
5.5 How valid is our model for Ubbink's future situation?

Chapter 6: Results and discussion

In chapter 6, we present and discuss the results of the level scheduling model and subsequently the material supply system model.

Research question 6: What are the results of the material supply model?
6.1 What are the results of the regular scenarios that are solved with the material supply model?
6.2 How do the results of similar regular scenarios, that differ with respect to only one input factor, compare with each other?
6.3 How sensitive are regular scenario results with respect to changes of fixed input parameters?
6.4 What components are a high risk to component stockouts?

Chapter 7: Conclusion and recommendations

This is the last chapter of our thesis. Here, we give our final conclusions, and we give recommendations based on our findings.

Research question 7: What conclusion and recommendations can we give based on the results?
7.1 What recommendations can we give Ubbink on how they should arrange their material supply the coming years, considering a tactical level?
7.2 How does this thesis assignment add to the body of knowledge?
7.3 How does this thesis assignment contribute to practice?
7.4 What are limitations of the research?
7.5 What research areas would be interesting to consider for future research/analysis?

1.3 Methodology

As a methodology for this thesis project, we follow the first 3 steps as proposed by (Heerkens & van Winden, 2012).

Phase 1: Problem identification
Phase 2: Formulating the problem approach
Phase 3: The problem analysis

After step 3, we deviate from the by Heerkens & van Winden (2012) prescribed seven phases, as we feel it does not fit this assignment. We propose the next following steps:

Phase 4: Finding suitable modelling / solution approaches
Phase 5: Apply the modelling / solution approach
Phase 6: Verify and validate the model / solution approach
Phase 7: Process results
Phase 8: Conclusion and recommendations

Phase 1 and phase 2 have already been executed in respectively chapter 1.2.2 and chapter 1.2.3. In chapter 1.2.2, we have constructed a problem cluster, which serves as an overview of the relationships between various ongoing developments at Ubbink. From our problem cluster, we selected a core problem that we tackle in this thesis assignment. Our core problem is defined as an action problem, which is a discrepancy between the norm and the reality.
Subsequently, we asked ourselves what we need to know in order to come up with a solution for our core problem. This was **phase 2**, "formulating the problem approach". In this phase, we composed knowledge

problems (research questions) that we need to answer to get the information we need. The section in which we composed the research questions is called "research design" (chapter 1.2.3).

In chapter 2, we do the problem analysis (**phase 3**). Here, we analyse the problem context more in depth. We divide this analysis into two pieces; we analyse the current situation and the future situation with respect to the material supply system.

In chapter 3, we review literature to learn about different perspectives in which we could approach/model our problem. This is **phase 4**. Eventually, we want to come up with our own approach and build our models accordingly, in which we integrate our situation with findings of the literature study. We also discuss the data requirements of the various methods we find, as it could be a decisive factor in choosing a modelling approach that fits our situation.

In **phase 5**, we apply the modelling approaches we found to our own situation. We construct the model(s) and explain how they work. We also discuss what we took as input data of our model. This is done in chapter 4 and 5, which regard the design of the models. Additionally, we discuss the validity of our model(s) and we verify the correctness of our model(s) (**phase 6**).

In chapter 6, we present and discuss our results (**phase 7**).
We finish off by giving conclusions and recommendations based on our findings (**phase 8**). This is done in the last chapter, chapter 7. Figure 7 summarizes our methodology.

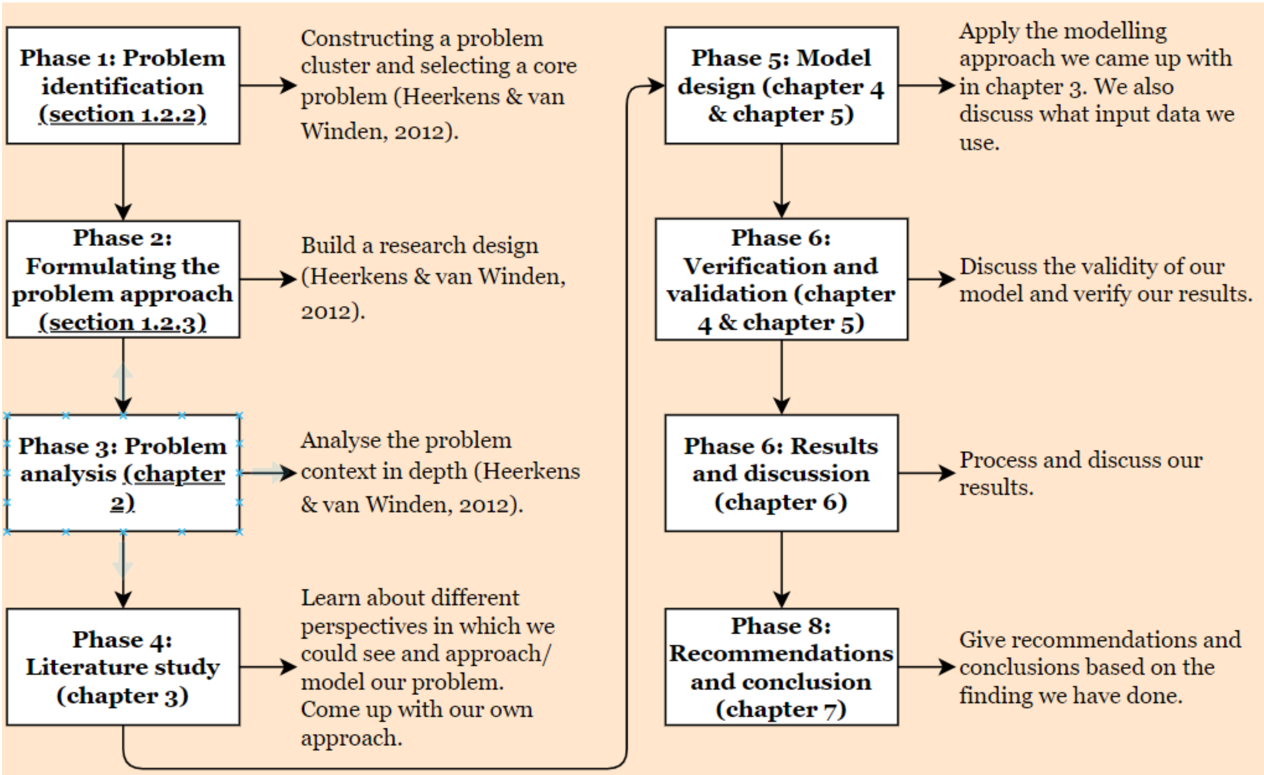


Figure 7: Methodology

2. Problem context

In this chapter, we zoom in on the **current situation** at Ubbink, as well as the **future situation with respect to material supply to the assembly lines**. The two situations together form the problem context, that we need to understand to move to further stages in the project. Eventually, the future situation becomes a more relevant subject as that is the situation for which we construct a model.

We start this chapter off by providing the current layout of Ubbink's plant in chapter 2.1.
In chapter 2.2 we discuss the possible part flows through the Ubbink plant.
In chapter 2.3 we analyse how the material supply process is currently carried out.
In chapter 2.4, we start describing the future situation at the Ubbink plant. In this section, we explain what Lean Manufacturing means, supported by literature findings.
In chapter 2.5 we explain the futuristic material supply system, with LCIA lines, Lean supermarkets, tugger trains and Kanban controlled replenishments. We discuss the key elements of the material supply system and how these elements interact with each other. The statements made in this section are supported by literature findings.
Chapter 2.6 addresses the possible new locations that LCIA lines could have in a future layout. A new allocation of the assembly lines impacts the performance of the material supply system.

Research question 1: What is the current situation with regards to material supply within Ubbink?
1.1 What is the current layout of the plant?
1.2 Which different ways can a part flow through Ubbink's plant?
1.3 How is the material supply process to assembly lines currently arranged?

Research question 2: What is the future situation with regards to material supply within Ubbink?
2.1 How does the newly adopted Lean philosophy impact Ubbink?
2.2 How is Ubbink going to integrate Kanban, LCIA, Lean supermarkets and tugger trains into the new material supply system?
2.3 What could be the future layout of the plant?

Figure 8: Research questions answered in chapter 2

2.1 Ubbink's plant layout

Figure 9 shows Ubbink's plant layout. The different departments within Ubbink's plant are dedicated to different categories: production, assembly, storage, or pre-assembly operations. In this section, we discuss per category what departments belong to that category.

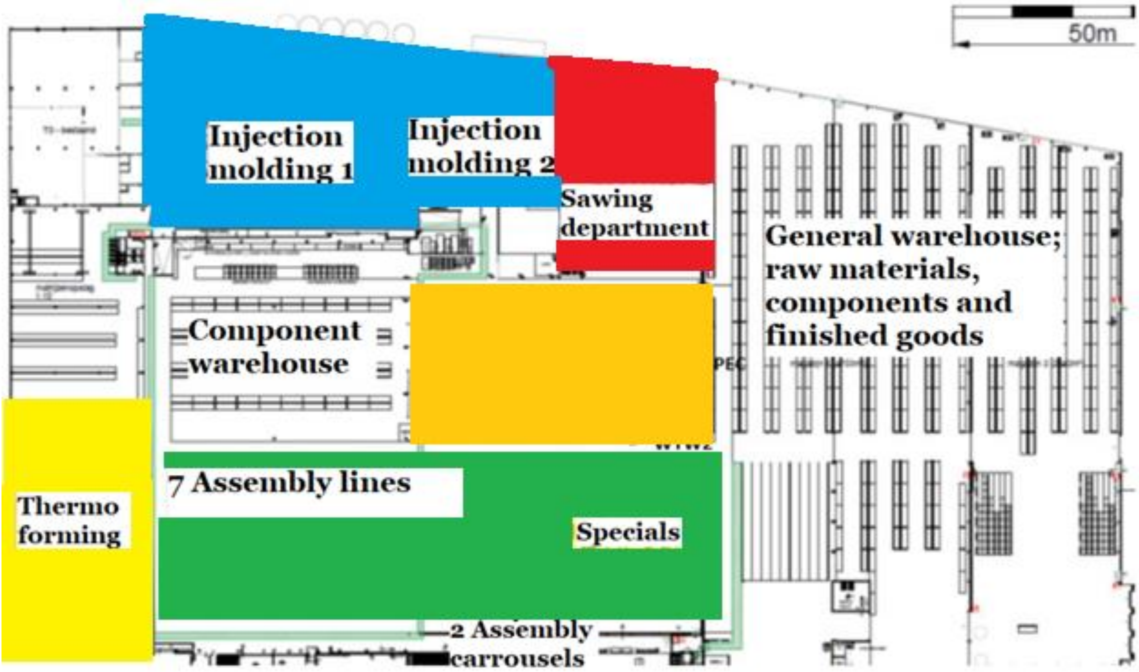


Figure 9: Plan of Ubbink's plant

2.1.1 Production

At the production department, raw material is turned into something useful, which can either be sold directly to a customer or can be used as a component for assembly.
Production can be divided in two different departments: **injection moulding and thermo forming.** The injection moulding machines operate **b** hours every day. The four thermo forming machines only operate **c** hours, every weekday.

Injection moulding and thermo forming both produce plastic parts by means of forming plastic with heat. However, the production processes differ a lot from each other.
By far, most plastic parts are being produced by means of injection moulding at Ubbink. In 2020, **d** parts were produced by means of thermo forming. On the other hand, **e** parts were produced by injection moulding. So that means that there are **f** parts produced with injection moulding for every part produced by means of thermo forming.

2.1.2 Assembly

Multiple assembly concepts are incorporated by Ubbink. There are concepts where multiple workers work in a sequence, single-person workstations, multi-person workstations and there is a carousel concept. For sake of simplicity, we refer to every area that is dedicated to assembly as an assembly line.

Every assembly line needs multiple components as input, after which they are assembled to create a finished product. Most of the assembly lines only operate during an 8-hour day shift. Some lines, however, are operational for a longer time period. Assembly is the most labour intensive department at the Ubbink plant.

Figure 9 shows where the assembly lines are located. In this thesis, we focus on the seven assembly lines on the left, the two assembly lines (carrousels) on the right and a new assembly line where a new product family called

Large product of Line X is going to be assembled. **These ten assembly lines will be replaced by LCIA lines** and therefore they will rely on **the new material supply system** as well.

2.1.3 Storage

We can differentiate between three different goods that are stored: raw materials (including packaging material), components (unfinished goods that need assembling) and finished goods.

Ubbink has three distinct storage locations: a component warehouse and a general warehouse both located at the plant in Doesburg and an extra warehouse in Zevenaar. In the component warehouse, only components are stored that need further processing at the assembly stations. The general warehouse contains raw materials, components, and finished goods.

Table 2: Division of storage components at Ubbink's storage locations

	Raw materials	**Components**	**Finished goods**	**TOTAL**
Average number of EURO pallet spaces occupied	Confidential	Confidential	Confidential	Confidential

2.1.4 Pre-assembly operations

Ubbink houses a sawing department, where tubes are sawed to smaller components. These components are used in assembly. There are some other small departments that execute pre-assembly operations. However, this falls outside the scope of this thesis.

2.2 Part flow

One single unit, which has been manufactured but not connected to other parts yet, is what we define as a **part.** A part can either be produced in-house, or the part is bought from an external supplier (outsourcing included). Additionally, a part can be used as input for assembly, or the part can be stored and sold to the customer directly without assembling. Combined, every part flows according to one of four (2x2) possible flows through the Ubbink plant.

Table 3 shows the four possible flows and their corresponding percentages, to indicate how much that flow is used. We consider the parts whose production was outsourced to come from an external supplier, so these parts are considered to follow either flow 3 or flow 4.

Table 3: The four possible flow possibilities at the Ubbink plant

Flows	Percentage of output per flow (in terms of numbers of pallets)
Flow 1: (Thermo forming or Injection moulding) – (Component warehouse or General warehouse) – Assembly – General warehouse - Customer	Confidential%
Flow 2: (Thermo forming or Injection moulding) - General warehouse - Customer	Confidential%
Flow 3: External supplier – (Component warehouse or General warehouse) – Assembly – General warehouse - Customer	Confidential%
Flow 4: External supplier - General warehouse - Customer	Confidential%

At Ubbink, most parts are produced in-house and therefore they follow either flow 1 or flow 2. These parts start as a (combination of) raw material(s) and enter either the injection moulding process or the thermo forming process.

After production, a flow 1 part goes either to the component warehouse or the general warehouse. After storage, the part gets picked again by an order picker to be brought to an assembly line. After execution of the assembly process, the part is a component of an assembled product. This product is brought to the general warehouse where it is stored until it is shipped to a customer.

Parts that follow flow 2 skip the assembly process. These parts go directly to the general warehouse after production. There, they await shipment to the customer.

Parts that follow flow 3 or flow 4 come from external suppliers. These parts are either; stored, assembled, and stored again waiting for shipment (flow 3) or they are just simply stored to be resold (flow 4).

The parts that are interesting for this thesis are those of either flow 1 or flow 3, since these flows incorporate material supply to the assembly lines. Figure 10 shows the flow chart diagram of flow 1. Here, the material supply process is highlighted. Appendix 1 shows the flow chart diagrams of all four flows.

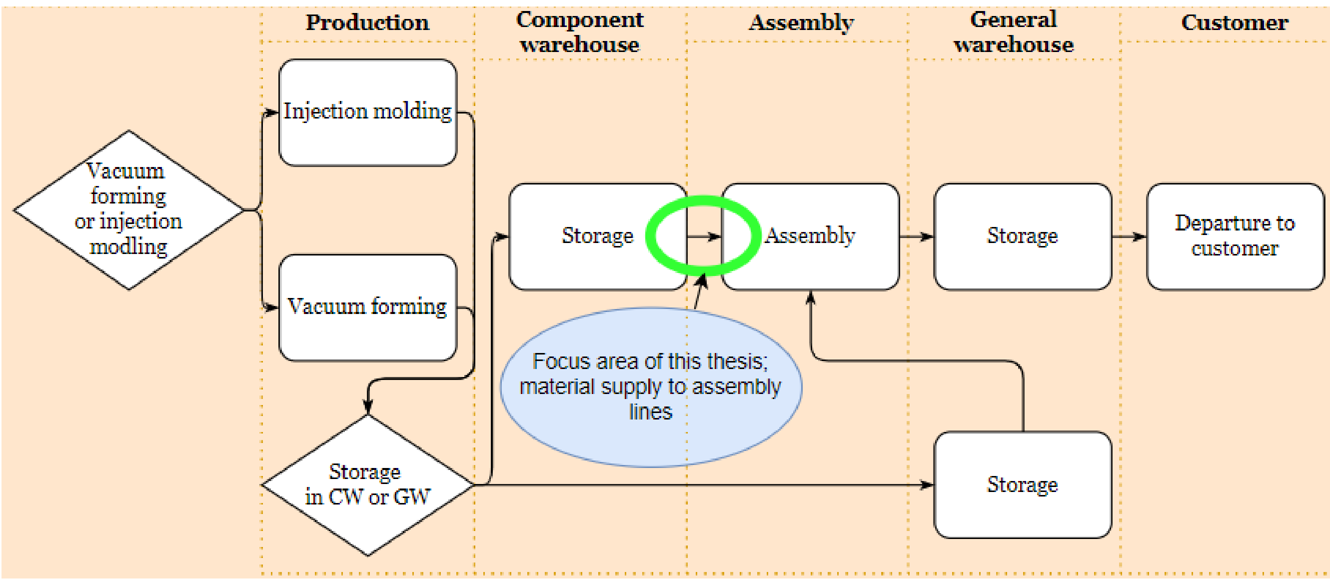


Figure 10: Flow 1 (highlighted the focus area of this assignment: material supply to assembly lines)

2.3 Current planning and material supply process

Ubbink has a few planners employed that schedule the jobs that need to be executed at the assembly lines. Each planner has a set of assembly lines for which he is responsible. Every week, the planners at Ubbink construct a new assembly schedule for the next week. The week plan contains for every line information about the jobs that need to be executed, the amounts to be assembled and the day it is scheduled to be assembled.

The assembly week plan is forwarded to two parties: the assembly line workers and the warehouse workers. It gives both parties an overview of what respectively must assembled and supplied at a certain time in the week. However, it is up to the planners to decide when to release jobs to be picked and to be assembled.

Currently, the picklists are released one or two days before the job is actually scheduled. This gives the warehouse workers the possibility to move the components in the warehouse to a place closer to the assembly lines. When this has been done, the picklist is put back in a closet. Now, it is up to runners to take the picklist again. Runners work in assembly and handle communication with planners and the warehouse pickers. The runners give the warehouse pickers the picklist shortly before the components are needed. Now, it is up to the warehouse pickers to replenish the lines with the components stated on the picklist.
Runners and warehouse pickers usually communicate by talking and calling with each other. The communication between the assembly line runner and the warehouse pickers can be described as ad hoc.

2.4 Lean manufacturing at Ubbink

Under the current operations manager, a "Lean manufacturing" revolution has started. Consequently, many business processes are going to change. In this section we discuss the Lean manufacturing philosophy and how it is going to be adopted at Ubbink.

Lean manufacturing was for the first time successfully implemented by Toyota, more than half a century ago. According to Bicheno & Holweg (2000), the aim of Lean manufacturing is to facilitate an uninterrupted flow in a sequence of operations that deliver perfect quality. The achieve this, continuous improvement in three dimensions is needed: waste reduction, value enhancement and people involvement.

Womack & Jones (1997) presents the term a "Lean way of thinking". The term represents the underlying improvement activities of the Lean approach. Womack and Jones recognize 5 principles for Lean thinking:

- **Specifying value:** Value should be specified from the perspective of the customer; customers buy results, not products.
- **Identifying the value stream:** The value stream considers all actors that bring the product to the customer, and their actions.
- **Flow:** Eliminate wasteful handling actions and movements. Avoid queues, inventories, and big batches.
- **Pull:** Let the customer pull the product from you. Production should answer actual demand.
- **Pursuing perfection:** There is always room to improve.

Becoming a company that fully adopts the Lean manufacturing philosophy takes time and may be difficult to maintain in practice. A shift in the mindset of employees working at the company is needed.

To which extent Ubbink can adopt Lean manufacturing remains to be seen, but developments in the right direction have been initiated and the feasibility of other Lean-oriented developments is being assessed.

2.5 Future material supply process

One of the processes that is subject to change due to adaptation of Lean manufacturing is the material supply process to the assembly lines.
We consider there to be **four new concepts**, that together form the **new material supply system** to the assembly lines: **Low-Cost Intelligence Automation (LCIA), The tugger train material supply concept, Kanban controlled replenishments** and **the Lean supermarket.**
In chapter 2.5.5, we explain how these four concepts together form the new material supply system.

2.5.1 Low Cost Intelligence Automation

A new assembly line concept called Low Cost Intelligent Automation (LCIA) is introduced to replace the existing, outdated, assembly lines.
LCIA serves as an optimal combination between machine and human. The strong points of machines are to execute a repetitive task with precision, without getting tired. Humans are able to observe the process, detect errors and it may be more cost-efficient to let humans execute single handling tasks (Blom Consultancy, 2011). Human functioning is the key focus of LCIA line design.

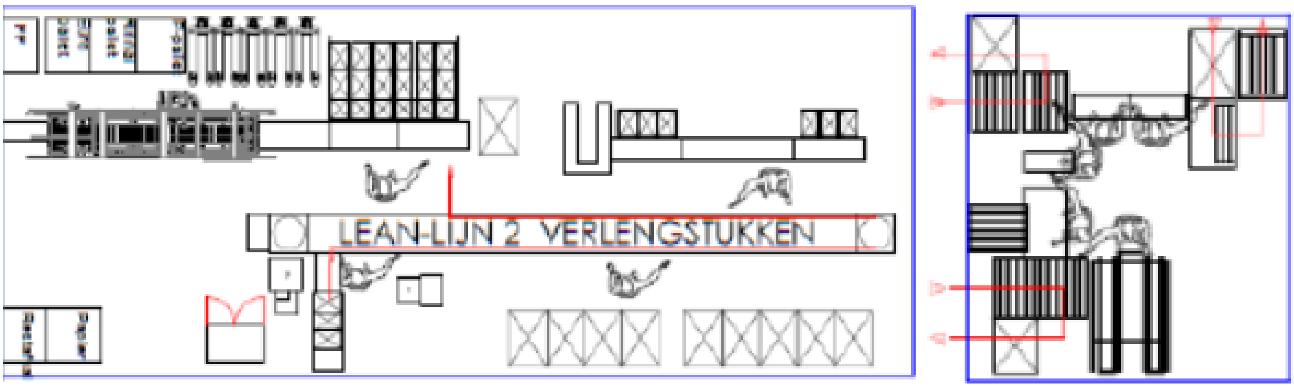
Usually, the design of a LCIA line is a **U-shape**. Workers working at a LCIA line have their own prescribed set of tasks. The workload per worker is balanced out by means of a Yamazumi analysis.

A key principle of LCIA is that **the worker that initialises the assembly process at the line, also finishes the assembly process**. So, the worker at the first workplace determines the pace of the assembly process. LCIA can be applied to all sorts of products and the size of the line could vary, depending on the type of product.

Other properties of a LCIA line are that the line is **as compact as possible** and that components are within reach of the workers. In the design, **unergonomic and unnecessary handling is reduced to a minimum**. The goal is to establish a flow.

There is limited space for WIP (work-in-progress) inventories reserved at the line, but these are deemed undesirable anyways at Ubbink.
Figure 11 shows how an old line concept at Ubbink compares to the proposed design of a LCIA line at Ubbink.

Figure 11: Old assembly line concept vs LCIA concept



The advantages of LCIA compared to conventional line designs can be recognized in three domains: productivity, flexibility and quality (Takeda, 2011).

Productivity

In the design of the LICA line, unnecessary handling and movements are minimized, which increases the percentage of handling and movements that add value.

Because the strong points of human and machine are recognized, the repetitive and precise tasks are automated. Playing into the strengths of both actors increases the overall productivity of the assembly process. There is not much room for work-in-progress inventory at a LCIA line. This prevents the line from becoming chaotic. It also keeps the line workable and prevents workers from becoming stressed, which could harm productivity.

Flexibility

LCIA lines are flexible in multiple domains; LCIA lines offer labour flexibility, product flexibility and they are movable.
A LCIA line offers labour flexibility as the line can be operated by a varying number of people. For example, a LCIA line can be operated by 3 persons, but two persons or one person can also keep the line running. Logically, the output per time unit decreases when the labour input decreases, and it increases when labour input increases. Nevertheless, it is a convenient for manufacturers to be able to scale labour input.

LCIA lines can be designed in such a way that various products can be assembled on the same line, which increases its product variety compared to those of old assembly line concepts.

The last domain of flexibility regards the movability of a LCIA line. No time-consuming instalment process needs to be carried out and no long reinstalment process is needed to place a LCIA line at another location.

Quality

The line is designed in such a way that it is intuitive what the next step is in the assembly process. Secondly, precise handling is automated as much as possible, preventing human errors from happening (Poke Yoke). Additionally, it is common to make use of sensors in the line, which scan the product, and thus execute an automated inspection of product quality.

2.5.2 Kanban controlled replenishments

Typically, Lean manufacturing systems make use of Kanban signalling to facilitate their pull system. Smalley (2017) explains Kanban as follows: Kanban can be seen an internal communication system, where the material handover process is facilitated by a Kanban system. If a downstream process consumes parts, there are Kanban signals sent back to the process upwards to replenish the consumed amount. Kanban signalling can be facilitated by the visual of an empty bin, with cards or with electronical signals. There are various different Kanban systems.

Ubbink wants to employ a Kanban system to trigger the component replenishments of assembly lines. The Kanban system that Ubbink adopts is similar to the well-known Kanban 2-bins system (Kanet & Wells, 2019). The classic form of a Kanban 2-bins system considers two bins storage. The first bin can be considered a working bin and the second bin can be considered a reserve bin. The working bin is the bin from which components are

taken to assemble with. The reserve bin becomes the working bin whenever the first bin is empty. When a bin is consumed, the empty bin becomes a signal that a new bin should be supplied. The reserve bin has to cover demand during the time it takes to supply a new bin. At Ubbink, the Kanban 2-bins system has a different form.\
The Kanban system that Ubbink adopts is similar to the 2-bins system, except for the fact that Ubbink does not restrict itself on only two bins in the buffer space, per component type. The amount of reserve bins is variable in Ubbink's Kanban system. Therefore, the amount of bin places per assembly line is considered to be a decision variable in the material supply system model.

Attached to every bin is a Kanban card with information about the component bin. When an empty bin is picked, the Kanban card is detached and used to pick the correct bin again from the supermarket. Figure 12 shows a bin rack that facilitates *container* bin storage at Ubbink. In the figure, there is place for one working bin and two reserve bins. When a *container* is empty, it is flipped to the other side of the rack waiting to be picked up. Figure 13 shows the design of a Kanban card that is used at Ubbink.

Figure 13: Rack with 3 container bins filled with components, at Ubbink (Kanban 2-bin system)

Figure 12: Design of a Kanban Card at Ubbink

2.5.3 Tugger trains

The idea is to adopt internal transportation with tugger trains, to move component bins to and from the LCIA lines. A tugger train consists out of a front part which resembles the locomotive of a real train. The front part pulls the three wagons, on which bins are stored, forward. The tugger train drives along the assembly lines, picking empty bins and replenishing the assembly lines with full bins.

The concept in which a tugger train replenishes assembly lines is also known as a Milk run system (Simić et al, 2020). Based on this terminology, a tour is called a milk run and the driver is called a milk man.

2.5.4 Lean supermarket

Kovács (2012) describes the Lean supermarket as a dedicated storage place between two processes where a prescribed amount of component inventory is stored. According to Kovács, the function of the supermarket is to store products to supply a downstream process. The supermarket should be able to cope with product

variations and/or batch sizes, without this leading to interruptions. He adds to this that the supermarket should be established close to the production area as this can decrease the risk and lead time of material supply.
Ubbink introduces three supermarkets, where the tugger train is going to pick components from. Supermarket 1 stores tube components, Supermarket 2 stores small components like labels and stickers and Supermarket 3 offers the rest of the components. The supermarkets are replenished by the warehouse frequently, to make sure they do not get out of stock. In chapter 2.6, we discuss the proposed locations of the supermarkets in the plant.

2.5.5 Functioning of the material supply system

In the previous section, we discussed the introduction of the concepts: **Low-Cost Intelligence Automation (LCIA), The tugger train material supply concept, Kanban controlled replenishments** and **the Lean supermarket.** In this paragraph, we summarize the relationships between these concepts and how they facilitate the new material supply system together.

For every finished product that is manufactured, the component inventory at the LCIA line decreases. Hence, the line needs to be fed consistently with components.

The LCIA lines possess bin storage racks for every component. Every component type has a **component-specific bin,** which is predetermined per component; a bin can either be a ***container***, an ***end box***, a ***quarter meter box***, a ***half meter box*** or a ***one meter box***. In order to communicate when certain components should be replenished, an empty bin with a Kanban card attached to it is flipped to the other side of the storage rack.

The number of components that fit within a bin is referred to as the **Kanban size**. The Kanban size of a component depends on the component's **Bin type** (table 4) and the size of the component. Consequently, the Kanban size is a fixed number for every component type individually.

Table 4: Different bin types at Ubbink that are part of the future material supply system

Bin types	Bin description	Component type
Container	Blue crate (60x40x30 cm)	Most of the assortment; all components that are not carried by the other bin types
Quarter meter box	Box (25x60x80 cm)	Smallest tube components
Half meter box	Box (50x60x80 cm)	Medium sized tube components
One meter box	Box (120x80x105 cm)	Large tube components
End box	Chest (150x80x60)	Final box components

We have analysed for every of the ten assembly lines that we consider, which five jobs are executed the most. For these jobs, all components that are input to the assembly process are identified and per component, the bin type is given. In figure 14, it is visualized how the bin types are distributed with respect to all jobs for which we have identified the bin type.
Additionally, we have visualized what the average Kanban size is per bin type considering all identified components with figure 15. Appendix 2 summarizes for every assembly line the jobs we have identified, the components that belong to those jobs and their corresponding bin types and Kanban sizes.

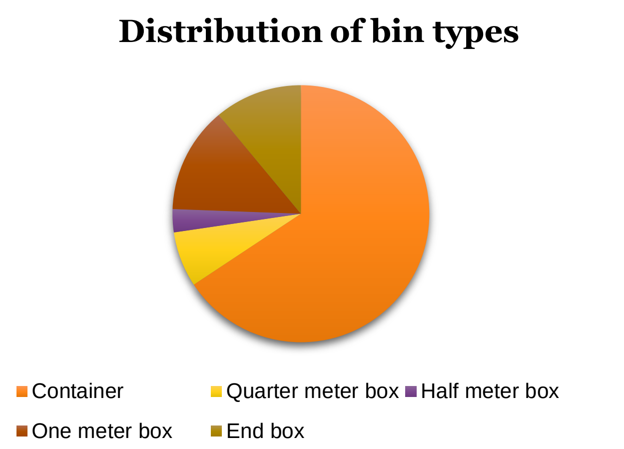


Figure 15: Distribution of bin types across Ubbink's component (that are identified in this assignment)

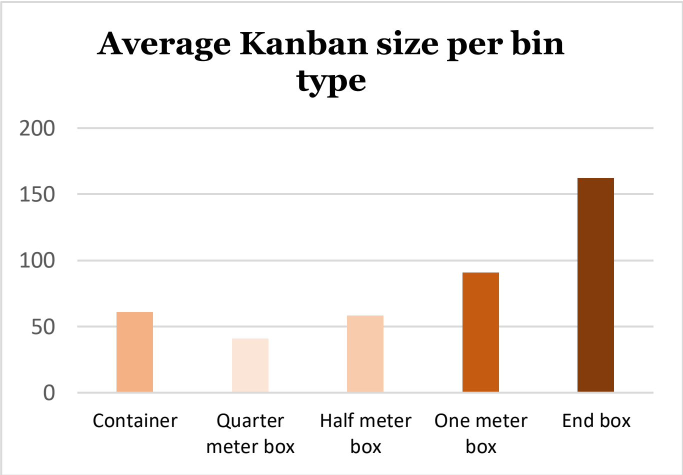


Figure 14: Average Kanban size per bin type (Kanban sizes ≥ 1000 excluded)

Tugger train and Kanban

The tugger train driver drives tours, or "milk runs", to replenish the assembly lines with full component bins and to take empty bins. After picking an empty bin, the Kanban card is detached from the bin and the empty bin is loaded on one of the three tugger train wagons. The tugger train driver brings the empty bins to the packing place for storage.

The Kanban card contains information about the bin that should be picked from the supermarket to replenish the lines. The supermarkets on their part are replenished by the warehouse.

After picking components from the supermarket and loading them on the wagons, the tugger train drives to the assembly lines to replenish the lines. The bins that are now empty are loaded on the tugger train again and the Kanban cards are detached from the bin. A new tour has started by now, and the process repeats itself. Figure 17 summarizes all the tasks a tugger driver executes in a tour.

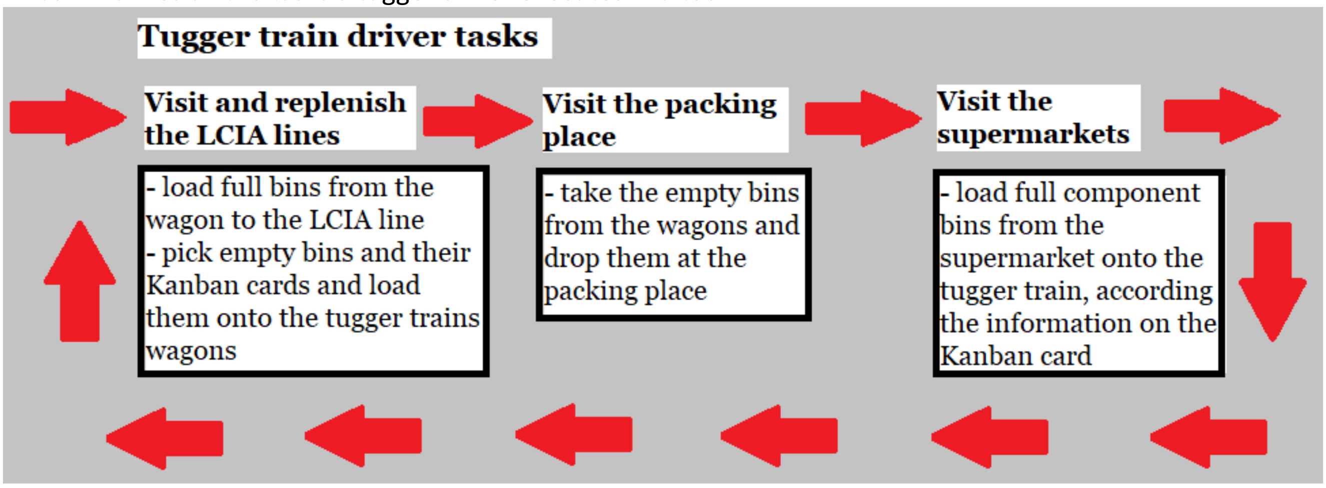


Figure 16: Tugger train driver tasks

Every tugger train pulls three different wagons forward. These different wagons have different properties (Table 5, Table 6 and Figure 16).

Table 6: Wagon properties of the wagons of the tugger train

Wagon	Bin carries	Bin capacity
Wagon 1	Containers, quarter meter boxes, half meter boxes	32 containers, or 16 quarter meter boxes, or 8 half meter boxes
Wagon 2	Final box chest	One final box component
Wagon 3	One meter boxes	2 one meter boxes

Table 5: Wagon capacity that is needed for one bin, per bin

Bin type	Capacity needed
Container	1/32 of wagon 1
Quarter meter box	1/16 of wagon 1
Half meter box	1/8 of wagon 1
Final box	1 wagon 2
One meter box	½ wagon 3

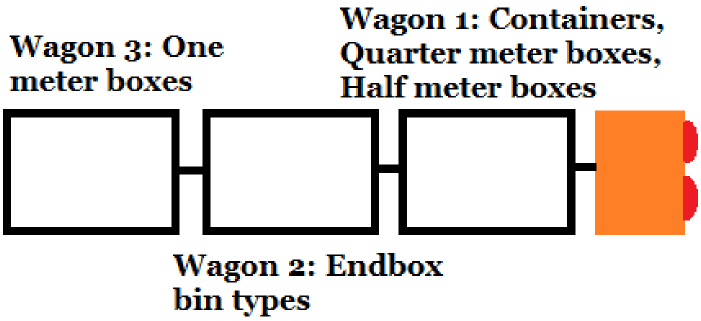


Figure 17: Tugger train wagon types

The Kanban system that Ubbink adopts is a closed system. Whenever a Kanban card is detached from an empty bin, it comes back attached to a full bin eventually. Therefore, the same number of Kanban cards always stay in the system.

2.6 Future layout

In this section we discuss where the supermarkets are located, and which assembly lines are replaced by LCIA lines. We finish the section by discussing the possibilities to alter the current layout.

2.6.1 Supermarkets and the packing place

Figure 17 below shows the proposed locations of the three supermarkets (1, 2 and 3) and the packing place. Supermarket 1 is going to store tube components. Hence, it is located close to the sawing department where tube components are sawed to their right dimensions. Supermarket 2 is going to store small components like stickers and labels. Supermarket 3 is located in the warehouse. It is the biggest supermarket, and it offers all the components that the other supermarkets do not offer.
The packing place is the location where empty bins can be dropped, at the end of every tour

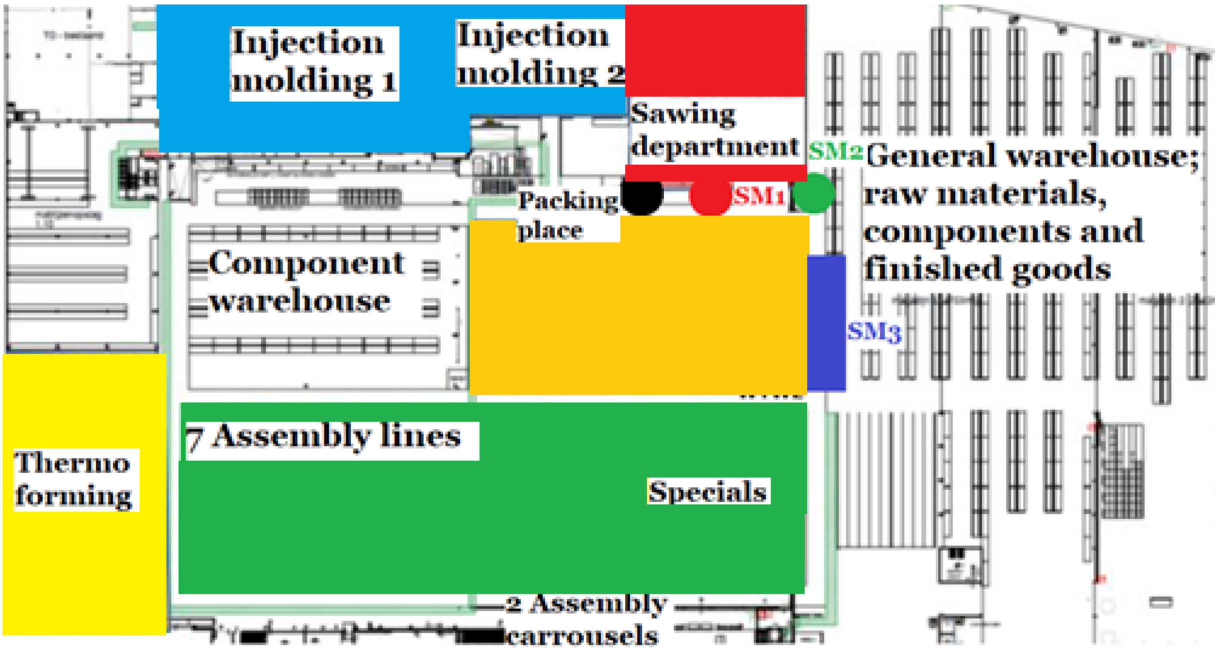


Figure 18: Ubbink plan with the proposed supermarket locations (A, B, C) and the packing place

2.6.2 LCIA lines

Figure 19 also shows which assembly lines become LCIA lines in the green rectangle. Seven assembly lines and 2 assembly carrousels will become LCIA lines, making it that 9 LCIA lines will be introduced. In addition, a new product called Large product of Line X will be introduced, for which an additional LCIA line will be introduced. Hence, we consider the introduction of 10 LCIA lines in the thesis.
There are possibilities to position the LCIA lines closer to the supermarkets, as opposed to the indicated position within the rectangle. Figure 18 shows another possible layout which positions the LCIA lines closer to the supermarkets (in the orange area).

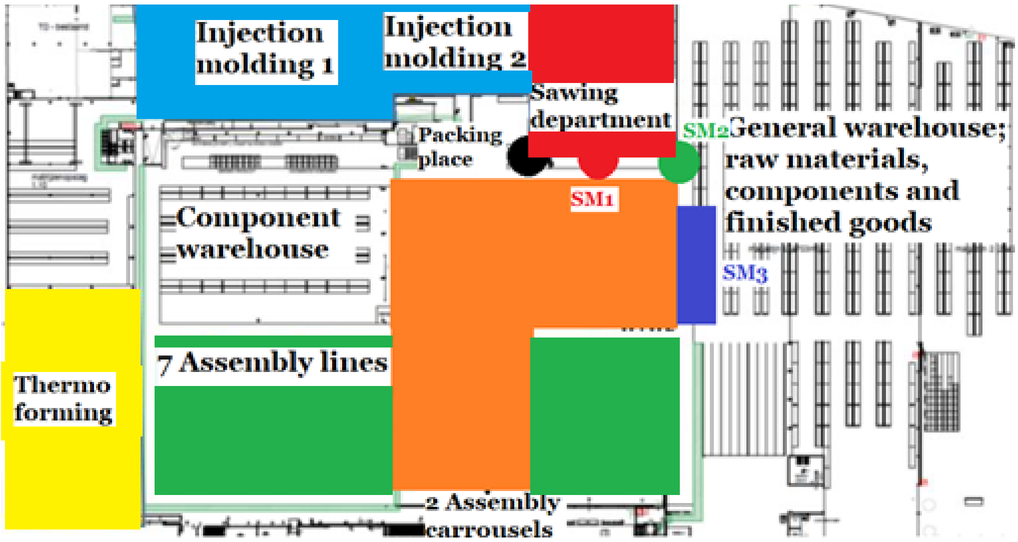


Figure 19: Possible new location of LCIA lines, closer to the supermarkets

2.7 Conclusion

A new material supply system is adopted at Ubbink. In the future, +10 assembly lines will act as customers in this system. The most important concepts of the new material supply system are: **Low-Cost Intelligence Automation (LCIA), tugger trains, Kanban controlled replenishments** and **the Lean supermarket.**

In short, the tugger train driver has 4 main tasks:

- Taking empty bins and the corresponding Kanban card from the assembly lines
- Bringing empty bins to the packing place and storing them there
- Loading new (full) bins from the supermarkets onto the tugger train
- Loading the new full bins from the tugger train on the assembly lines

3. Literature study

This literature study helps us to find inspiration and information, to come up with our own solution design, that is tailored to solving our core problem. In this project, the solution approach consists out of the construction of two models; a **level scheduling model** and a **material supply system model.** In this literature study, we find modelling approaches for both our models.
We have utilized the literature database of Scopus for this literature study.

Research question 3: How can we model an application that produces a level assembly schedule?
3.1 What objective is most suitable to minimize the amount of variation of supply capacity needed in a schedule?
3.2 What solving approach is most suitable for our application?

Research question 4: How can we model the material supply system?
4.1 How are the key concepts of the material supply system viewed in the literature?
4.2 Which modelling approach is most suitable to model our material supply system (considering Kanban controlled replenishments using tugger trains)?
4.3 How can we include a solving approach in the model, in which the aim is to minimize costs against a predefined average line utilization?

Figure 20: Research questions answered in the literature study, chapter 3

We divide this literature study in two sections. In chapter 3.1, we discuss literature that considers similar problem instances as levelling in-house supply capacity. We end this section with by drawing a conclusion. Here, we highlight our most interesting findings, and we conclude what information we use to build our application.

In chapter 3.2, we analyse literature that considers similar material supply concepts as we have in Ubbink's future material supply system. We start with a brief literature study about key concepts of the new material supply system. After, we investigate literature that has considered Kanban controlled replenishments by using tugger trains. Here, we look to find literature studies that have modelled this situation, preferably modelling instances that considered multiple scenarios, with similar decision variables and a similar objective. We end this section with a conclusion.

3.1 Levelling in-house supply capacity

In this section, we review literature to find suitable objectives that we could adopt in our level scheduling model. Secondly, we review what solving approaches have been used and we determine what is most suitable for our level scheduling application.

In the future, Ubbink will have multiple assembly lines asking for part supply by the tugger train(s). In order to keep in-house supply capacity constant, we have to create an assembly schedule which reduces the variation in component demand over all the assembly lines during the day.

In the literature, problems that consider levelling part demand are referred to as the "level scheduling problem" (LSP). The "level scheduling problem" can be regarded as a collective name, under which several problems fall that consider levelling part demand or part supply. The ORVP problem is such a "level scheduling problem". The ORVP has the objective to minimize the variation in output of particularly production processes (Kubiak & Sethi, 1991). A levelled output at the production facility leads to a levelled input at the subsequent assembly facility.

The specific problem of levelling inputs to level the capacity of part supply has not been considered much. Therefore, we review literature that considered similar problems (like the ORVP), to find useful information for our own application.

3.1.1 The modelling objective

Level scheduling was first considered in the well-known book called Toyota Production System (Monden, 1998). Monden was Professor at the Tsukuba University in Japan. He published the first version of his book in 1983. In order to solve the output variation problem for a single mixed model assembly line, Monden developed a simple greedy heuristic called the goal-chasing method, which did not produce high quality results.

In reaction to Monden's contribution, more researchers started to consider the problem of level scheduling. Kubiak & Sethi (1991) provide a mathematical formulation for the level scheduling for a single mixed-model assembly line in just-in-time production systems. The "levelling" is focussed on output in this case.

What is interesting for our application is that the objective function in Monden's mathematical model aims to minimize the total quadratic difference between the real amount of cumulatively produced parts and the desired amount of cumulatively produced parts.

We could use a similar objective for our problem. We could determine, based on the jobs that need to be done on a particular day, what the average supply capacity needed per hour (or a different time bucket for that matter) is. The average supply capacity needed per time bucket can be considered to be the desired supply capacity per time bucket. The aim would be to minimize the difference between the desired amount of supply capacity and the real supply capacity needed to replenish the assembly lines, as a sum over all time buckets.

Other literature sources that also considered the OVRP have made use of similar mathematical formulations as Kubiak & Sethi (1991), such as Bautista et al. (1999) and Boysen et al. (2009). Jin & Wu (2003) have considered the objective of minimizing the quadratic difference for a different problem instance.

3.1.2 Heuristic/optimization approaches

In this section, we review what solution approaches are applied to find solutions for problems within the domain of level scheduling. We finish this section of by concluding what would be the most suitable approach for our case.

Bautista et al. (1996) proposed some improvements for the goal-chasing method of Monden to tackle Monden's level scheduling sequencing problem. In addition to this, an exact procedure based on Bounded Dynamic programming is proposed. When some assumptions are relaxed, the exact procedure shows itself to be able to produce promising results. The considered problem instances are small compared to our problem.

Kubiak et al. (1997) models the mixed-model, multi-level JIT scheduling problem as a nonlinear integer programming problem, with a min-max objective function. An efficient DP procedure considering implicit enumeration is developed. Due to the NP-hardness of the problem, the time to find a solution significantly depends on the number of products considered.

Bautista et al. (1999) have dealt with the CORV (Constrained Output Rate Variation) problem, which is similar to the output rate variation problem. In this problem instance, part consumption is balanced with the use of resources, with respect to an "ideal" prefixed total consumption load. A mathematical model is presented to formulate the problem. A heuristic algorithm is proposed to solve the CORV problem.

Boysen et al. (2009) applies Dynamic Programming and the heuristic Simulated Annealing for their Level Scheduling problem, which aims at distributing the part consumption induced by the production sequence evenly over time for a mixed model assembly line. For the bigger problem instances, only Simulated Annealing could be used to find a reasonably good solution.

Pereira & Vilà (2015) developed a new branch-and-bound procedure to solve the Output Rate Variation problem. In this procedure, new and previously proposed lower and upper bounds are used. The algorithm includes dominance rules that make use of the symmetry in the problem. Additionally, a labelling procedure is adopted to avoid repeated exploration of previously examined solutions.
The new techniques, combined with a Bounded Dynamic Programming method to obtain upper bounds, result in branch-and-bound algorithm that works efficiently. The algorithm is able to solve realistically sized instances to optimality, for which previously only heuristics were deemed appropriate as a solving method.

3.1.3 Conclusion

The objectives that we have seen of Kubiak & Sethi (1991), Jin & Wu (2003) and Boysen et al. (2009) all regard minimizing a quadratic difference between a target level and a real level of part usage or output. We could a similar objective in which the aim is **to minimize the quadratic difference between the target tugger train capacity demanded per time bucket and the estimated tugger train capacity needed in that time bucket**.

We have reviewed literature that uses either exact and heuristic approaches in order to solve level scheduling and variation problems. Due to the size of our problem, it is not be possible to solve our problem exact. Imagine having five assembly jobs to be executed on every out of ten assembly lines. This would mean that there are $(5!)^{10}$ or 120^{10} unique solutions to our problem. Also, Boysen et al. (2009) proved a similar, but smaller problem, to be NP-hard. Therefore, we deem a heuristic to be the only suitable approach to find a solution for our problem. What heuristic we apply for our level scheduling model is addressed in chapter 4.

3.2 Modelling the material supply system

This section is divided up in three separate parts. First, we do a brief literature study about the key concepts of the material supply system in chapter 3.2.1. In chapter 3.2.2, we discuss the modelling approaches we found in the literature and the solving approaches we have reviewed. We finish off by concluding what findings we use in our material supply model.

3.2.1 Key concepts of material supply system

First let us introduce the four key concepts of the future material supply system: Kanban, Lean Supermarket, tugger trains and LCIA. These four concepts together form the future material supply system. In this section, we briefly write down to which extent these concepts have already been considered by literature as a research topic.

One of the first literature sources that considered Kanban as a topic was Lee et al. (1987). In this paper, research was conducted about how Kanban fit in the US manufacturing environment and to which extent it could be used as improvement. Over time Kanban controlled system gained more and more interest within the manufacturing industry and so did research about Kanban controlled systems. Research fields related to Kanban were for example; determining the optimal number of Kanban cards (Bohez, 2004), optimizing a certain Kanban system (Yang et al., 2010) and also new Kanban mechanisms were introduced (Tardif & Maaseidvaag, 2001).

Lean supermarkets and part supply using tugger trains are concepts that have gotten less attention in the literature compared to Kanban systems. However, the supermarket inventory system is not new, as this concept was part of the Lean Manufacturing philosophy implemented by Toyota about fifty years ago (Holweg, 2007). There is a considerable amount of literature available about decentralized storage locations similar to the Lean supermarket concept (Wang & Hodgson, 1991). Nevertheless, the specific term "supermarket" to refer to a decentralized storage location has only been in use since about 2006 (in literature). From the literature research that have been done we can deduce that researchers almost always combine Lean supermarkets with a Kanban controlled system. Sometimes, Lean supermarkets are called Kanban supermarkets (Emde & Boysen, 2012).

Research papers about tugger train (or tow train) part supply, have been considered since 2012. Within the literature, we find that most sources consider tugger train part supply together with decentralized storage locations (supermarkets) and Kanban controlled replenishments.
One of the first literature sources that discussed this topic was Emde & Boysen (2012). In the paper, the pros and cons of Lean supermarkets in a Just-in-Time setting (e.g. Kanban) are discussed by means of a literature study, with the following findings:

Pros:
- There is potential to reduce in-process inventory, by being able to replenish small lots more frequently.
- It is easier to execute emergency deliveries.

Cons:
- Supermarkets consume space close to the assembly lines, which may be costly.
- Parts in the supermarket are stored in shelves designed for ease of access such that workers can pre-package parts in a comfortable manner. This type of storage is typically less space-efficient than traditional warehouse storage.

There is a decent amount of literature available to get a better understanding of a supply system with tugger trains and supermarkets with Kanban controlled replenishments. The system that is employed at Ubbink has a lot of similarities to systems that are considered in the literature. However, it should be noted that many literature sources focus in their approach/models on the automotive sector (Simić et al., 2020, Faccio et al., 2013, Peng et al., 2020 and Zhou & Zhu, 2021), which has some characteristics that are a bit different compared to Ubbink's situation.

Low-Cost Intelligent Automation has not been considered as a research topic by the literature. There is however some information to be found about it in online textbooks or informative webpages that consider Lean implementation.

3.2.2 Material supply modelling

In this section, we discuss literature findings regarding models that consider tugger train part supply within a Kanban controlled system. Typically, this kind of literature also considers (a) decentralized storage location(s) to pick the parts from.

The goal of this literature study is to find methods to model Ubbink's futuristic part supply system. We want to be able to experiment with the model to see what the influence of a change in scenario is on decision variables and subsequently on our objective, **costs**. The cost function depends on the decision variables: buffer levels per assembly line and the amount of tugger trains that drive around.
The main goal of the model is to find a close to optimal material supply setting (low costs) that allows for an acceptable high average line utilization.

It was not until 2012 that the topic of part supply using tugger train in a Kanban controlled environment, started to gain traction. Emde & Boysen (2012) consider the decision problem of determining an optimal amount of supermarket on the shop floor for the automotive industry. A mathematical model is developed, and a dynamic programming model is presented for the Supermarket Location Problem (SLP). The results of the study suggest that supplying multiple assembly lines by a small number of supermarkets is superior to just having one centralized storage area. However, it is also concluded that there is an optimum number of supermarkets to be found.

Later in 2012, Boysen and Emde were authors of the work Emde et al. (2012). The article investigates the loading problem of tugger trains, which is focussed on minimizing the inventory close to the assembly, while avoiding shortages that cause manufacturing delays. The problem is formulated in a mathematical model and an algorithm is constructed to solve the problem. It is shown that when the delivery frequency is increased, inventory on the line decreases and fewer wagons per train are needed.

Faccio et al. (2013) provide a framework that fits our situation quite well, although it is tailored to the automotive sector. The framework helps with designing a Kanban controlled system feeding system to multiple mixed-model assembly lines, including supermarkets and tugger train part supply. The framework contains an approach for both the long term and the short-term, by providing respectively a static analytical model and a dynamic simulation model.
Because of the extent to which Ubbink's assembly schedule is subject to change on a daily basis, we consider the short-term dynamic simulation approach more suitable for this thesis. A model that is focussed on the short-term approach could also be applied by Ubbink themselves to acquire information. Faccio et al. (2013) chooses to build a discrete event simulation program this purpose.

Faccio et al. (2013) uses the simulation model to run multiple scenarios. They experiment with different scenarios by changing the long-term decision variables *number of tugger trains* and *service level* and by changing short-term decision variables *tow train capacity* and *refilling interval.* Changes in decision variables affect various performance measures: Tow train utilization (%), the number of tours completed in the system, total distance covered (meters), average number of bins loaded for trip (Bins/trip), number of delayed deliveries and instant inventory level in the assembly system (number of parts). When performances of each scenario are measured, a decision tool is created that solves the trade-off between the fleet dimension and the inventory stock levels.

Staab et al. (2015) have also programmed a tugger train system by means of discrete event simulation. According to Staab et al. (2015), tugger train systems may have to deal with stochastic influences, road congestion and demand fluctuations. Therefore, modelling by means of discrete event simulation is convenient, as these occurrences can easily be included in the model. In order to measure the performance of the model, performance measures such as security of supply, level of service, number of employees needed, and the congestion of the tugger train traffic are adopted.

Lolli et al. (2016) has simulated various scenarios in which different feeding policies are evaluated. The scenarios differ from each other in terms of the number of Kanban per feeding tour. The number of Kanban represent the number of cards (or bins, etc) per component type.
The analysis is cost-based in the sense that the sum of inventory costs and the labour costs due to handling is minimized. The decision variables are the coverage time (the time covered by the inline SKUs) and the number of Kanban taken in charge per forklift trip.

Kundu et al. (2019) developed a discrete event simulation in order to model the tugger train replenishment system. The goal of the model is to reduce costs, by experimenting with the number of Kanban, number of water

spiders (number of warehouse pickers) and the unitary loading/unloading time per bin. The cost function includes inventory costs, stock-out costs, handling costs and work in process costs.
Due to the large solution space, the chosen methodology to find a good solution is a hybrid approach, in which a model is combined with an optimization meta-heuristic (Particle Swarm Optimization).

3.2.3 Conclusion

Material supply systems can be modelled in various ways, and it depends on your goal what you should choose as your modelling method.
Based on the literature and the goal of our project, simulation seems to be the most convenient method to model the material supply system.
As we have seen in Staab et al. (2015) and Faccio et al. (2013), simulation offers the possibility to incorporate a wide variety of input parameters and decision variables in the model. Also, simulation programs offer the functionality to run the model for multiple different scenarios.
For these scenarios, we can experiment with different settings (values of decision variables) and evaluate how well we performed. We can steer our experimentation by using an optimization heuristic.
Additional advantages of simulation are that we can visually show management what we have modelled and how the model works. Also, simulation makes easier to model driving behaviour of tugger trains, such as situations where trains block each other when they are waiting in front of the same station.

4. Model design – Level scheduling model

We develop two models in this thesis project; a level scheduling model (chapter 4) and a simulation model (material supply system, chapter 5). Figure 20 shows the relationship between the two models.

Basically, the level scheduling model is able to create a levelled schedule, which can be used as input for the simulation model. We hypothesized earlier, that we expect the simulation model to yield better outcomes, when a levelled schedule is used as input, as opposed to an input schedule that is not "levelled".

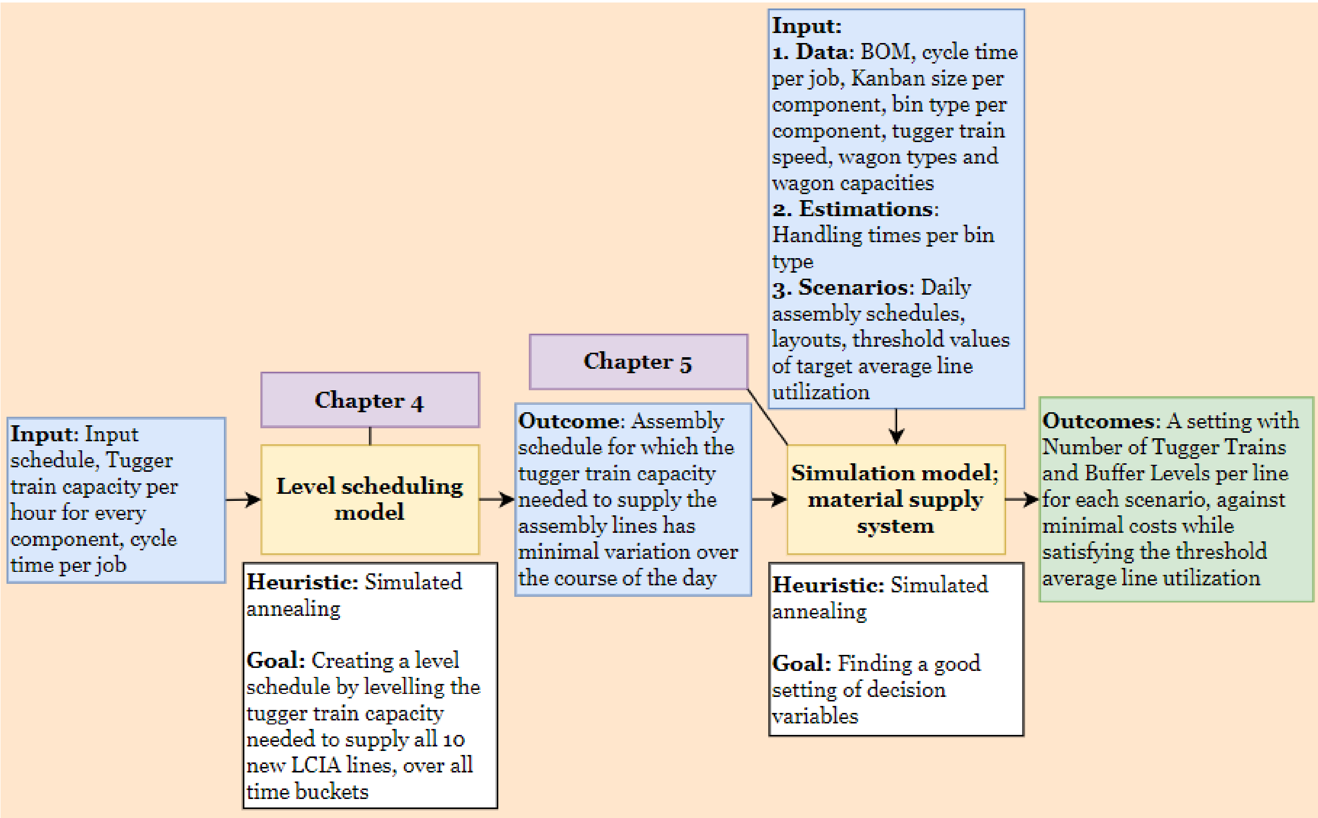


Figure 21: Relationship between the two models that are constructed in this thesis project; level scheduling model and the simulation model

In this chapter, we describe and explain the level scheduling model. First, we give a general description of the model in chapter 4.1. Subsequently, we discuss the simplifications we have done to construct the model (chapter 4.2), the model inputs (chapter 4.3), the model outputs (chapter 4.3), and we give a model formulation (chapter 4.4 and 4.5). After this, we explain the heuristic that is incorporated in the model in chapter 4.6. The heuristic should guide us to finding (near) optimal solutions for whatever input schedules we give to the model. After, we discuss the heuristic's performance.
We finish off by briefly discussing the model's credibility in chapter 4.7 and we conclude the chapter at last in chapter 4.8.

4.1 General model description

In the near future, up to ten new LCIA lines will be introduced. Every working day, there are a (number of) job(s) scheduled to be executed on each LCIA line. These jobs need to be replenished constantly.

Earlier, we took on the hypothesis that schedules that ensure the tugger train capacity needed to supply all lines to stay equal over the whole day, the so called level schedules, could yield costs savings. Less tugger trains and/or less buffer area space could still be sufficient to satisfy the target average line utilization when we use level schedules as input to our material supply system model, as opposed to unlevelled schedules.

To this end, we propose the development of the level scheduling model. The level scheduling model serves as an application, which transforms an input schedule into a level schedule. **The goal of the model is to create a schedule that keeps the material supply capacity needed during the day equal over the course of the whole day.** Basically, we want to compensate the scheduling high supply capacity demanding jobs with low supply capacity demanding jobs.
It should be noted that when supply capacity is mentioned in this report, we refer to tugger train capacity, the means of supply that is considered in this thesis project.

4.2 Simplifications

In the level scheduling model, we do not consider changeover times to play a role. In reality, there is a changeover time when an assembly line switches from one job to another. Also, the time length of a change over time may depend on job precedence.

In the model, assembly jobs are considered to have duration of an integer amount of equal time buckets. The length of a time bucket is predetermined by the user of the model.
This modelling choice eases the measurement of the amount of variation there is in the collective schedule over the whole day. In reality however, assembly jobs can be scheduled to more detailed time lengths.

We do not consider release dates, due dates, change over times etc. in the scheduling model. There is also no complexity with jobs that have to be executed in a particular sequence. A scheduled job is always executed in one go, which fits non-pre-emptive scheduling.

4.3 Inputs and outputs

Our level scheduling model uses an input (assembly) schedule as input, as well as a job attribute called *tugger train capacity per hour*. The input schedule contains information about the jobs that need to be executed per assembly line, and the time buckets in which the jobs are scheduled to executed.

The objective of the model is to minimize the **quadratic differences** between the job attribute ***tugger train capacity per hour*** per time bucket and the average tugger train capacity per time bucket, summed over all time buckets (e.g. with a length of 15 minutes, 30 minutes, 1 hour etc) during a working day. Since the sum quadratic differences is minimized over all time buckets, we minimize the variation in tugger train capacity needed during the whole working day.

4.3.1 Tugger train capacity per hour

Every job needs a specific set of components to be supplied to assembly lines by material supply system suppliers, in order to prevent its component bin racks from emptying. It depends on a couple of factors, how much tugger train capacity per hour is needed to fulfil the material supply for one specific job.

- The mean cycle time of a job
- BOM (containing BOM quantities, the set of components, bin type per component)
- The Kanban size per component (number of components to be replenished by one Kanban card, in other words; the number of components that fit in the bin type that corresponds to the component)
- Tugger train wagon data; wagon types and capacity per wagon types

Every component has a fixed bin type and a fixed Kanban size. We elaborate more on the various bin types in chapter 5 (also see chapter 2.5).

For every assembly line, we have identified the 5 jobs that are most often executed. For these jobs, we have collected data about the cycle time, BOM and Kanban size (Appendix 2). With the data, we can calculate the **tugger train capacity per hour for every job** (Appendix 2).
An example calculation of how *tugger train per capacity* is calculated is presented in Appendix 3.

4.4 Scheduling notation

Since we built a model in the scheduling domain, we can give our model the following notation:

$$\mathrm{R}_{10} \mid\mid \sum_{s=1}^{S}\left(y-\sum_{a=1}^{10} w_{a,s}\right)^{2} \qquad (1)$$

Here:
R_{10} represents the (10) **unrelated** LCIA lines that we consider. We call the jobs unrelated because the duration of their processing time is not related to anything.
$\sum_{s=1}^{S}\left(y-\sum_{a=1}^{10} w_{a,s}\right)^{2}$ *(2)* represents the objective of minimizing the sum of quadratic differences between the average tugger train capacity needed over all lines per time bucket and the actual expected tugger train capacity needed per time bucket, over all time buckets. See chapter 4.5 for an explanation about this objective function.

Considering our simplifications (chapter 4.4), we do not incorporate release dates, due dates, change over times, job sequences etc. in the model. in the scheduling model. A scheduled job is always executed in one go, which fits non-pre-emptive scheduling.

4.5 Mathematical formulation

In order to reduce variation per time bucket, we propose to use an objective based on what we found in literature study chapter 3.1.1.
We formulate our model according to the following mathematical formulation:

Sets:

a	Set of all assembly lines system; $a = 1, \dots, A$
s	Set of time buckets during a manufacturing day; $s = 1, \dots, S$
j	Set of jobs; $j = 1, \dots, J$

Decision variable:

$X_{a,j,s}$	*Boolean*	The scheduling of a job j at line a at time bucket s; 1 if the position is occupied by job j, 0 if that is not the case

Dependent variables:

$w_{a,s}$	*Real*	Tugger train capacity per line, per time bucket

Parameters:

TC_j	*Real*	Tugger train capacity per hour for job j at line a
D	*Time*	Time length of an assembly day; 8 hours
L_j	*Time*	Duration of job j in number of time buckets.
T	*Time*	Size of one time bucket s in hours
$Y_{a,j}$	*Boolean*	1 if job j belong to line a, 0 if job j does not belong to line a
y	*Real*	Average tugger train capacity over 10 lines, per time bucket

Objective function:

$$Min\ z = \sum_{s=1}^{S}\left(y - \sum_{a=1}^{10} w_{a,s}\right)^2 \tag{2}$$

s.t.

$$y = \frac{\sum_{j=1}^{J} TC_j * L_j}{S} \tag{3}$$

$$L_j * Y_{a,j} = \sum_{s}^{S} X_{a,j,s} \quad \forall\, a\ \in\ \mathrm{A}, \forall\ \mathrm{j}\ \in\ \mathrm{J} \tag{4}$$

$$w_{a,s} = \sum_{j=1}^{J} X_{a,j,s} * TC_j \quad \forall\, a\ \in\ \mathrm{A}, \forall\, s\ \in\ S \tag{5}$$

$$X_{a,j,s} + X_{a,j,G} \leq 1 \quad \forall\, a\ \in\ \mathrm{A}, \forall\ \mathrm{j}\ \in\ \mathrm{J}, \forall\ \mathrm{G} \geq \mathrm{s} \pm \mathrm{L_j} \tag{6}$$

$$X_{a,j,s} \in \{0,1\} \tag{7}$$

Our objective function (2) aims **to minimize the quadratic differences between the *average tugger train capacity per hour needed per time bucket*** and **the *total expected tugger train capacity per hour needed per time bucket,* summed over all time buckets**.

Constraint (3) calculates the summed average tugger train capacity per hour for one time bucket over all ten lines. The outcome of the equation depends on the input values we give to parameters tugger train capacity per hour for job j (TC_j), duration of job j (L_j) and the number of time buckets (S).

Constraint (4) makes sure that a job is executed in as many time buckets as its duration is. Job durations are expressed in a number of time buckets.

Constraint (5) calculates the total tugger train capacity per hour per time bucket ($w_{a,s}$), depending on which job j is executed at line a during time bucket s. Subsequently, $w_{a,s}$ is used to calculate the objective function value.

Constraint (6) ensures that a job is always scheduled in consecutive time buckets. A job cannot be scheduled in a time bucket a time length equal to the duration of a job from the first scheduled time bucket of a job.

Constraint (7) ensures that $X_{a,j,s}$ is interpreted as a binary variable.

4.6 Heuristic: Simulated annealing

There are many variations possible when we consider a **collective schedule of 10 assembly lines**. We simply cannot evaluate all possible combinations (e.g. 10 lines with each 4 jobs leads to 6.34e13 possible schedules considering a collective schedule) and calculate their objective function values. Therefore, we propose a simulated annealing heuristic to guide the exploration/exploitation of solution schedules of our level scheduling problem.

Simulated annealing (SA) was developed in 1983 to deal with highly nonlinear problems (Busetti, 2003). A SA algorithm is based on the nature process in which metal cools down and anneals.

A SA algorithm needs a **feasible starting solution** to start the algorithm with. In our case, a feasible starting solution is a collective schedule in which every assembly line has a number of jobs assigned to it in a random sequence.

Next, the objective value of the starting solution is calculated. In order to initialize the algorithm, the objective value of the starting solution is set as the current solution and as the best solution. During the algorithm, a neighbour schedule is computed every iteration, by performing **swap operations** on the current solution schedule. If the objective value of the neighbour schedule is smaller than the current solution's value, we always accept the neighbour solution as our new solution.

If the neighbour's objective value is larger than our current solution, the objective value is input to an exponential acceptance function, which computes a number between 0 and 1 and compares this value to a uniformly drawn random number between 0 and 1. The chance of accepting a solution as the current solution partially depends on the current temperature, which is an element of the acceptance function.

A well designed SA algorithm's parameters are chosen such that in the beginning almost all solutions are accepted as the current solution (exploration), whereas in the end only better solutions are accepted as the current solution (exploitation).

Figure 21 presents a flow chart of the SA algorithm (we call it SA1 for this application) that is made for this application. Appendix 4 visualizes the steps that are taken in one iteration, specifically with respect to the SWAP operations that are carried out and the calculation of a new objective value.

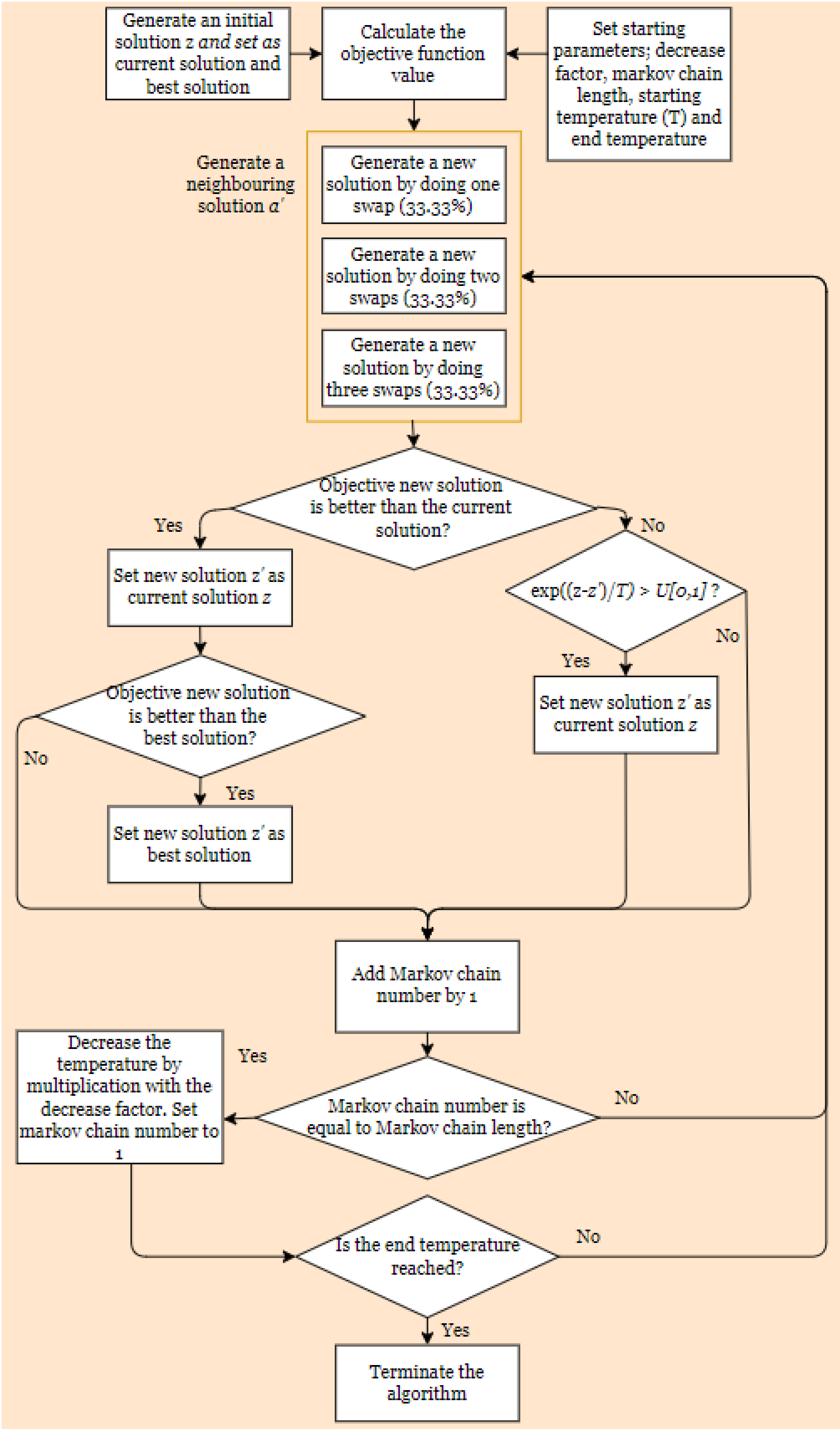


Figure 22: Simulated annealing algorithm of the level scheduling model; SA1

4.6.1 Parameter determination

As can be seen in Figure 21, there are a couple of parameters that are input to our model: The Markov chain length, decrease factor, starting temperature and the end temperature.
Based on how we choose these parameters, we can steer the performance of our heuristic.
In order to determine the parameters of our SA1 algorithm, we followed an approach similar to (Doole & Pannell, 2007). In the upcoming subsections, we explain the choices we have made in the determination of our parameters.
Note that this section discusses the determination of parameters for a levelling scheduling model with time buckets of 0.25 hour considering ten assembly lines. The objective function tends to produce higher values for models with smaller time buckets as input. The graphs that we refer to in this section are made with Input schedule 1 as model input (see Appendix 8).

4.6.1.1 Starting temperature

In order to have a good balance between exploration and exploitation, we need to choose the starting temperature, since it has a big effect on the acceptance probability. Recall, that we saw the following formula in the simulated annealing algorithm to calculate the acceptance probability.

$$e^{\frac{(Current\ Solution - New\ Solution)}{Temperature}} > U[0,1] \qquad (9)$$

Per temperature level, we evaluate one Markov chain that is set to a certain length. The length of a Markov chain is equal to the number of different experiment settings that are evaluated at that temperature level.
We want to choose a starting temperature such that the first Markov chains all have an acceptance ratio of almost 1 (almost every new solution is accepted). Experimenting in an Excel spreadsheet showed that we would have an acceptance probability of 99% if we were to choose a starting temperature of 500, considering a deviation between the current solution and the new solution's objective equal to 5. A gap of 5 is quite large considering the objective values we can find for the schedules.
Appendix 5 graphically shows the acceptance ratio (y-axis) per chain number (x-axis). Here, we show that the acceptance ratio for the first chains is about 1. The chain number represents the number of schedules that are considered at one temperature level.
In order to calculate the acceptance ratio, the following formula was applied:

$$Acceptance\ ratio = \frac{Number\ of\ new\ solutions\ accepted}{Markov\ chain\ length} \qquad (10)$$

4.6.1.2 End temperature

The end temperature needs to be chosen such that the acceptance probability $\left(e^{\frac{(Current\ Solution - New\ Solution)}{Temperature}}\right)$ of the plotted graph is close to 0, considering a small deviation between the current solution and the new solution's objective value. This means that there are no worse solutions accepted in these iterations, but only better solutions. In this phase, the algorithm is only exploiting. The first graph in Appendix 5 shows that we reach a state of not accepting any new (worse) solutions at the 1500^{th} Markov chain. Here, an End temperature of 0.0000001 is chosen.

4.6.1.3 Decrease factor and Markov chain length

We still have to determine the decrease factor and the Markov chain length. This has influence on the number of iterations we do. When we choose a decrease factor of 0.99 and a Markov chain length of 30, we get to start 2223 new Markov chains before the algorithm terminates. In total, we can do 66690 iterations. Running this takes us about 14 seconds.
In the table below, we have summarized the model parameters for a model in which we consider time buckets of 0.25 hour.

Table 7: Simulated annealing parameters of SA1

Parameters	Time bucket length = 0,25
Starting temperature	500
End temperature	0.0000001
Decrease factor	0.99
Markov chain length	30
Time to solve the model	15 seconds

4.6.2 Heuristic performance

We test our heuristic by running the level scheduling model with a randomized input schedule as input. In the schedule, there are 4 assembly lines that each have 8 assembly jobs that last an hour (Figure 23). In this example, every job has a unique value for the attribute *Tugger train capacity per hour.*
There exists one schedule for this problem instance, such that the objective value (sum of quadratic differences of *Tugger train capacity per hour*)*,* over all time buckets, is exactly 0 (Figure 22).

We know what the optimal schedule is, since we actually computed it before we computed the random schedule. The random schedule is derived schedule from the optimal schedule.
We computed the optimal schedule by creating a 4x4 grid filled with U(0,1) numbers in a spreadsheet (Table 8) first. After, we normalize Table 8, we get the grid shown in Table 9.

Table 9: Random grid 6x4, computed in Excel

	Line 1	Line 2	Line 3	Line 4	Sum
Time bucket 1	0,647515	0,127342	0,28998	0,975724	2,04056
Time bucket 2	0,527709	0,951371	0,269074	0,614776	2,36293
Time bucket 3	0,731782	0,036681	0,922526	0,850954	2,541944
Time bucket 4	0,82861	0,45597	0,019177	0,742159	2,045916
Time bucket 5	0,470292	0,760237	0,204226	0,288356	1,72311
Time bucket 6	0,443245	0,231364	0,000534	0,576714	1,251857
Time bucket 7	0,90273	0,528913	0,091716	0,295536	1,818895
Time bucket 8	0,498745	0,517788	0,065785	0,570574	1,652892

Table 8: Normalized grid of table 8

	Line 1	Line 2	Line 3	Line 4	Sum
Time bucket 1	0,317322	0,062405	0,142108	0,478165	1
Time bucket 2	0,223328	0,402624	0,113873	0,260175	1
Time bucket 3	0,287883	0,01443	0,362922	0,334765	1
Time bucket 4	0,405007	0,222868	0,009373	0,362752	1
Time bucket 5	0,272932	0,4412	0,118522	0,167346	1
Time bucket 6	0,35407	0,184817	0,000426	0,460687	1
Time bucket 7	0,496307	0,290788	0,050424	0,162481	1
Time bucket 8	0,301741	0,313262	0,0398	0,345198	1

When we multiply every element in Table 9 with 300, we create the optimal schedule shown in Figure 22.

Line 1			Line 2			Line 3			Line 4				
Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration	Quad. Differences	
1A	95,2	1	2B	18,7	1	3G	42,6	1	4G	143,4	1	300	0
1E	67	1	2C	121	1	3B	34,2	1	4C	78,05	1	300	0
1F	86,4	1	2H	4,33	1	3A	108,9	1	4D	100,4	1	300	0
1G	122	1	2A	66,9	1	3F	2,8	1	4B	108,8	1	300	0
1H	81,9	1	2G	132	1	3D	35,6	1	4E	50,2	1	300	0
1B	106	1	2E	55,4	1	3E	0,1	1	4A	138,2	1	300	0
1D	149	1	2D	87,2	1	3C	15,1	1	4F	48,74	1	300	0
1C	90,5	1	2F	94	1	3H	11,9	1	4H	103,6	1	300	0
												Average	Sum of Quad. Differences
												300	0

Figure 23: Optimal schedule, data coming from table 9

If we randomize the job position in Table 9 for every line, this gives us the randomized input schedule shown in Figure 23.

Line 1			Line 2			Line 3			Line 4				
Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration	Quad. Differences	
1A	95,2	1	2A	66,9	1	3A	108,9	1	4A	138,2	1	409,1	11911,5
1B	106,2	1	2B	18,7	1	3B	34,2	1	4B	108,8	1	267,9	1028,5
1C	90,52	1	2C	120,8	1	3C	15,1	1	4C	78,05	1	304,5	20,2
1D	148,9	1	2D	87,2	1	3D	35,6	1	4D	100,4	1	372,1	5200,5
1E	67	1	2E	55,4	1	3E	0,1	1	4E	50,2	1	172,8	16186,1
1F	86,36	1	2F	94,0	1	3F	2,8	1	4F	48,74	1	231,9	4637,7
1G	121,5	1	2G	132,4	1	3G	42,6	1	4G	143,4	1	439,9	19584,3
1H	81,88	1	2H	4,3	1	3H	11,9	1	4H	103,6	1	201,7	9661,3
												Average	Sum of Quad. Differences
												300	68230,0

Figure 24: Randomized Input schedule of figure 22 (level scheduling performance experiment)

We have determined a fitting starting temperature and a fitting end temperature for this example ourselves, such that in the beginning of the SA1 algorithm almost all solutions are accepted. In the final stage of the algorithm only better solutions are accepted. The Markov chain length and decrease factor are chosen such that we explore 66690 solutions.
After running the model with the input schedule in figure 23 as input schedule, we find the following level schedule as our model outcome (figure 24):

Line 1			Line 2			Line 3			Line 4				
Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration	Quad. Differences	
1H	81,9	1	2A	66,9	1	3H	11,9	1	4A	138,2	1	298,89	1,2
1D	149	1	2H	4,33	1	3E	0,1	1	4G	143,4	1	296,8	10,2
1G	122	1	2D	87,2	1	3G	42,6	1	4F	48,74	1	300,12	0,0
1F	86,4	1	2G	132	1	3B	34,2	1	4E	50,2	1	303,09	9,6
1B	106	1	2E	55,4	1	3D	35,6	1	4H	103,6	1	300,78	0,6
1E	67	1	2C	121	1	3F	2,8	1	4B	108,8	1	299,42	0,3
1A	95,2	1	2B	18,7	1	3A	108,9	1	4C	78,05	1	300,85	0,7
1C	90,5	1	2F	94	1	3C	15,1	1	4D	100,4	1	300,06	0,0
												Average	Sum of Quad. Differences
												300	22,7

Figure 25: Outcome schedule of Level scheduling heuristic performance experiment

We also know what respectively the optimal schedule (Figure 22) is and what the worst possible schedule (Figure 25). Computing the worst possible schedule was done by sequencing the jobs from highest to lowest tugger train capacity per hour, on every line.

Line 1			Line 2			Line 3			Line 4				
Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration	Quad. Differences	
1D	148,9	1	2G	132,4	1	3A	108,9	1	4G	143,4	1	533,6	54558,7
1G	121,5	1	2C	120,8	1	3G	42,6	1	4A	138,2	1	423,1	15160,4
1B	106,2	1	2F	94,0	1	3D	35,6	1	4B	108,8	1	344,6	1987,5
1A	95,2	1	2D	87,2	1	3B	34,2	1	4H	103,6	1	320,2	406,2
1C	90,5	1	2A	66,9	1	3C	15,1	1	4D	100,4	1	272,9	732,3
1F	86,4	1	2E	55,4	1	3H	11,9	1	4C	78,1	1	231,8	4650,9
1H	81,9	1	2B	18,7	1	3F	2,8	1	4E	50,2	1	153,6	21428,0
1E	67,0	1	2H	4,3	1	3E	0,1	1	4F	48,7	1	120,2	32328,1
												Average	Sum of Quad. Differences
												300,0	131252,1

Figure 26: Worst possible schedule of level scheduling performance experiment

Since we know that an optimal schedule (figure 22) has an objective equal to 0, we can compute optimality gaps. We define the optimality gap as the percentual difference between the solution that we found (objective of 22.7) and the optimal solution (objective of 0).

In order to compute the optimality gaps, we compare the found solution (figure 24) with our starting solution (figure 23) and worst possible solution (figure 25). This is shown in Table 10.

Table 10: Optimality gap – of level scheduling performance experiment; comparing the solution in figure 24 with the starting solution (Figure 23) and the worst possible solution (Figure 25)

	Sum of quadr. differences	**Optimality gap**
Starting solution	68230	22.7/(68230-0)=0.00033%
Worst possible solution	131252.1	22.7/(131252.1-0)=0.00017%

These optimality gaps are very small and therefore we deem the level scheduling model to perform well. However, we have to keep in mind that we considered only one instance here.

4.7 Model credibility

The model produces similar schedules to the input schedule, except for the fact that job positions have swapped. This was the exact intention of the model.
When we compute the objective value for input schedule 1 and compare this with the value of the levelled schedule of input schedule 1. It is easy to observe that the level schedule produces a schedule that is much better: input schedule 1 has a sum of quadratic differences of 4.82. The level schedule of input schedule 1 has an objective value of 0.18.
Also, our example in 4.6.2 shows the model to perform well for one example.

4.8 Conclusion

In this chapter, we have given a description of our level scheduling model. After, we defined the simplifications that we have done to construct the model and what is consider to either input or output to the model. Subsequently, we provided both a mathematical formulation as well as a scheduling notation. In the last section, we proposed a heuristic algorithm with Simulated Annealing, which guides our search to find level schedules. We determined the following parameter setting for the heuristic (Table 11).

Table 11: Parameter setting of level scheduling Simulated annealing algorithm

	Time bucket length = 0,25
Starting temperature	500
End temperature	0.0000001
Decrease factor	0.99
Markov chain length	30
Time to solve the model	15 seconds

Lastly, we showed our model to perform well (optimality gaps < 0.001) by solving an example and verified the credibility of the model.
Appendix 6 provides documentation about how the level scheduling model can be used by others who would want to use the model.

5. Model design – Simulation model; material supply system

In this chapter, we describe the simulation model of the material supply system. With the simulation model, we imitate Ubbink's future material supply system. The goal is to be able to experiment with model inputs (*Number of tugger trains* and *Buffer level per assembly line*) and measure effect is on performance indicators *Costs* and *Average line utilization.* To this end, various scenarios with different inputs will be examined. In this chapter, all relevant cornerstones that were part of model development are discussed.

First, we describe our model conceptually in chapter 5.1. Here, we discuss assumptions, simplifications, model inputs, model outputs and the model's objective function.

In chapter 5.2, we explain the solving heuristic that is included in the model, to guide our search for (near) optimal material supply settings for the various scenarios we consider. The solving heuristic's aim is to minimize costs.

In chapter 5.3, we discuss the technical implementation of the model, which is done in Siemens Plant Simulation (Version 14).

Lastly, we assess the credibility of our model as we verify and validate the model in chapter 5.4.

5.1 Conceptual model

With the simulation model, we aim to imitate the functioning of Ubbink's future material supply system for a **one day schedule**. In chapter 2.5.5, we have provided a brief description of the material supply system. In this section, we present the conceptual model of the simulation model. The conceptual model describes the functioning of the model, which we have implemented in the model.

First, we give a general model description. After, we discuss assumptions, simplifications, model inputs, model outputs and the model's objective function.

5.1.1 General model description

In chapter 2.5 (future material supply process), we have discussed the material supply process that we need to consider in this model.

Summarizing, we observed that are two separate processes, that communicate with each other:

1. The **assembly process**, in which components are consumed to assemble final products (Figure 26). Due to the finite component bin capacities at the assembly lines, new component orders are necessary. Somehow, these orders need to be signalled. This is done by empty bins with Kanban cards attached to them. In the paragraph *Assembly process,* we discuss this process in detail.
2. The **replenishment process (Figure 27)**, where for every component c:
    1. The empty bin of component c and the attached Kanban card of component c are picked by the tugger train driver
    2. The empty bin of component c is stored at the packing place
    3. A full bin of component c, filled with a number of components that corresponds to the Kanban size, is loaded onto the wagon at the supermarket
    4. A full bin of component c is loaded from the tugger train to the bin rack at the assembly line

In the paragraph *replenishments*, we discuss more extensively how replenishments are communicated and carried out.

Assembly process

Figure 26 shows the logic that we need to incorporate in the model, in order to emulate the assembly process. After a component is consumed, the stock levels of the components are adjusted. If the consumption of a component has led to the component bin being empty, the empty bin with a Kanban card attached to it is flipped to the other side of the rack, where it is ready to be picked up by a tugger train driver.

In the simulation model, the assembly process can be considered to be a black box process. The inflow of components and outflow of product is simulated, but what exactly happens during the assembly process itself falls outside the scope of this thesis. The implementation of the simulation model is discussed in chapter 5.4.

Whenever a new job starts, it starts with all its component stocks maxed out. So the bin racks are filled and its bins are filled to maximum capacity. This also entails that the first job of the day on every line starts with full components stocks.

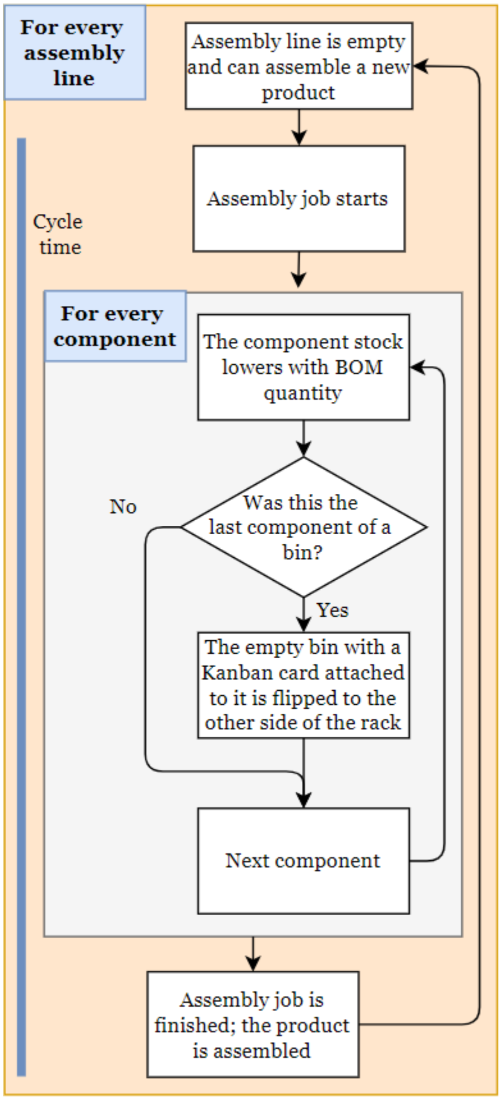


Figure 27: Flowchart of the assembly process

Replenishments

Figure 27 below shows the replenishment process, which is being executed by tugger train drivers. A tugger train driver drives tours, passing all ten assembly lines, the packing place and the three supermarkets.

At the assembly line, empty bins are picked and loaded onto the trains and full bins are loaded from the trains onto the bin racks of the assembly line. The empty bins are stored at the packing place. Full component bins are picked at the supermarkets and loaded on the tugger train.
In the upcoming paragraphs, this process is explained more extensively.

Assembly lines

When a tugger train driver arrives at an assembly line, he stops if his wagons contain full bins to load onto component buffers of that assembly line. Even if it means that it must wait for another tugger train that is occupying the space in front of the assembly line.
The tugger train also stops if there are no other tugger train occupying the space before the line, but when there are empty bins with new Kanban cards to pick up.
However, the tugger train drives past an assembly line if it has no components to load onto the component buffers of that line a and the line is already occupied by another tugger train.

Packing place and supermarket

After visiting all the assembly lines, the tugger train stores the empty bins at the packing place and loads new full bins (according to its Kanban cards) onto the tugger train at the supermarkets. After the last supermarket is visited, the tugger train proceeds to drive to the assembly lines to replenish them again.
It should be noted that the tugger train driver only stops at either the packing place or the supermarket if he respectively needs to store empty bins or needs to pick components from the supermarket. If not, he drives past these stations and continues the tour.

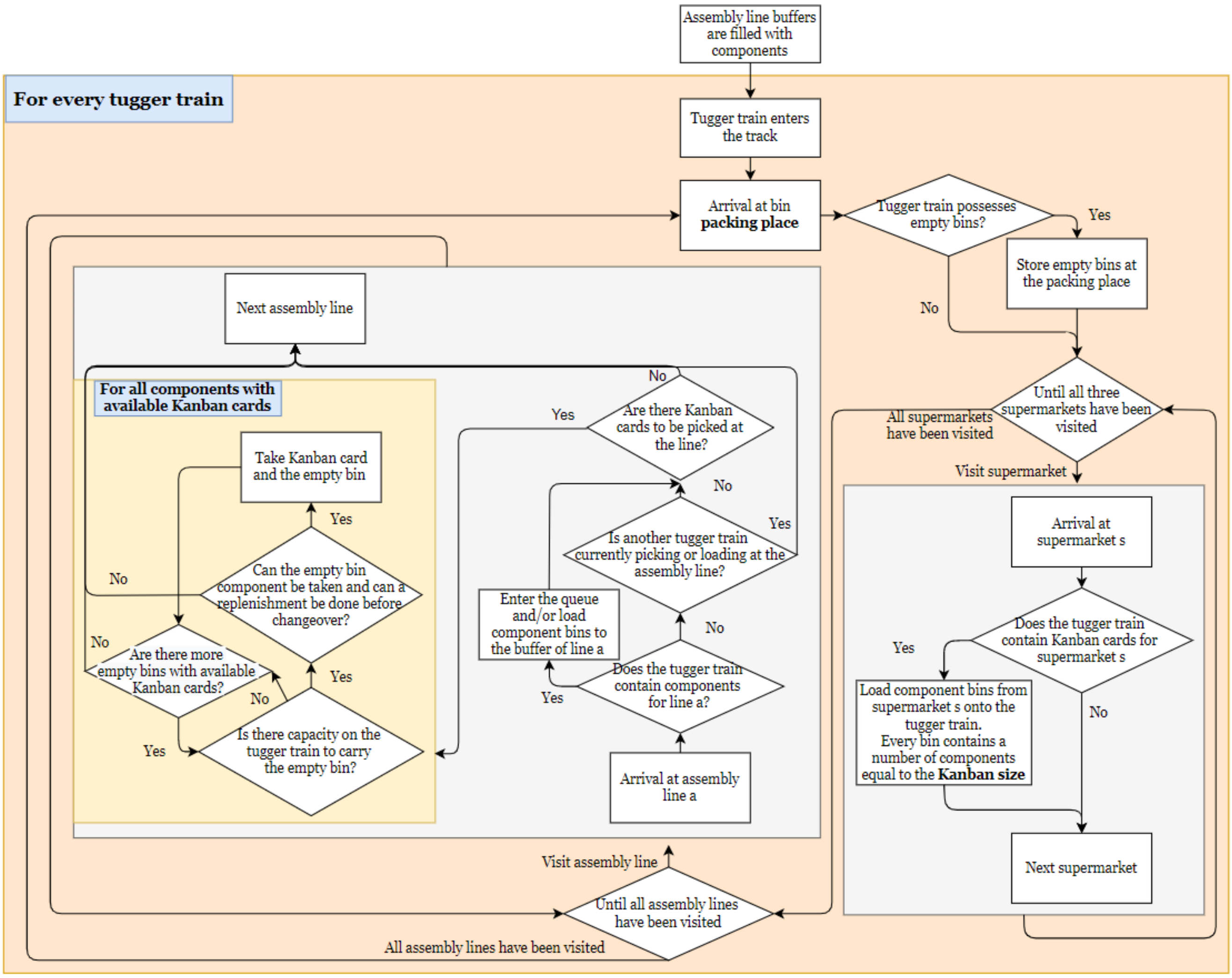


Figure 28: Replenishment process

Schedule

There is a third process that we need to consider in model, as the simulation time passes: **Keeping track of the collective assembly schedule**. When a job has reached its end time, a changeover has to be executed to start the assembly process of a new job. Doing a changeover is assumed to take 10 minutes. During this time, the line is converted to host a new job. Bin racks with full component bins, that belong to the assembly process of the new job, are placed at the assembly line. When this has been done, the assembly of the new product can start. Figure 28 shows how the steps of the changeover process. In the simulation model, the changeover process can be considered a black box process.

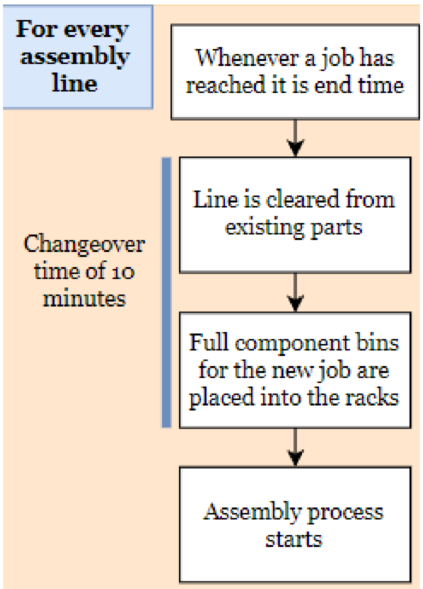


Figure 29: Job changeover process

5.1.2 Assumptions and simplifications

We have made several assumptions and simplifications for our simulation model. In this section, we sum them up.

Assumptions

Components are always available to be picked from the supermarkets; in reality, it happens that components that are needed for assembling are not available in the warehouse. Thus, the warehouse is not able to replenish the supermarkets. In our model this occurrence does not take place; supermarkets always contain the demanded component bins. With this assumption, more supply capacity is demanded from the material supply system, applying more pressure on the material supply system as a whole.

Change over times are always 10 minutes; we have discussed the changeover times with a process engineer. The outcome of the discussion was that it is reasonable to take it as 10 minutes for every changeover. In reality, changeovers may differ per assembly line and may depend on preceding jobs.

Box components (with bin type End Box, with only 1 bin place in the bin rack) release a Kanban card when there is 33% of the components left in the bin; the policy on when a Kanban card should be released for the replenishment of box components is undecided. However, it seems to be fair and reasonable to take 33%. This ensures that there is enough opportunity to replenish the box component in time.

Tugger train X can always pass (an)other tugger train(s) that block(s) the road; a tugger train can always pass other tugger trains that are waiting in front of a station (assembly line or supermarket), if the train did not need to be at the station where the queue was to either load or pick full component bins. We suspect that this assumption is in line with reality.

Assembly lines and tugger trains do not break down; assembly lines and tugger trains are not subject to break downs. They also do not need (preventive) maintenance.

Simplifications

In every tour, a tugger train passes every assembly line; in our simulation model, a tugger train cannot take a shortcut and has to drive the same route every tour. This could be different in reality, in some cases. Due to modelling constraints, we had to make this simplification.

Assembly jobs are finished after a prescribed amount of time; in our simulation model, there is no focus on whether the demand of an assembled product is actually satisfied. If a job is scheduled to end at 2PM, it cannot be executed past 2PM. Regardless of what the output was during those 2 hours.

Locations of the packaging place, supermarkets and LCIA lines differ (slightly) compared to their real expected locations; this simplification has been done to make modelling a little easier. It should have 0 effect on the results of the simulation.

Not every component is included in the model; some jobs contain a few components that are not suited for transport with tugger trains. These components have been excluded from the model, as we consider them to fall outside our scope. An example of such components are rolls and aluminium tubes.
In the model, BOM quantities of tube components are set to 1; whenever a component's BOM quantity is not expressed as an integer number in Ubbink's system (primarily tube components are said to have a BOM quantity of (for example) 0.04), we take the Bom quantity as 1 and change the Kanban size accordingly as well (so the net part usage stays the same). This simplification can be regarded as a modelling convenience that does not affect the modelling outcome.

Loading operations are executed immediately after arriving; when a tugger train performs a loading operation at an assembly line, all the component bins that have to be loaded to the bin racks at that assembly line are stored immediately, in the simulation model. After this has been done, the tugger train pauses for the estimated time the loading action would have taken. In reality, the loading process is a continuous process, where the bins are loaded separately from each other during the whole loading time.

Sizes of tugger trains are not a factor in the model; in the model, the tugger trains are modelled as small objects. They are modelled smaller, than they are in reality. This makes queueing easier in the model as it would be in reality.

The dimensions in the simulation model have all been reduced by half; what would be 1 meter in the real world, is labelled as 0,5 meter in the model. As a consequence, the speed of the tugger train in the simulation model, is reduced by half as well.

5.1.3 Model input

As in the general model description, we divide this section up in three different parts; assembly, replenishments, and the schedule. In order to ease our explanation, we introduce the following set notations.

Input – assembly process

Input parameters:
Cycle times: Cycle time stand for how long it takes to assemble a finished product, from the start of the assembly process to the finish. For every job, there is a constant fixed cycle time available. However, we know that the cycle times are not constant in reality. Therefore, we opt a **triangular distribution**. A detailed explanation about this distribution and the chosen parameters is given in the paragraph *Additional explanation about parameters*.

BOM*:* The Bill of Material gives us which component types are part of job j, the number of components per component type of job j and the component quantity (BOM quantity) needed per component type to produce one finished product of job j.

Kanban size: The Kanban size of every job j is fixed for every job. The Kanban size stands for the number of components per full component bin.

Appendix 2 contains per job information about the cycle time, the BOM and the Kanban sizes of its components.

Input – replenishments

Decision variables

Number of tugger trains*:* The number of tugger trains driving in the system.

Buffer levels: The buffer level of assembly line a. Basically, this variable determines for every bin type how many bins there should be in the bin racks at an assembly line a. Further explanation about buffer levels is given in the paragraph *Additional explanation about parameters.*

Input parameters:

Bin types: Every component c is transported in a specific bin type. The bin type of a component determines which wagon type is able to transport that bin. In Appendix 3, we already discussed what different bin types there are.

Tugger train speed: The tugger train speed is set at 8 km/h.

Standard buffer level: The standard buffer level is level 3. Further explanation about buffer levels is given in the paragraph *Additional explanation about parameters.*

Handling times: We differentiate between 20 different handling actions, depending on the action type (4 actions) and the bin type (5 bin types). A detailed explanation about the distribution and the chosen parameters for these handling times is given in the paragraph *Additional explanation about parameters.*

Tugger train wagon data*:*

- *Wagon types: There are three different wagon types; wagon types differentiate from each other with respect to the bin types they are able to carry (Appendix 3)*
- *Wagon capacities: Every wagon type has its own capacity (the number of bins it can possibly carry, Appendix 3)*

Input – schedule

Input schedule*:* A collective schedule containing a number of jobs (with start- and end time) for every assembly line.

Changeover time*:* The changeover time stands for the time it takes to start another job after the previous job is stopped due to a changeover. We got told by the Senior process engineer to put the changeover time at 10 minutes. The changeover time is fixed and constant, regardless of the kind of jobs that are involved in the job changeover.

Additional explanation about parameters

In this section, we provide an additional explanation about some of the input parameters that we already discussed in the previous section. We discuss the **cycle times per job** and their corresponding triangular distribution, the **buffer levels per assembly line** and the **handling times** and their corresponding triangular distribution.

Cycle times

Every job has a fixed cycle time that can be found in Ubbink's system. However, a constant cycle time does not comply with reality. Unfortunately, we do not have any means to fit a probability distribution to the cycle times. Therefore, we propose **triangular distributed cycle times**, to at least incorporate some uncertainty with respect to the time length of an assembly process.

Triangular distribution
A triangular distribution has three important parameters: a, b and c (see Figure 29). Parameters a and b represent the left and the right side of the distribution, respectively the minimum and maximum values. c represents the mode of the distribution, not to be mistaken with the mean of the distribution that is calculated with the following formula: $mean = \frac{a+b+c}{3}$

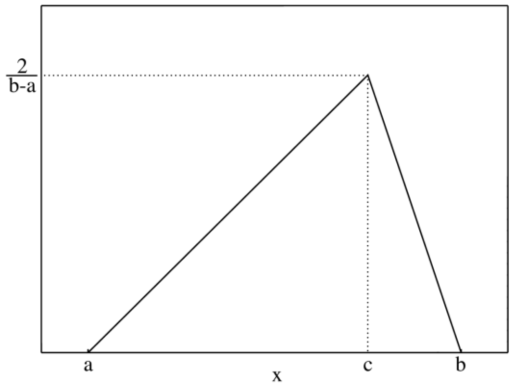


Figure 30: Example of a Triangular distribution (Wikipedia, 2021)

For our cycle time, we choose our mode c such that it is equal to the mean. In other words, in a similar figure as Figure 29, c would be exactly in the middle between a and b.

We take the fixed cycle times from Ubbink's system as the mean cycle time of a job. Appendix 2 shows the mean cycle time of every job j. In the simulation model, we take the following parameters as input of our triangular distribution: ($a = 0.7 * c, b = 1.3 * c, c = mean\ cycle\ time$).

Number of bins in bin rack per bin type, per buffer level

In the table below, for all bin types and for every buffer level, the number of bins that fit in the bin rack are given. The standard buffer level is level 3. When an assembly line operates at buffer level 3, it does not incur any extra costs, nor does it yield savings.

Table 12: Number of bins in bin rack per bin type, per buffer level

Buffer level per assembly line a	**Nr. of Container bin places**	**Nr. of Quarter meter box bin places**	**Nr. of Half meter box bin places)**	**Nr. of One meter box bin places**	**Nr. of End box bin places**
2 ($l = 2$)	2	3	2	1	1
3 ($l = 3$)	**3**	**4**	**3**	**2**	**1**
4 ($l = 4$)	4	5	4	3	1
5 ($l = 5$)	5	6	5	4	1
6 ($l = 6$)	6	7	6	5	1
7 ($l = 7$)	7	8	7	6	1
8 ($l = 8$)	8	9	8	7	1

Handling times

Together with a logistical engineer and a warehouse worker, we have measured the execution of handling actions. On the basis of our time measurements, we have made educated estimations of how long a handling action generally would last. Our time estimations are shown in Table 13. It is not possible for us to fit a probability distribution to the time length of handling actions, since we have carried out a small number of measurements. Therefore, we choose to use a triangular distribution with the mean time estimation as mode c.
We choose a and b respectively as: $a = 0.3 * c$ and $b = 1.7 * c$.
Compared, to the triangular distribution of the cycle times, we a bigger deviation with our choice of a and b. It is hit or miss whether the situation allows for a quick action or a time consuming action.

Table 13: Mean time estimations of handling actions

Loading full bins from the supermarket to the tugger train

Container	Confidential
End box	Confidential
Quarter meter box	Confidential
Half meter box	Confidential
One meter box	Confidential

Picking empty bins with Kanban cards attached

Container	Confidential
End box	Confidential
Quarter meter box	Confidential
Half meter box	Confidential
One meter box	Confidential

Loading full bins from the tugger train to the line

Container	Confidential
End box	Confidential
Quarter meter box	Confidential
Half meter box	Confidential
One meter box	Confidential

Storing empty bins at the packing place

Container	Confidential
End box	Confidential
Quarter meter box	Confidential
Half meter box	Confidential
One meter box	Confidential

5.1.4 Model output

For every simulation run, we track model performance with indicators in three categories; key performance indicators, tugger train behaviour and wagon capacity usage.

Key performance indicators

Costs: The cost function is made up out of two cost components: *buffer costs* and *tugger train costs*. Buffer costs concern the amount of extra space that is occupied by bin racks, expressed in money. Tugger train costs concern the cost for having T tugger trains driving around during the simulation run.

Working time (per assembly line): The amount of time an assembly line is operational (effective time that assembly jobs are executed).

Average line utilization (per line): the amount of time that an assembly line was operational, as a percentage of the complete time that the assembly line could have been operational.

Average line utilization (for all lines): the amount of time all assembly lines were operational, as a percentage of the complete time all assembly lines could have been operational.

Number of stockouts (per component): the number of times a component was out of stock.

An explanation about how the average line utilization indicators and how the costs are calculated is provided in chapter 5.1.5.

Tugger train behaviour

For every tugger train, we track the percentage of the time the driver is executing a handling action, the percentage of time the train is driving and the percentage of time the train is standing still due to it being blocked by another tugger train. Summing these 3 percentages together should equal 100%.

Average wagon capacity usage

For every tugger train, we track per wagon type how its capacity is used. As a result, we can calculate and the average wagon capacity usage, per wagon type, considering all tugger trains.

5.1.5 Model objective

With our model, we try to find a (close to) optimal setting of decision variables ***Number of tugger trains*** **(T)** and ***Buffer level per assembly line*** **(BL_a)**, for every scenario. An optimal setting would be a setting for which the values of our decision variables minimize the ***costs*** (objective function), while the ***average line utilization (over all 10 lines)*** is still above a pre-defined threshold value.

The objective function can be formulated as follows:

$$Min\ C = T * TC + \sum_{a=1}^{10} (BL_a - SBL) * BC * BA_a \qquad (11)$$

Sets

a	Set of assembly lines: $a = 1, \dots, 10$

Decision variables:

T	The number of tugger trains driving in the system
BL_a	Buffer level of assembly line a (see the paragraph *Number of bins in bin rack per bin type, per buffer level* in chapter 5.1.3)

Parameters

Notation	Data	Function
TC	Real	Tugger train cost per day
SBL	Integer	Standard buffer level; $SBL = 3$
BC	Real	Buffer costs; daily cost of 1 m^2 buffer
BA_a	Real	Surface area needed for an increase in buffer level on assembly line a (in m^2)

Here, the *costs* (C) are made up out of two independent cost components:
1. **Tugger train costs**: Costs of driving T tugger trains; $T * TC$ *(11)*
2. **Buffer costs**: Costs of having additional buffer space at the LCIA lines; $\sum_{a=1}^{10} \sum_{c \in \boldsymbol{M_a}} (BL_a - SBL) * BC * BA_a$ *(12)*
In the next two paragraphs, the cost components *Tugger train costs* and *Buffer costs* are explained in detail.

The ***average line utilization (over all 10 lines)*** (ALU) is calculated as follows.

$$ALU = \frac{\sum_{a=1}^{A} LU_a}{A} \qquad (12)$$

Here, the *line utilization for one assembly line a* (LU_a) is determined at the end of every simulation run for every assembly line a.
A setting of decision variables can only represent a feasible solution if and only if:

$$ALU \geq Predefined\ minimal\ average\ line\ utilization \qquad (13)$$

Tugger train costs

The parameter *Tugger train cost* is a daily cost factor. It is built up out of salary costs and depreciation costs. The salary costs regard the salaries of tugger train drivers, considering 8 hours of driving the train. The depreciation costs regard depreciation on the investment of the front part of the train (the locomotive) and depreciation on the three wagons.
Table 14 shows the calculation of the (daily) *Tugger train cost*.

Table 14: Tugger train costs (Sources: orderbevestiging Movexx 200768 and Peters (2021))

Cost factors	**Costs**
Tugger train driver cost	€f per hour; g*f=€gf daily
Depreciation cost of the front part tugger train	*Investment cost*: €h per piece
	Depreciation cost: Yearly depreciation considering a 5 year lifetime: €i Daily depreciation (considering 239 working days per year and no residual value): €i/239 = €j
Depreciation cost for 3 wagons	*Investment cost (for three wagons)*: €k
	Depreciation cost: Yearly depreciation considering a 10 year lifetime: €l Daily depreciation (considering 239 working days per year and no residual value): €l/239 = €m
Daily tugger train costs	Daily tugger train cost: gf+m+j

Buffer costs

The cost component *buffer costs* is calculated as follows:

$$Buffer\ costs = \sum_{a=1}^{10} (BL_a - SBL) * BC * BA_a \tag{14}$$

When the buffer size (BL_a) exceeds the standard buffer size SBL (parameter), costs are incurred. An increase of 1 for BL_a, leads to extra costs of $BC * BA_a$. Note, that a decrease in buffer level such that the value of the buffer level is smaller than standard buffer level 3, actually saves costs. The Paragraph *Number of bins in bin rack per bin type, per buffer level* in chapter 5.1.3 discusses the number of bin places in a bin rack that corresponds to certain buffer level, per bin type.
In the next paragraphs, we discuss the parameter values of BC and BA_o.

Surface area needed for an increase in buffer level in m² ($\boldsymbol{BA_a}$)

We know for every job, out of which components it is made up and which bin types belong to those components. Hence, we also know what bin racks have to stand at the buffer place, as every component has its own unique type of rack. The bin rack types differ from each other with respect to their shape and their size.

For every type of bin rack, we can measure how much surface space the bin rack takes up and we know how many bins fit on it (Table 15). When we divide the column *Area needed for the bin rack at standard buffer level* with *Bin places at standard buffer level* we can calculate the *Area needed for 1 extra bin place (m2),* which represents the extra space that is needed if the bin rack would be enlarged.

Table 15: Extra surface space needed if the buffer level is increased by 1

Bin type	Bin rack places corresponding to standard buffer level (level 3)	Area needed for the bin rack at standard buffer level (m^2)	Surface space needed for 1 extra buffer level (m^2)
Container	3	1.113	0.371
Quarter meter box	4	1.94	0.485
Half meter box	3	2.592	0.864
One meter box	2	4.2	2.1
End box	1	N/A	N/A

Total area occupied reserved for the placement of bin racks

Every LCIA consists out of two areas; an area which is reserved for the assembly process and an area where the bin racks stand. As we know, LCIA lines are able to execute multiple jobs. For every LCIA line, the surface space that is reserved for the bin racks solely depends on **the job that exists out of the set of components which bin racks need the largest surface area**.

We have calculated for every job how much space is needed for all component bin racks at the standard level (Appendix 7). This way, we find out what job needs the largest surface space for its bin racks per LCIA line (Table 16, column 2). The extra surface space that is needed if the buffer level is increased by 1 is also calculated (Table 16, column 3). An example calculation is presented in Appendix 7, where we calculate the surface area needed for *Job ?*.

Table 16: Area needed to increase the buffer level, per assembly line

LCIA line	Job that requires the most bin rack space per assembly line	Total bin rack space in m^2 considering the standard buffer level SBL	Surface area needed for an increase in buffer level in m^2 (BA_a)
Line 1	Job A	7,791	2.597
Line 2	Job B	7.791	2.597
Line 3	Job C	38.052	18.284
Line 4	Job D	6.9216	1.227
Line 5	Job E	6.0946	1.113
Line 6	Job F	12.2686	4.571
Line 7	Job G	14.4946	5.313
Line 8	Job H	13.3816	4.942
Line 9	Job I	19.7736	6.911
Line 10	Job J	22.8606	8.64

Buffer costs; daily cost of 1 m^2 buffer (BC)

The cost of extra buffer space per m^2 is calculated by using data about the contribution to profit of 2019, per department.

The current assembly area has a surface space of n m^2. The yearly profit as a result of assembly was €o. This gives a profit of o/n per m^2 assembly area. When we consider there to be 239 working days in a year, the daily profit was (o/n)/239 per m^2 assembly area.

Because in the future situation with the introduction of the LCIA lines, the *productivity per m²* is expected to double (more or less), this would mean that the daily profit made per m^2 assembly area is 2*((o/n)/239). Therefore, $\boldsymbol{BC}$ = 2*((o/n)/239).

5.2 Solving heuristic: Simulated Annealing

We need to incorporate a solving method in the material supply system model. Doing just one experiment does not provide us with answers to our main research question: **How should the material supply at Ubbink's LCIA lines be arranged at a tactical level?** It is needed to evaluate various scenarios, that are on their part each evaluated with various settings of decision variables.
This should be done in a smart way, to find (close to) optimal settings for every scenario. Again, solving optimally is deemed impossible. We expect that solutions (a setting of decision variables) can vary as follows (Table 17):

Table 17: The range and estimated number of possible combinations per decision variable (material supply setting): first the range is stated; secondly, the number of possible values that fall in that range

Nr of tugger trains	Buffer level line 1	Buffer level line 2	Buffer level line 3	Buffer level line 4	Buffer level line 5	Buffer level line 6	Buffer level line 7	Buffer level line 8	Buffer level line 9	Buffer level line 10
1-6; 6 *	2-6; 5 *	2-6; 5 *	2-6; 5 *	2-6; 5 *	2-6; 5 *	2-6; 5 *	2-6; 5 *	2-6; 5 *	2-6; 5 *	2-6; 5 *

* Range that we expect a decision variable to fall in ; The number of possible values that fall in the range

Hence, we estimate there to be 6*5*5*5*5*5*5*5*5*5*5=58593750 possible solutions, of which only one is the optimal solution. Therefore, we propose a second Simulated Annealing algorithm (SA2), to solve the material supply system model, finding good solutions. Figure 30 below shows a flow chart of the algorithm.

The SA2 algorithm has an interesting design. Where a "standard" SA algorithm only has one parameter *Starting Temperature*, one parameter *Decrease Factor* and one parameter *End Temperature*, this SA algorithm has two of those.

The SA2 algorithm starts by assessing a feasible solution, meaning that we need to start with a material supply setting which satisfies an average line utilization over all lines that is higher than target average line utilization. This solution is accepted as the current solution and as our best solution.

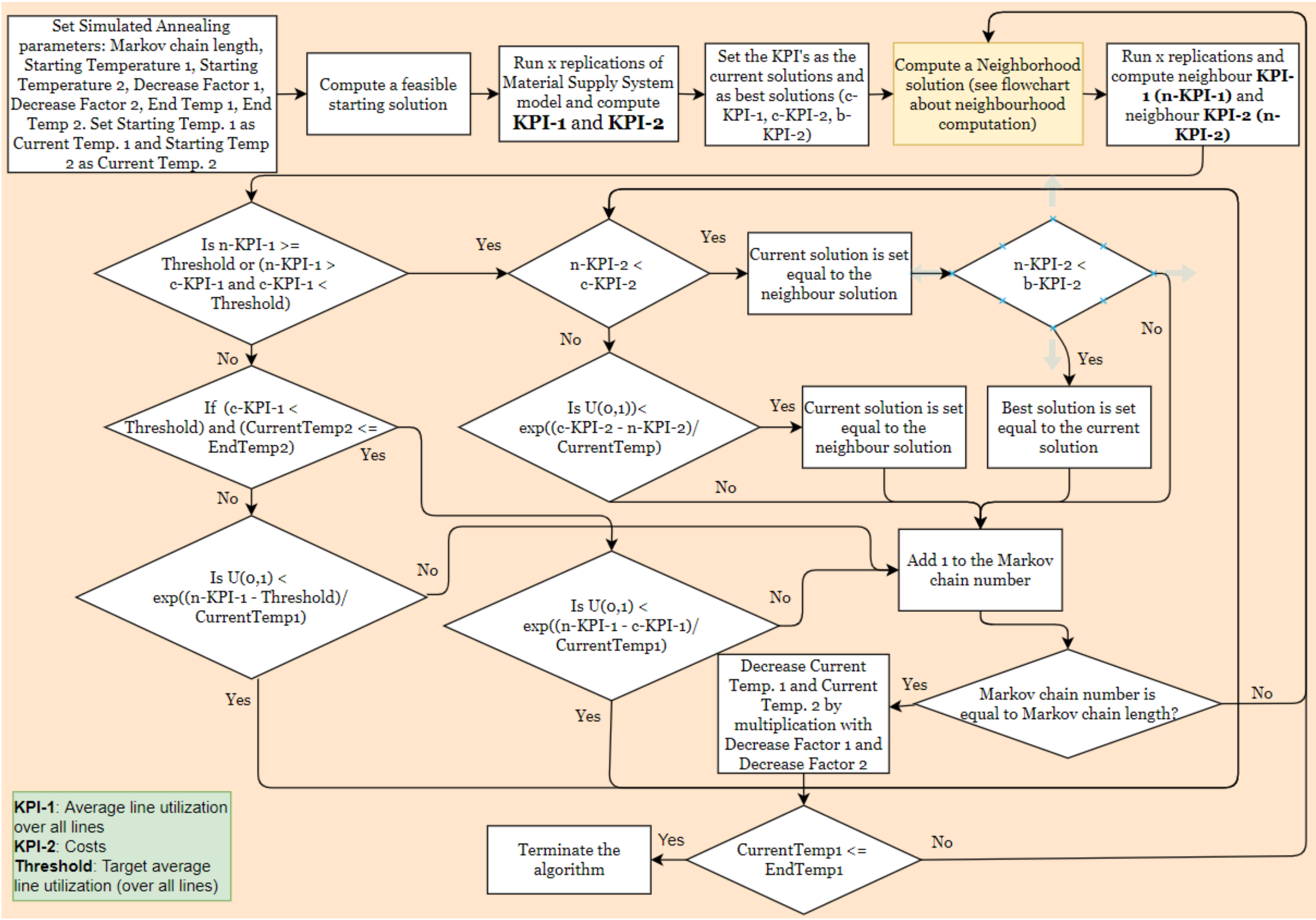


Figure 31: Simulated annealing algorithm incorporated in the material supply system model (SA2)

After a solution is accepted as the current solution, we create a neighbour solution (a neighbouring setting of decision variables) by using our neighbourhood operator. Appendix 9 shows a flow chart of how the neighbourhood operator functions.

For this neighbour solution, we run x replications with different random number streams as input. All x replications together form one experiment. **For every experiment, the cost of the material supply setting (KPI-2) is calculated as well as the average line utilization over all lines (KPI-1), taken as an average over all replications.**

Next, it is checked if the neighbour solution's **KPI-1 Average Line Utilization (Over all lines)**, taken as an average over x replications, **is larger than the (predefined) threshold value or larger than the KPI-1 of the current solution**. If this is indeed the case, we know that the neighbourhood solution is at least an improvement with respect to KPI-1. Hence, we accept the solution with respect to KPI-1 and we can move to the second part of the algorithm. However, if KPI-1 is smaller than the threshold value, the solution is **infeasible**. Based on an acceptance probability $\left(\frac{e^{NeighbourUtilization - Threshold}}{CurrentTemperature2}\right)$, we accept or reject the opportunity to move to the second part of the algorithm.

In the second part of the algorithm, the neighbourhood solution is accepted/rejected based on the value of **KPI-2 Costs.** The solution is accepted if KPI-2 is smaller than the current costs or whether the acceptance probability $\left(\frac{e^{\text{CurrentTotalCosts} - \text{NeighbourTotalCosts}}}{\text{CurrentTemperature}}\right)$ is such that we accept a worse cost.

After we have either selected a new current solution or whether we rejected the neighbour solution (so we stick with the old current solution as current solution), we use the current solution as input again to construct a neighbour solution. The algorithm keeps on going until we have reached the end temperature. The Markov chain length determines how many experiments are executed at a certain temperature level.

5.2.1 Parameter determination

We have chosen our starting temperature such, that for the first Markov chain every neighbourhood solution (worse solutions up to a deviation of 100 in cost and a deviation of 0,1% in utilization) are almost accepted with certainty (98% chance). This condition is satisfied if we choose a **starting temperature** equal to 5000.
We stop the algorithm when worse solutions deviation of 100 in cost are rejected with 99,999% certainty. We reach this situation when the **end temperature** is set at 11.

In the parameter determination, we also have to take time limitations into account. It is fine for if solving one scenario takes about 3 hours. We know that one replication takes 3 seconds and that we need to do 8 replications per experiment (see chapter 5.2.4). If we choose a **decrease factor** of 0.95 and a **Markov chain length** of 8, we consider 59 different Temperature levels before reaching the end temperature. This means that we have to carry out 59*8=472 different experiments. This takes about 472*8*3=11328 seconds, which is equivalent to 11328/3600=3.15 hours.

For the first 22 Markov chains, we are able to accept infeasible solutions. We set **starting temperature 2** at 0.03, meaning that we accept solutions with an average line utilization that are 0,1% worse with 97% probability. **End temperature 2** of 0.003 is reached after 22 different Temperature levels. After the end temperature is reached, we cannot accept infeasible solutions anymore.

In one run of the algorithm, we explore 9000 settings of decision variables. Every replication takes about 1.5 seconds to run. Table 18 shows the parameter settings of SA2.

Table 18: Parameter setting simulated annealing algorithm (SA2) incorporated in the material supply system model

Start temperature 1	5000	Start temperature 2	0.03
Decrease factor 1	0.95	Decrease factor 2	0.95
End temperature 1	11	End temperature 2	0.003
Markov chain length	8		

5.3 Experimental design

We discuss the inputs of the regular scenarios that we solve with our model in chapter 5.3.1. We determine the number of replications that we need to do per experiment and the warm-up length of one simulation run in respectively chapter 5.3.2 and chapter 5.3.3.

5.3.1 Scenarios

As we are not sure what the effect of certain input factors are on the outcomes of the material supply system model, we need to run different scenarios. The scenarios differ from each other in three different aspects:

1. The plant layout (paragraph *Plant layout*)
2. The input schedules (paragraph *Input schedules*)
3. The target average line utilization (paragraph *Target average line utilization*)

The table 19 shows all 28 regular scenarios we evaluate.

Table 19: All 28 regular scenarios and their corresponding input settings

Scenario	Layout	Input schedule	Target avg. line utilization	Scenario	Layout	Input schedule	Target avg. line utilization
Scenario 1	Lay out 1	Input schedule 1	99%	Scenario 15	Lay out 2	Input schedule 1	99%
Scenario 2	Lay out 1	Input schedule 2	99%	Scenario 16	Lay out 2	Input schedule 2	99%
Scenario 3	Lay out 1	Input schedule 3	99%	Scenario 17	Lay out 2	Input schedule 3	99%
Scenario 4	Lay out 1	Input schedule 4	99%	Scenario 18	Lay out 2	Input schedule 4	99%
Scenario 5	Lay out 1	Input schedule 5	99%	Scenario 19	Lay out 2	Input schedule 5	99%
Scenario 6	Lay out 1	Input schedule 6	99%	Scenario 20	Lay out 2	Input schedule 6	99%
Scenario 7	Lay out 1	Input schedule 7	99%	Scenario 21	Lay out 2	Input schedule 7	99%
Scenario 8	Lay out 1	Input schedule 1	97%	Scenario 22	Lay out 2	Input schedule 1	97%
Scenario 9	Lay out 1	Input schedule 2	97%	Scenario 23	Lay out 2	Input schedule 2	97%
Scenario 10	Lay out 1	Input schedule 3	97%	Scenario 24	Lay out 2	Input schedule 3	97%
Scenario 11	Lay out 1	Input schedule 4	97%	Scenario 25	Lay out 2	Input schedule 4	97%
Scenario 12	Lay out 1	Input schedule 5	97%	Scenario 26	Lay out 2	Input schedule 5	97%
Scenario 13	Lay out 1	Input schedule 6	97%	Scenario 27	Lay out 2	Input schedule 6	97%
Scenario 14	Lay out 1	Input schedule 7	97%	Scenario 28	Lay out 2	Input schedule 7	97%

Plant layout

There are 2 possible layouts that we both consider in the regular scenarios (see figure 31 and figure 31). In Figure 31, the assembly lines lie further away from the supermarkets than in figure 32.

Figure 32: Layout 1

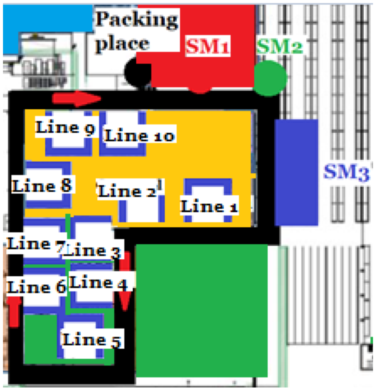


Figure 33: Layout 2

The layouts differ from each other with respect to the positioning to LCIA lines, and thus also with respect to the tours that the tugger trains need to drive. This translates to a difference between the tour lengths of the two layouts. The perimeter of layout 1 is q meters, whereas the perimeter of layout 2 is r meters. It is expected that a choice in layout has an influence on the number of tugger trains and buffer space needed to satisfy the threshold average line utilization.

Input schedules

We run scenarios with seven different input schedules as input. The reason for this is twofold:

1. We want to show that different inputs schedules require different material supply settings.
2. We want to showcase that "level schedules" (Input schedules 5,6 and 7) are superior to unlevelled schedules with the same contents (Input schedules 1, 2 and 4). It should be noted that input schedule 3 cannot be "levelled", as every assembly line only has one job assigned in this schedule. Hence, it is not possible to create other combinations of this schedule since no swapping operations can be performed.

Table 20 summarizes which schedules are input to the model. Appendix 8 presents the content of the seven input schedules.

Table 20: The 7 input schedules considered in the regular scenarios

Schedule	Content
Input schedule 1	Random schedule with no Large product of Line X jobs scheduled on line 3
Input schedule 2	Input schedule with Large product of Line X jobs scheduled for the whole day on line 3
Input schedule 3	Only the job with the highest *Tugger train capacity per hour*
Input schedule 4	The four jobs with highest *Tugger train capacity per hour* (at every line starting with the job with highest *Tugger train capacity per hour*, followed by the job with the second highest *Tugger train capacity per hour*, etc.). Every job lasts two hours.
Input schedule 5	Levelled schedule of input schedule 1
Input schedule 6	Levelled schedule of input schedule 2
Input schedule 7	Levelled schedule of input schedule 4

Target average line utilization

When we run experiments, we set a threshold value which represents the target average line utilization that we strive for. A material supply setting is deemed infeasible if its corresponding performance indicator, average line utilization, is smaller than the threshold value.

As discussed with the senior process engineer, we choose to solve scenarios against a 97% target average line utilization and a 99% target average line utilization. In other words, for half of the scenarios (97%) we strive for an average line utilization in which assembly lines are operational 58:12 time units in one hour. For the other half, we strive for an average line utilization in which assembly lines are operational 59:24 time units in one hour.

5.3.2 Number of replications

In order to incorporate uncertainty in the model with respect to handling times and cycle times, we use random number streams as input to our model. As a result, the outcome of key performance indicator **average line utilization (over all lines)** differs per simulation run. Hence, multiple replications need to be done in order to get a reliable average value for this key performance indicator. We determine the amount of replications according to the method found in Mes (2019).

In our analysis, we want to find a 95% confidence interval of the true mean value of the KPI, where the bounds of the confidence interval have a relative error of 0.5%.
The bounds of the left and the right side of the confidence interval are calculated as follows: $X_n \pm t_{n-1,1-a/2} * \sqrt{S_n^2/n}$. Here, X_n is the mean of the KPI over all replications until replication n. $\pm t_{n-1,1-a/2}$ stands for either the left or the right side of the student distribution. S_n^2 is the sample variance of the KPI over all replications until replication n. Subsequently, the relative error (γ') is calculated as $\gamma' = \frac{\left(t_{n-1,1-\frac{a}{2}} * \sqrt{\frac{S_n^2}{n}}\right)}{X_n}$.

Since, the KPI **average line utilization (over all lines)** is a percentage, we feel the need to narrow the confidence interval down; in our case, we only accept 95%-confidence intervals with a relative error smaller of equal to 0.5%.

In order to determine the number of replications that we need to do to find confidence intervals narrow enough, we have run 20 replications multiple times, for the same scenario with different decision variables as input. As a result, we find that decision variables have considerable impact on the variance between values of the average line utilizations; some input settings reach a relative error of 0.5% after less than 5 replications, whereas other input settings only reach this after 15+ replications. Typically, we observe that material supply settings that allow for a high average line utilization per line, need less replications to set a narrow confidence interval with a low relative error. This is logical, as the uncertainty does not have an effect on the performance of assembly lines that may not have any stock outs regardless of uncertainty being incorporated in model. For these lines, the line utilization may even be at 100% every replication, which reduces the variation of the value of KPI average line utilization.

Appendix 10 shows how different input settings need a different number of replications in order to narrow the confidence interval down enough. Since in our case, it is only important to have accurate assessment of KPI values close to 0.97 to 0.99, we think it is justified to have a low number of replications. Based on what we found in Appendix 10, doing just 8 replications seems more than reasonable. Also, doing less replications per experiment allows us to experiment more considering time limitations.

5.3.3 Warm-up length

All assembly lines start with full component bins (full buffers). We have discussed this issue with experts. It was decided that it is representative for the future system to model it like this. Hence, at the very beginning of the simulation, there will be no component demand. Therefore, every assembly line has a line utilization of 100% for at least the first ten to fifteen minutes. Whether the assembly line can keep this level of utilization depends on the decision variables and obviously its own parameters (cycle time, component bin types, component Kanban sizes etc.).
We have not chosen to incorporate a warm-up period in the model. After a job changeover, a job always starts with maxed out component bin racks, in terms of number of components stocked in the bin rack. We felt that there is no need to exclude the start of a working day when the buffers are full, but to include arbitrary moments during the day of when jobs start out with maxed out stock levels as well. So, we have chosen to include both of these in the model, resulting in the model having no warm-up period.

5.4 Technical implementation

In this section, we describe how we implement the simulation model. First, we explain the appearance of the model in chapter 5.4.1. After, we discuss where input can be entered in the model (chapter 5.4.2). Lastly, we shed light on how different methods in the simulation model communicate with each other, for them together to imitate the material supply system. This is done in chapter 5.4.3.

5.4.1 Model appearance

We modelled the complete model (with all its objects and methods) in one root frame (Figure 33).

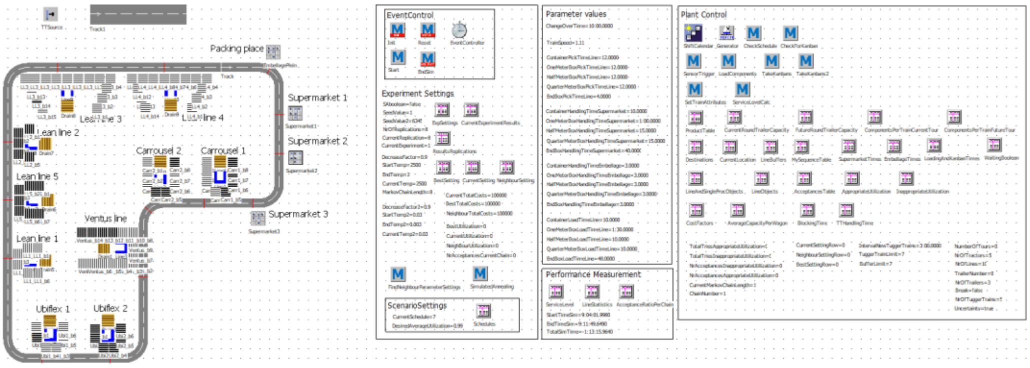
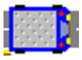
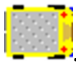


Figure 34: Root frame of the material supply system model; simulation model (layout 2)

We modelled two different layouts of the material supply model. Figure 35 below shows the model appearance of layout 1. Figure 36 below shows the model appearance of layout 2.

Both figures showcase a screenshot made while the model ran. You can see the tugger train when they are driving around , when they are performing a handling action  or when the train is waiting in line for a station where needs to stop to perform a handling action .

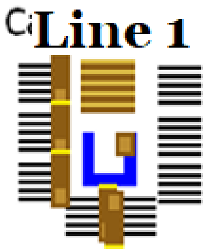


Figure 35: Example of an LCIA line as displayed in the simulation model

The assembly lines in the model look like the one in figure 34. The black-white striped squares represent a component bin rack of a certain component. The smaller brown squares on top of the striped squares represent one component. The number of brown squares on top of the striped squares represent the number of components that are stored in the bin rack.

In figure 34, we see that there are five bin racks filled, indicating that this job relies on five components as input. From object  we know that there is an assembly process being executed right now. Every time an assembly process starts, the number of components in the component bin rack decreases by its BOM quantity.

The way the assembly process is modelled can be considered a black box. The model knows based on the job that is currently scheduled how many components and which components are input to the process. It also knows the cycle time of the assembly job. This is all the model is concerned about with respect to the assembly process.

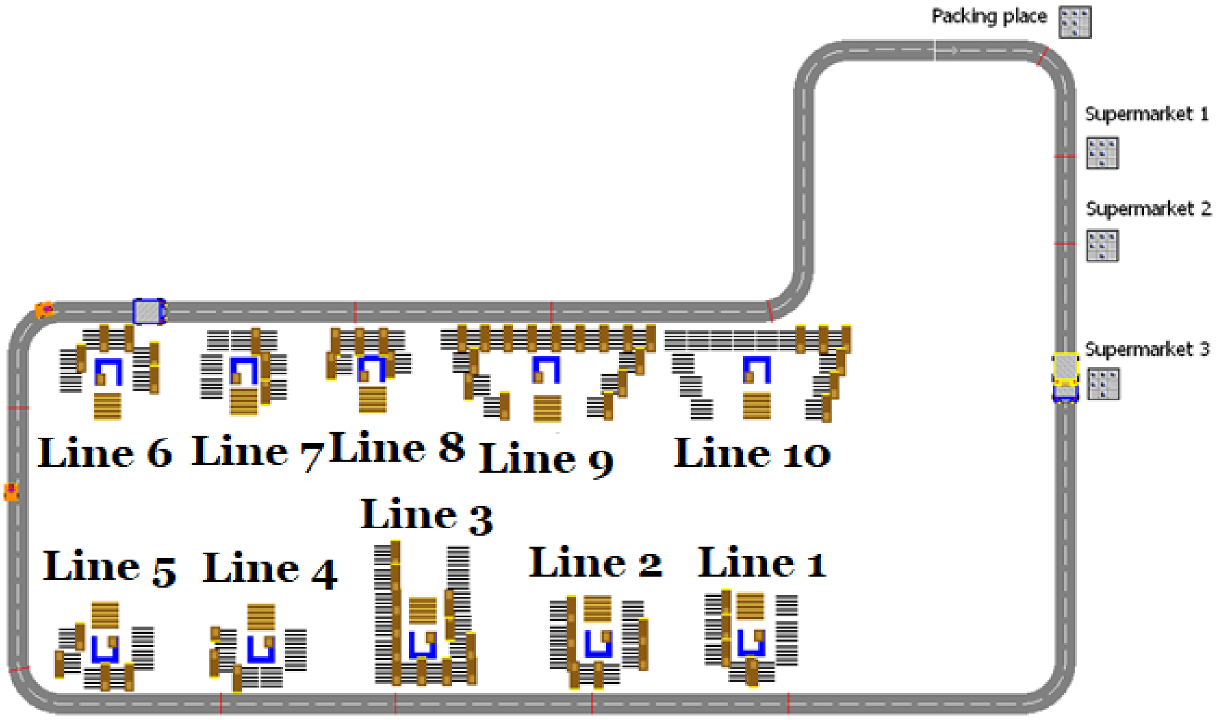


Figure 36: Model appearance of layout 1 (as in the simulation model)

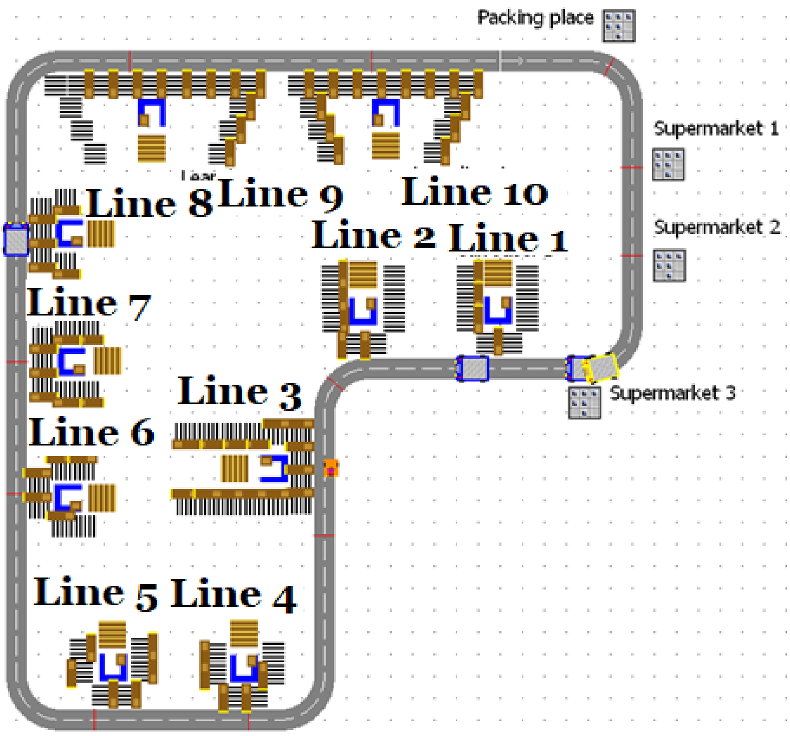


Figure 37: Model appearance of layout 2 (as in the simulation model)

In Appendix 12, we discuss how others can use the model and how they can enter different inputs, to evaluate different scenarios. Additionally, a brief explanation is provided, on how different methods in the simulation model work together to imitate the material supply system in a simulation model.

5.5 Model credibility

In this section, we discuss the model credibility. We verify the model by checking whether we correctly implemented the conceptual model.
We validate the model by reassessing the validity of the assumptions we have done.

5.5.1 Verification

Since we have built a simulation model, we can just watch the trains move and see if they show the behaviour we expected. Watching the model showcases train behaviour as we intended it. However, we have to dive deeper in the matter to see if actually everything is correctly simulated.
As a start, we have debugged the model for hours and fixed every bug we could find. However, some bugs may be hidden. To this end, we applied additional verification tactics.

Verification technique 1

As a first verification technique, we run all our scenarios with very high buffer levels and a high number of tugger trains (*Number of tugger trains = 8* and all *buffer levels* = 6), which basically ensures us to reach a 100% average line utilization over all assembly lines. We call this material supply setting, setting 1.

Additionally, we also run our model with a very low buffer level and amounts of tugger trains. Here, the number of Tugger trains and the buffer levels are set to 2 (setting 2).

Table 21: Verification technique 1 (Verification)

	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14
Setting 1	100%	100%	*95%	100%	100%	100%	100%
Setting 2	81%	75%	55%	73%	81%	75%	75%

As can be seen above, the results showcase that when more tugger trains and when the buffer levels are higher, compared to a situation where these settings are low. This is a first good sign that things go well in the model.
Scenarios 8 to 14 all contain layout 2. However, it is verified that the choice in layout does not affect the functioning of the model. So it does not matter what layout we choose in order to verify the model.

Verification technique 2

After every Kanban card that has been picked, we should see the table containing information about futuristic contents of tugger train wagons change, as well as the table that contains information about the free capacity of the tugger train wagons.
These instances are examples of model updates. These updates need to be carried out, in order for the model to work correctly. While debugging the model, extensive attention has already been paid to this issue. The correct functioning of the "update-issue" has been checked for all input schedules given as input. It seems that everything is working fine.

Verification technique 3

When a line has a utilization of 100%, we can calculate how much products of a job were expected to be assembled. After all, we know how long the job has been operating and we also know its mean cycle time. Hence, we can calculate the expected number of assembled products:

$$Exp.number\ products\ assembled = \frac{total\ assembly\ time\ job\ j}{mean\ cycle\ time\ job\ j}$$

For all the seven scenarios that we consider in this thesis project, we measured the number of products assembled at a specific time (07:45 or 13:45) for a random product on a random assembly line. The first measurement is carried out at 07:45 (Simulation time) and the other is carried out at 13:45. We compare the measurement with the number of products that were expected to be assembled at this time.

Table 22: Expected number of products produced vs real number of products produced (Verification)

	07:45	13:45
Scenario 8	Ass. Line 6 – Job 1 Exp. Amount: 200 Real amount: 202	Ass. Line 8 – Job 2 Exp. Amount: 566,33 Real amount: 565
Scenario 9	Ass. Line 5 – Job 3 Exp. Amount: 120 Real amount: 122	Ass. LINE 10 – Job 4 Exp. Amount: 185 Real amount: 184
Scenario 10	Ass. Line 2 – Job 5 Exp. Amount: 240 242	Ass. Line 7 – Job 6 Exp. Amount: 562.5 566
Scenario 11	Ass. Line 3 – Job 7 Exp. Amount: 60 Real amount: 60	Ass. Line 4 – Job 8 Exp. Amount: 220 Real amount: 221
Scenario 12	Ass. Line 9 – Job 9 Exp. Amount: 180 Real amount: 182	Ass. Line 1 – Job 10 Exp. Amount: 620 Real amount: 620
Scenario 13	Ass. Line 10 – Job 11 Exp. Amount: 180 Real amount: 180	Ass. Line 8 – Job 12 Exp. Amount: 565 Real amount: 565
Scenario 14	Ass. Line 4 – Job 13 Exp. Amount: 120 Real amount: 121	Ass. Line 9 – Job 14 Exp. Amount: 15 Real amount: 16

As in every case, the expected amount is very close the real amount, we have no reason to think that something is going wrong in simulating the assembly process.

Verification technique 4

As a fourth means of verification, we can clock cycle times and handling times. We simply track in the model how much time certain actions take, and we assess whether that makes sense. No peculiarities were found.

Verification technique 5

Lastly, we have checked whether job changeovers are indeed being carried out. We ran the simulation model with input schedules 1 to 7 and we checked whether at the end of the day, the correct jobs are actually being assembled. Fortunately, this is the case for every input schedule. This indicates that job changeovers are indeed being carried out, as it should be done according to input schedule that is given as an input.
Additionally, we executed some random checks during the course of working day. Again, no issues were found.

5.5.2 Validation

Our model imitates the function of a material supply system that does not exist yet. Currently (10-11-2021), only two LCIA lines are operational, in what is called a starting phase. The material supply system of the starting phase is different from the system that we consider to be the future material supply situation, which is described in chapter 2.5.5. There are three key differences;

1. **Currently, the tugger train driver does not devote all his time to driving the tugger train and performing the corresponding handling actions**; as only two LCIA lines are operational, the tugger train driver has some free time on his hands to perform other activities.
   This will not be the case in the future when more LCIA lines will be operational. Then, the tugger train driver is supposed to devote his time completely to replenishing LCIA lines only.
2. **Currently, certain full component bins are placed on the wagons as a standard;** so, these component bins are not loaded on the tugger train wagon as a result of a Kanban steered order, but as a result of a safety policy.
   The main reason for this is to build in extra safety with respect to component availability at the assembly lines. In the future material supply system, this should not be happening. Therefore, we have not considered this safety policy in the model.
3. **Currently, not every bin type is replenished with the tugger train;** Components that either have End box or *One meter box* as bin type, are not replenished by the tugger train. This, because the Ubbink's logistic team consider the loading process of these bins to be too time inefficient.
   In the future however, these bin types are supposed to be replenished by the tugger train. Hence, the model also includes the replenishment of these bin types.

Because of the three key differences we have identified, the current state of the material supply system is considerably different from what it should be eventually. Therefore, we cannot use it to (partially) assess the validity of our model.
However, we may be able to assess the validity of our model by validating the assumptions and the estimations we have done.

Assumptions

All assumptions that have been made, have been made upon approval of either a senior process engineer or a logistical engineer. This has been done around the time of June 2021 (this section is written in October 2021). We consider these assumptions to be valid.
However, we have taken the freedom to reassess the assumptions with another process engineer (second opinion, October 2021). The outcome of the assessment is summed up below:

Assumption 1: ***Components are always available to be picked from the supermarkets;*** this assumption is not in line with reality. However, we do not have data on components availability. So, there is no way to model this more accurately anyways.
We argue that this assumption does not hurt the validity of the model, but the assumption should be considered when interpreting model outcomes. Assuming that components can always be picked from the supermarket puts the material supply system under maximum pressure. Running the model under this assumption can be considered an ideal situation for Ubbink as well as a "worst case" scenario for the material supply system itself.

Assumption 2: ***Change over times are always 10 minutes;*** this assumption is not in line with reality. However, we do not have data on changeover times. So, there is no way to incorporate changeover times more accurately in the model anyways.

According to the second opinion, ten minutes sounds like a reasonable time duration for a changeover. Additionally, it is noticed that this assumption should have little influence on the model validity.

Assumption 3: ***Box components (with bin type End Box, only 1 bin fits in the component bin rack) release a Kanban card when there is 33% of the components left in the buffer;*** Because the policy of releasing Kanban cards for Box components is undetermined as of yet, we needed to make an assumption about it for our model. According to our second opinion, releasing a Kanban card at 33% is reasonable. This assumption should have little influence on the validity of the model.

Assumption 4: ***Tugger train X can pass (an)other tugger train(s) that block the road;***
It has not yet been proved whether this is possible everywhere in the plant. However, we believe that when this assumption cannot be fulfilled, the future material supply system is bound to fail regardless. There would be too much congestion in the model for the system to work. It is expected however by our second opinion that tugger trains can move past each other.
It should be noted that tugger trains queue behind each other when a tugger train has to visit a station that is currently occupied by another tugger train.

Assumption 5: ***Assembly lines and tugger trains do not break down;*** There was no data available to model line breakdowns or tugger train breakdowns, so we assumed there to be no break downs.
We already know that this assumption does not hold for the assembly lines. No line breakdowns means that more pressure is applied on the material supply system. As with assumption 1, running the model under this assumption can be considered an ideal situation for Ubbink as well as a "worst case" scenario for the material supply system itself. Hence, we argue that this assumption does not hurt the validity of the model, but the assumption should be considered when interpreting model outcomes.
The assumption does not hold for the tugger trains neither. It is down to Ubbink's maintenance policy how severe the effect of tugger train breakdowns is.

Estimations

Together with a logistical engineer, estimations have been made about the twenty possible handling times; every bin type (5 types) can be involved in 4 different handling actions.
However, we can also observe the current loading process of full *container* bins and the picking process of empty *container* bins. Hence, we are able to measure the duration of the handling actions.

Due to current space limitations in the Ubbink plant, the tugger train is unable to access every component bin rack. Hence, it takes considerably more time (about 20 seconds) to load a full bin that is far away to its bin rack, compared to a bin that is close to its bin rack (about 8 seconds).

The same goes up for picking empty bins and taking their Kanban cards. When the bins are close to the tugger train, it takes about 10 seconds per bin to load them onto the tugger train and to their Kanban cards. However, if the empty bin is located further away from the tugger train, this action takes about 20 seconds. It should be noted that the observed action of picking empty bins and taking their Kanban cards incorporates handling steps that were originally not supposed to be part of the handling action.

As input to our model, we estimated a *container* loading action to take about 10 seconds. We estimated the time to pick an empty bin and to take its Kanban card to be 12 seconds. Based on the time measurements we have done, we feel that this is still an accurate estimation.

5.6 Conclusion

The material supply system is modelled as a simulation model. In the model, we solve various scenarios (branched on input schedule, layout and target average line utilization), with the aim to find (near) optimal material supply settings for minimal costs. A material supply setting consists of the decision variables *number of tugger trains* and *buffer level per LCIA line*. The costs of a setting depend on the values of the decision variables, which are part of the cost function. In order to solve the scenarios, a solving heuristic is incorporated in the simulation model, called Simulated Annealing.

In the last section, we verified and validated the model. Apart from watching the model's behaviour and debugging all methods for days on end, we have applied other verification techniques. As a result of our efforts, we are certain that we correctly implemented the conceptual model.
Since the material supply system that we model with the simulation model is not implemented yet, validating the system is difficult. However, we were able to validate assumptions by discussing their validity with a process engineer (second opinion). It seems that the model is valid, but it is recommended to consider the assumptions that have been done when interpreting model outcomes.

6. Results and discussion

This chapter is divided in three sections. In chapter 6.1, we present the experimental results that we have gathered for all the 28 regular scenarios that we have ran. We finish the section off by discussing and explaining the results of the regular scenarios.
Additionally, we run an additional set of scenarios. In these scenarios, input parameters that were considered fixed in our regular scenarios, are changed. The results can be found in chapter 6.2, Sensitivity analysis. We end the section with a discussion about the results.
Lastly, we execute five single runs for a number of predetermined material supply settings. The goal here is to recognize at a component level, which type of components have a high stockout risk. The findings are presented, discussed, and explained in chapter 6.3. Below, we state which research questions are answered in this section.

Research question 6: What are the results of the material supply system model?
6.1 What are the results of the regular scenarios that are solved with the material supply model?
6.2 How do the results of similar regular scenarios, that differ with respect to only one input factor, compare with each other?
6.3 How sensitive are regular scenario results with respect to changes of fixed input parameters?
6.4 What components have a high stockout risk?

Figure 38: Research question 6

6.1 Regular scenarios

In this section, we present and discuss the results of the regular scenarios (chapter 5.3.1) that we have solved with our SA2 heuristic.
For every regular scenario, we have gathered the corresponding outcome material supply setting as well as various performance indicators. Appendix 14, Table 55, shows which material supply settings we have found for each scenario. The corresponding key performance indicators are also given in Appendix 14, Table 55.
It should be noted that we did not solve scenarios 3, 10, 17 and 24. These scenarios overloaded with up to 20 tugger trains to come close to the target average line utilization, which apart from this being impossible in a real world scenario, also gave difficulties running the simulation model. Since these scenarios incorporated a schedule with only the busiest job scheduled on every line, we consider this to be a worst-case scenario that cannot be facilitated by the material supply system.

Appendix 14, Table 56, shows per scenario what tugger train behaviour was measured considering the material supply settings that were found in Appendix 14, Table 55. The tugger train behaviour consists out of the following aspects; the percentage of time the trains were blocked, the percentage of time a handling actions was executed and the percentage of time the train was driving.
Appendix 14, Table 57, shows how the capacity of the tugger train wagons was used in each of our regular scenarios. The results consider the material supply setting that was found in Appendix 14, Table 55.

In the upcoming sections, we discuss the results of our regular scenarios with respect to:

1. material supply settings (decision variables)
2. level schedule scenarios vs. unlevelled schedule scenarios
3. scenarios with layout 1 vs. scenarios with layout 2
4. scenarios considering a target average line utilization of 97% vs. scenarios considering a target average line utilization of 99%

5. scenarios with input schedule 1 (that exclude Large product of Line X jobs) vs. scenarios with input schedule 2 (that include Large product of Line X jobs)
6. scenarios are analysed and compared with respect to tugger train behaviour
7. scenarios are analysed and compared with respect to wagon capacity usage

6.1.1 Discussion – Material supply settings

Appendix 14, Table 55, shows us all the material supply settings we have found for all the scenarios we have solved. It is scenario dependent, how much tugger trains are deployed and how high the buffer levels are. Note that scenarios incorporating IS 3 have not been solved. When running the simulation model, we found that these scenarios could not be solved for settings that could be replicated in real life (e.g. scenarios incorporating 20 tugger trains). The problem is that only 1 tugger train can be served at supermarket 3. However, the demand to be served at Supermarket 3 was so high that only one server was not sufficient. As a result, we have not taken the effort to solve them at all, as it is impossible to solve them for realistic settings

Most scenarios have material supply setting with either 4 or 5 tugger trains. Only four scenarios surpass the 5 tugger train mark. Typically, these scenarios are solved against a target average line utilization of 99%. Also, these scenarios are either unlevelled or/and have Large product of Line X jobs scheduled.

The buffer levels we found vary between 2 and 5, where a buffer level of 5 is a rarity.
We observe that the algorithm prefers to keep the buffer levels of lines that host “small number of components jobs” high. The buffer costs for these lines are relatively low, while the line utilization of a line with a small buffer space contributes just as much to the average line utilization as the line utilization of a line with larger buffer space.
We also see that it is generally preferred to keep the buffer level at least at level 3, when jobs with components with *One meter box* as bin type are scheduled on the LCIA line. A buffer level of 2 would mean that there would be only one *One meter box* bin place in the bin rack, which can never be sufficient.

6.1.2 Discussion - Level scheduling

In Table 23 below, we present a comparison between unlevelled schedules and their levelled counterparts.

Table 23: Comparison between regular scenarios; unlevelled scheduled (left) vs. their levelled counterparts (right)

Unlevelled schedules					Level schedules					
Scenario	**Layout**	**Input schedule**	**Target avg. line utilization**	**Costs (€)**	**Scenario**	**Layout**	**Input schedule**	**Target avg. line utilization**	**Costs**	**Cost difference**
Sc. 1	Lay out 1	IS 1	99%	Confidential	Sc. 5	Lay out 1	IS 5	99%	Confidential	64.87
Sc. 2	Lay out 1	IS 2	99%	Confidential	Sc. 6	Lay out 1	IS 6	99%	Confidential	30.78
Sc. 4	Lay out 1	IS 4	99%	Confidential	Sc. 7	Lay out 1	IS 7	99%	Confidential	507.62
Sc. 8	Lay out 1	IS 1	97%	Confidential	Sc. 12	Lay out 1	IS 5	97%	Confidential	55.61
Sc. 9	Lay out 1	IS 2	97%	Confidential	Sc. 13	Lay out 1	IS 6	97%	Confidential	-61.3
Sc. 11	Lay out 1	IS 4	97%	Confidential	Sc. 14	Lay out 1	IS 7	97%	Confidential	191.04
Sc. 15	Lay out 2	IS 1	99%	Confidential	Sc. 19	Lay out 2	IS 5	99%	Confidential	49.31
Sc. 16	Lay out 2	IS 2	99%	Confidential	Sc. 20	Lay out 2	IS 6	99%	Confidential	-8.68
Sc. 18	Lay out 2	IS 4	99%	Confidential	Sc. 21	Lay out 2	IS 7	99%	Confidential	572.49
Sc. 22	Lay out 2	IS 1	97%	Confidential	Sc. 26	Lay out 2	IS 5	97%	Confidential	30.65
Sc. 23	Lay out 2	IS 2	97%	Confidential	Sc. 27	Lay out 2	IS 6	97%	Confidential	41.26
Sc. 25	Lay out 2	IS 4	97%	Confidential	Sc. 28	Lay out 2	IS 7	97%	Confidential	598.71
			Average	**1118.21**				**Average**	**945.51**	**172.70**

It becomes clear from the table above that level scheduling is in most cases more cost efficient than a random input schedule. The average cost difference is 172.20. When we analyse where the savings are made, we observe that the savings can result from either lower buffer levels or less tugger trains driving around.

There are two comparisons, in which the unlevelled schedule actually came out better than its levelled counterpart. In both cases, IS2 was involved. The levelled schedule of IS1 (IS5) also did not yield big cost savings when compared to IS1 scenarios. The reasoning behind that this could be explained as follows; For some input schedules, levelling capacity is not that important. In these scenarios, tugger trains are used primarily to pick up empty bins quickly and to share the time of executing handling actions. When this is the case, adding tugger trains to increase the overall capacity of the supply equipment is of secondary importance and has little effect on the average line utilization.

The effectiveness of level scheduling is especially apparent for scenarios considering IS4 and IS7. The cost difference between these scenarios is significant, with savings from varying from about €200.- to €600.-. It was to be expected that the biggest difference would be found when these scenarios would be compared. IS4 is the opposite of a level schedule, as 4 jobs are scheduled on every line, and they are sequenced from high to low tugger train capacity. IS7 is the level schedule of IS4.

6.1.3 Discussion - Layout

In Table 24 below, we present a comparison between scenarios incorporating layout 1 and their counterparts that incorporate layout 2.

Table 24: Comparison between regular scenarios with layout 1 (left) compared with their counterparts with layout 2 (right)

Layout 1					Layout 2					
Scenario	**Layout**	**Input schedule**	**Target avg. line utilization**	**Costs (€)**	**Scenario**	**Layout**	**Input schedule**	**Target avg. line utilization**	**Costs**	**Cost difference**
Sc. 1	Lay out 1	IS 1	99%	Confidential	Sc. 15	Lay out 2	IS 1	99%	Confidential	145,92
Sc. 2	Lay out 1	IS 2	99%	Confidential	Sc. 16	Lay out 2	IS 2	99%	Confidential	136,32
Sc. 4	Lay out 1	IS 4	99%	Confidential	Sc. 18	Lay out 2	IS 4	99%	Confidential	181,61
Sc. 5	Lay out 1	IS 5	99%	Confidential	Sc. 19	Lay out 2	IS 5	99%	Confidential	130,36
Sc. 6	Lay out 1	IS 6	99%	Confidential	Sc. 20	Lay out 2	IS 6	99%	Confidential	96,86
Sc. 7	Lay out 1	IS 7	99%	Confidential	Sc. 21	Lay out 2	IS 7	99%	Confidential	246,48
Sc. 8	Lay out 1	IS 1	97%	Confidential	Sc. 22	Lay out 2	IS 1	97%	Confidential	256,05
Sc. 9	Lay out 1	IS 2	97%	Confidential	Sc. 23	Lay out 2	IS 2	97%	Confidential	67,72
Sc. 11	Lay out 1	IS 4	97%	Confidential	Sc. 25	Lay out 2	IS 4	97%	Confidential	18,41
Sc. 12	Lay out 1	IS 5	97%	Confidential	Sc. 26	Lay out 2	IS 5	97%	Confidential	231,09
Sc. 13	Lay out 1	IS 6	97%	Confidential	Sc. 27	Lay out 2	IS 6	97%	Confidential	170,28
Sc. 14	Lay out 1	IS 7	97%	Confidential	Sc. 28	Lay out 2	IS 7	97%	Confidential	426,08
			Average	**1119,66**				**Average**	**944,06**	**175,60**

As one would have expected, having your assembly lines closer to the supermarkets (layout 2), as opposed to having them further away (layout 1), yields cost savings. The height of these cost savings is scenario dependent. On average, the cost savings are 175.60 for all the scenarios that we considered.

6.1.4 Discussion – Target average line utilization

Below in Table 25, we present a comparison of scenarios with a target average line utilization of 99% compared to their scenario counterparts with a target utilization of 97%.

Table 25: Comparison between regular scenarios; settings with a 97% target average line utilization vs. similar settings aiming for 99%

Target average line utilization of 99%					Target average line utilization of 97%					
Scenario	**Layout**	**Input schedule**	**Target avg. line utilization**	**Costs (€)**	**Scenario**	**Layout**	**Input schedule**	**Target. avg. line utilization**	**Costs**	**Cost difference**
Sc. 1	Lay out 1	IS 1	99%	Confidential	Sc. 8	Lay out 1	IS 1	97%	Confidential	300,14
Sc. 2	Lay out 1	IS 2	99%	Confidential	Sc. 9	Lay out 1	IS 2	97%	Confidential	491,44
Sc. 4	Lay out 1	IS 4	99%	Confidential	Sc. 11	Lay out 1	IS 4	97%	Confidential	658,58
Sc. 5	Lay out 1	IS 5	99%	Confidential	Sc. 12	Lay out 1	IS 5	97%	Confidential	290,88
Sc. 6	Lay out 1	IS 6	99%	Confidential	Sc. 13	Lay out 1	IS 6	97%	Confidential	399,36
Sc. 7	Lay out 1	IS 7	99%	Confidential	Sc. 14	Lay out 1	IS 7	97%	Confidential	342
Sc. 15	Lay out 2	IS 1	99%	Confidential	Sc. 22	Lay out 2	IS 1	97%	Confidential	410,27
Sc. 16	Lay out 2	IS 2	99%	Confidential	Sc. 23	Lay out 2	IS 2	97%	Confidential	422,84
Sc. 18	Lay out 2	IS 4	99%	Confidential	Sc. 25	Lay out 2	IS 4	97%	Confidential	495,38
Sc. 19	Lay out 2	IS 5	99%	Confidential	Sc. 26	Lay out 2	IS 5	97%	Confidential	391,61
Sc. 20	Lay out 2	IS 6	99%	Confidential	Sc. 27	Lay out 2	IS 6	97%	Confidential	472,78
Sc. 21	Lay out 2	IS 7	99%	Confidential	Sc. 28	Lay out 2	IS 7	97%	Confidential	521,6
			Average	**1248.4**				**Average**	**815.33**	**433.07**

Clearly, the costs of settings with a 97% target average line utilization are than those of their counterparts with a 99% target. Logically, when the target utilization is lower, the SA2 algorithm finds a material supply setting

that yields low costs. A setting that would have been infeasible if the target was 99%, may be feasible if the target average line utilization equals 97%.
We observe that savings are made with respect to both buffer levels and the number of tugger trains driving around.

6.1.5 Discussion – Large product of Line X jobs

In this section, we briefly assess what the effect is of excluding Large product of Line X jobs in the schedule, compared to including them in the schedule. Our regular scenarios included two similar input schedules (IS1 and IS2). The only difference between them is that IS1 excludes Large product of Line X jobs and has less tugger train capacity demanding jobs scheduled instead of the Large product of Line X jobs, whereas IS2 includes the assembly of Large product of Line X jobs. Table 26 shows how input schedules excluding Large product of Line X jobs (left side) compare with scenarios that include the same input schedule including Large product of Line X jobs.

Table 26: Regular scenario comparison; the effect of scheduling Large product of Line X jobs

No Large product of Line X jobs on line X (Input schedule 1)					Large product of Line X jobs on line X (Input schedule 2 or Input schedule 1 with Large product of Line X jobs)					
Scenario	**Layout**	**Input schedule**	**Target avg. line utilization**	**Costs (€)**	**Scenario**	**Layout**	**Input schedule**	**Target avg. line utilization**	**Costs**	**Cost difference**
Sc. 1	Lay out 1	IS 1	99%	Confidential	Sc. 2	Lay out 1	IS 2	99%	Confidential	-769,12
Sc. 8	Lay out 1	IS 1	97%	Confidential	Sc. 9	Lay out 1	IS 2	97%	Confidential	-577.82
Sc. 15	Lay out 2	IS 1	99%	Confidential	Sc. 16	Lay out 2	IS 2	99%	Confidential	-778.72
Sc. 22	Lay out 2	IS 1	97%	Confidential	Sc. 23	Lay out 2	IS 2	97%	Confidential	-766.15
			Average	**475.38**				**Average**	**1198.33**	**-722.95**

As can be seen in the table above, it does make a big difference if Large product of Line X jobs are excluded, compared to including Large product of Line X jobs in the schedule. Up to two tugger trains can be saved and multiple buffer levels can be lowered, if Large product of Line X jobs are excluded from the schedule.

Since increasing a buffer level is expensive for line X, the algorithm tries to keep the buffer level of line X as low as possible. So, when the Large product of Line X jobs are not scheduled at line X, the buffer level is put at 2. The loss of line utilization is compensated by increasing buffer levels at other assembly lines.
However, when Large product of Line X jobs are scheduled at line X, the buffer level cannot be put lower than 3 since that would yield an unrecoverable loss with respect to the line's utilization.

6.1.6 Discussion - Tugger train driver behaviour

In the table below, we present the tugger train driver behaviour per scenario. As handling actions can be considered to be the most value adding action a tugger train driver can execute, we have sorted Table 27 on total percentage of time a handling is being executed. So, we can easily recognize which scenario settings led to an efficient usage of labour resources.

Table 27: Tugger train behaviour per regular scenario (sorted on perc. of time a handling action is being executed, per train); large to small

	Blocked	Handling					Driving
Scenario	**Perc. of time train is blocked (per train)**	**Perc. of time at packing place (per train)**	**Perc. of time loading empty bins/picking Kanban cards (per train)**	**Perc of time loading full bins to bin racks (per train)**	**Perc. of time at the SM (per train)**	**Perc. of time handling (per train)**	**Perc. of time driving (per train)**
Sc. 27 (L2, IS7, 97%)	17%	3%	13%	22%	18%	**58%**	25%
Sc. 15 (L2, IS1, 99%)	12%	3%	12%	17%	16%	**48%**	40%
Sc. 16 (L2, IS2, 99%)	18%	3%	11%	19%	16%	**48%**	34%
Sc. 19 (L2, IS5, 99%)	11%	3%	12%	17%	16%	**48%**	41%
Sc. 20 (L2, IS6, 99%)	18%	3%	11%	18%	16%	**48%**	34%
Sc. 23 (L2, IS2, 97%)	17%	3%	11%	19%	16%	**48%**	35%
Sc. 8 (L1, IS1, 97%)	11%	3%	12%	16%	15%	**47%**	42%
Sc. 9 (L1, IS2, 97%)	16%	3%	11%	18%	16%	**47%**	37%
Sc. 13 (L1, IS6, 97%)	16%	3%	11%	18%	16%	**47%**	37%
Sc. 22 (L2, IS1, 97%)	11%	3%	12%	16%	15%	**47%**	42%
Sc. 26 (L2, IS5, 97%)	11%	3%	12%	16%	15%	**47%**	42%
Sc. 12 (L1, IS5, 97%)	12%	3%	12%	16%	15%	**46%**	42%
Sc. 7 (L1, IS7, 99%)	15%	3%	10%	15%	14%	**42%**	43%
Sc. 21 (L2, IS7, 99%)	16%	3%	10%	15%	14%	**42%**	42%
Sc. 14 (L1, IS7, 97%)	14%	3%	10%	15%	14%	**41%**	45%
Sc. 25 (L2, IS4, 97%)	14%	3%	10%	15%	14%	**41%**	45%
Sc. 28 (L2, IS7, 97%)	14%	3%	10%	15%	14%	**41%**	45%
Sc. 2 (L1, IS1, 99%)	17%	2%	9%	15%	14%	**40%**	43%
Sc. 6 (L1, IS6, 99%)	17%	2%	9%	15%	13%	**40%**	43%
Sc. 1 (L1, IS1, 99%)	10%	3%	10%	13%	13%	**39%**	51%
Sc. 5 (L1, IS5, 99%)	10%	3%	10%	13%	13%	**38%**	52%
Sc. 11 (L1, IS4, 97%)	14%	2%	9%	14%	13%	**38%**	48%
Sc. 18 (L2, IS4, 99%)	16%	2%	7%	11%	10%	**31%**	53%
Sc. 4 (L1, IS4, 99%)	16%	2%	7%	11%	10%	**30%**	54%

Based on what we see in Table 27, we can deduce the following;

- Layout 2 allows for a more efficient usage of resources in comparison to Layout 1.
- Scenarios that are solved for material supply settings that include relatively a lot of tugger trains, tend to have a low percentage of handling time.

Layout 2 facilitates a closer distance between the supermarkets and the assembly lines. Hence, the tugger trains only need to drive a close distance in order to arrive at the next station. Time that would have been spent on driving in layout 1, can be saved and spend on handling in layout 2.

We also find that scenarios that are solved for material supply settings that include relatively a lot of tugger trains, tend to have a low percentage of handling time.
From this, we can conclude that increasing the number of tugger trains is not only a decision of adding the necessary extra capacity to pick and supply bins. It is also done to be quicker in picking empty bins and to spread the total time that is induced by handling.

In other words, the purpose of having multiple tugger trains driving around can be found in three different domains.
Firstly, tugger trains give you the supply capacity to transport components from A to B.
Secondly, the more tugger trains there are driving around, the more responsive the material supply setting is with respect to picking empty bins and Kanban cards. The more tugger trains, the quicker replenishments can be done.
Thirdly, when multiple tugger trains drive around in the material supply system, the handling can be spread over multiple trains as well, making the average duration of a tour per tugger train shorter.

We have seen that it is scenario dependent how the tugger train driver divides his time. However, we consider scenario 7 to be a reasonable representation of a normal workday of over a couple of years (Figure 38).

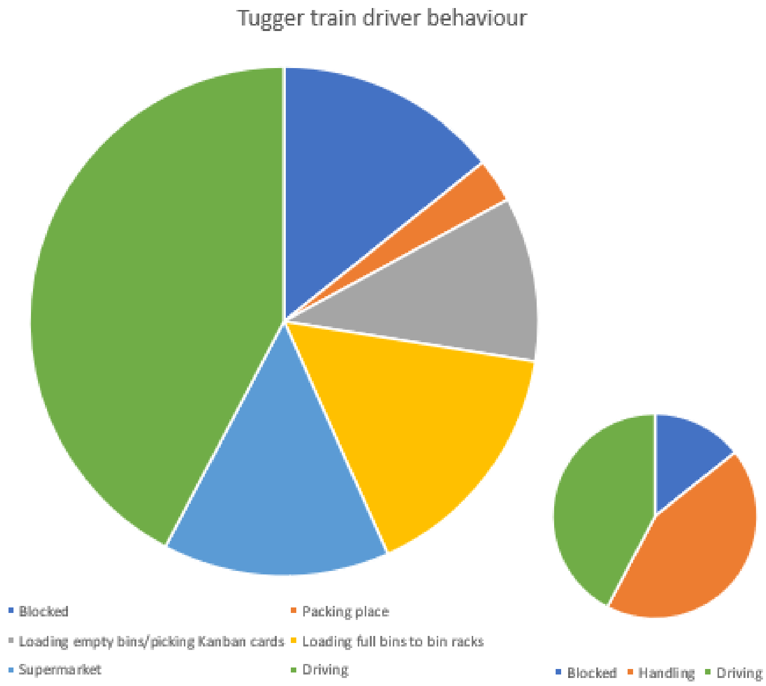


Figure 39: Tugger train driver behaviour (regular scenario 7)

6.1.7 Discussion - Wagon capacity usage

The wagon capacity is measured after a tugger train has visited all supermarket, but before the tugger train has visited any assembly lines. At that point in time, the tugger train is loaded with full component bins. It should be noted that the number of *container* places that is occupied at the start of a tour equals the number of *container* places that were occupied by empty bins the previous tour.
With the table 28 below, we present the average wagon capacity usage per scenario.

Table 28: Average wagon capacity usage per regular scenario

Scenario	Layout	Input schedule	Target avg. line utilization	Wagon 1 average capacity usage	Wagon 2 average capacity usage	Wagon 3 average capacity usage	Average wagon capacity usage
Sc. 27	Lay out 2	IS 6	97%	15%	17%	26%	19%
Sc. 13	Lay out 1	IS 6	97%	12%	13%	19%	15%
Sc. 9	Lay out 1	IS 2	97%	11%	12%	19%	14%
Sc. 8	Lay out 1	IS 1	97%	12%	16%	8%	12%
Sc. 12	Lay out 1	IS 5	97%	12%	16%	8%	12%
Sc. 20	Lay out 2	IS 6	99%	9%	11%	16%	12%
Sc. 16	Lay out 2	IS 2	99%	9%	11%	15%	12%
Sc. 23	Lay out 2	IS 2	97%	9%	10%	15%	11%
Sc. 2	Lay out 1	IS 2	99%	8%	10%	14%	11%
Sc. 7	Lay out 1	IS 7	99%	10%	10%	12%	11%
Sc. 6	Lay out 1	IS 6	99%	8%	9%	14%	10%
Sc. 11	Lay out 1	IS 4	97%	9%	10%	12%	10%
Sc. 14	Lay out 1	IS 7	97%	9%	10%	12%	10%
Sc. 15	Lay out 2	IS 1	99%	10%	13%	7%	10%
Sc. 19	Lay out 2	IS 5	99%	9%	12%	6%	9%
Sc. 22	Lay out 2	IS 1	97%	9%	12%	6%	9%
Sc. 26	Lay out 2	IS 5	97%	9%	12%	6%	9%
Sc. 1	Lay out 1	IS 1	99%	8%	11%	6%	8%
Sc. 5	Lay out 1	IS 5	99%	8%	11%	6%	8%
Sc. 21	Lay out 2	IS 7	99%	7%	8%	9%	8%
Sc. 25	Lay out 2	IS 4	97%	7%	8%	8%	8%
Sc. 28	Lay out 2	IS 7	97%	7%	8%	7%	7%
Sc. 4	Lay out 1	IS 4	99%	6%	6%	7%	6%
Sc. 18	Lay out 2	IS 4	99%	4%	5%	5%	5%

Considering all scenarios, we deem the average wagon capacity usage to be quite low, as it ranges from 5% to 19% on average. To put these number into perspective, 5% of 32 *container* places equals 1.6 *container* places being occupied, at the start of every tour. 19% of 32 equals 6.08 *container* places.
This indicates that tugger trains are primarily deployed to spread the time incurred by executing handling actions and to be responsive to component demand. Tugger train capacity is less of a restrictive factor.

We observe that it depends on the scheduled jobs and the number of tugger trains driving around in that scenario what the wagon capacity usage is. A high number of tugger trains driving around in combination with low component demand yields a low average wagon capacity usage. A low number of tugger trains driving around combined with high component demand yields a high average wagon capacity usage.

Furthermore, it is scenario specific from what wagon type the capacity is used. Some scenarios have many jobs scheduled with *One meter box* components as bin type, which is why the capacity usage of wagon 3 may be relatively high. For example, the only difference between sc.1 (5 tugger trains) and sc.2 (6 tugger trains) with respect to its input schedule, are the jobs that are scheduled on line 3; sc. 1 does not have Large product of Line X jobs scheduled and sc. 2 has Large product of Line X jobs scheduled. The Large product of Line X jobs need many components with *One meter box* as bin type. Even though the amount of tugger trains in sc. 2 is 1 higher than those of sc. 1, the wagon capacity usage of wagon 3 which carries the *One meter box* bins is 8% higher.

It is noticeable that scenarios with a target average line utilization of 97% have the highest average wagon capacity usage. The main reason for this is that these scenarios can fulfil their target utilization with less tugger trains as they do not need to spread the execution of handling actions as much. This leads to the average wagon capacity usage being higher.

Similarly, we see some scenarios with level schedules as input schedules outperform their counterpart with an unlevelled schedule with respect to efficient usage of wagon capacity. The reason is that less tugger trains are part of the material supply settings that are found for level schedule scenarios.

6.2 Sensitivity analysis

We have run six additional scenarios (Table 29), which help us to clarify a couple of unexplored relationships. In these scenarios, we change an input parameter that was fixed in regular scenario 7.

Table 29: Additional scenarios – sensitivity analysis

Scenario	Layout	Input schedule	Target avg. line utilization	Scenario change
Sc. 29	Lay out 1	IS 7	99%	**Changeover times** of 5 minutes
Sc. 30	Lay out 1	IS 7	99%	**Tugger train speed** * 1.5
Sc. 31	Lay out 1	IS 7	99%	**Kanban sizes of components with container as bin type** that were smaller than 20, are doubled and its bin type is changed to quarter meter box
Sc. 32	Lay out 1	IS 7	99%	**Cycle times** are reduced by 10%
Sc. 33	Lay out 1	IS 7	99%	**Handling times** are reduced by 10%
Sc. 34	Lay out 1	IS 7	99%	**Handling times** are increased by 10%

In this section, we compare the results of scenario 7 with the six new scenarios. Of every of the six scenarios, the value of one parameter that was fixed in regular scenario 7 is changed. Specifically, the following parameters are changed: changeover time, tugger train speed, Kanban sizes of components, cycle times, handling times (decrease) and handling times (increase).

For every scenario, we have gathered the corresponding outcome material supply setting as well as various performance indicators. Appendix 15, Table 1, shows which material supply settings we have found for each scenario. The corresponding key performance indicators are also given in Appendix 15, Table 1.

Appendix 15, Table 2, shows per scenario what tugger train behaviour was measured considering the material supply settings that were found in Appendix 15, Table 1.

Appendix 15, Table 3, shows how the capacity of the tugger train wagons was used in each of our regular scenarios. The results consider the material supply setting that were found in Appendix 15, Table 1.

Appendix 15, Table 4, show what material supply setting we found for scenario 7. The corresponding key performance indicators are also given. This table serves a comparative purpose.

6.2.1 Changeover time of 5 minutes – scenario 29

In scenario 29, we set the changeover time from 10 minutes to 5 minutes. This leads to more time being available for assembly. Hence, the total daily demand coming from the assembly lines increases.
We find a solution for scenario 29 that is close to the result of scenario 7, in terms of costs. The resulting material supply setting is also similar, apart from an additional tugger train compensated by some lower buffer levels.

The reason we do not see a significantly different result in term of costs, compared with scenario 7, can be explained. Although a decrease in changeover time leads to more daily component demand, there is also extra time available for the assembly lines to be utilized. In all extra 5 minutes of assembly time, the 99% component availability is more or less maintained.

6.2.2 Tugger train speed increase (*1.5) - scenario 30

As expected, an increase in tugger train speed from 8km/h to 12km/h leads to significant savings. In this case, we find that some buffer levels are reduced to save some costs.
Looking at the tugger train behaviour of both scenarios, we observe that there is a 2% decrease with respect to the driving time of the tugger trains in scenario 30 compared to scenario 7.

6.2.3 Change in Kanban sizes and bin types - scenario 31

In scenario 31, the Kanban sizes of components with *container* as bin type that were smaller than 20 are doubled, and their bin type is changed to *quarter meter box*. This way, high risk components with *container* as bin type are made less vulnerable.

A change in bin type from *container* to *quarter meter box* means that the number of components stored at the line more than doubles. Doubling the Kanban size leads to a doubling of the number of components stored at the line. Additionally, a *quarter meter box* bin rack has an extra bin place compared to the *container* bin rack, considering the same buffer level.
Again, we see that this new scenario leads to significant savings. Due to changing the bin type, we should have changed the buffer costs be incurred when increasing/decreasing a bin level in our model. However, we have not done this, since the change is small.
Because of the change in bin type, we also observe a slight decrease in handling time per tugger train driver, percentage wise. This is logical, since the times a Kanban card is released for the q*uarter meter box* components are reduced with 50%, as opposed to what it was in scenario 7. After all, apart from the handling operation of loading full bins from the supermarket onto the tugger train (10 vs. 15 sec.), all handling times are the same regardless of the bin type.

6.2.4 Cycle times decreased (by 10%) - scenario 32

A decrease in cycle times leads to more pressure on the material supply system. In order to deal with the increased pressure, 2 extra tugger trains are deployed in the material supply setting of scenario 32, compared with the setting of scenario 7.

Although the component demand increased, the deployment of extra tugger trains caused the percentage of handling time per train to decrease with 9% and the wagon capacity usage also decreased.

6.2.5 Handling times decreased (by 10%) – scenario 33

For scenario 33, we find the same resulting material supply setting and corresponding costs, as for scenarios 30 and 31. We observe that there is reduction in handling times percentage wise. The wagon capacity usage slightly decreases as well.

6.2.6 Handling times increased (by 10%) – scenario 34

When the handling times increase by 10%, we find that we need deploy two extra tugger trains in order to reach our target average line utilization. So, a slight increase in handling times already leads to a significant increase in costs.

Although the handling times increased, the deployment of extra tugger trains caused the percentage of handling time per train to decrease with 10%.

6.3 Component-based analysis

In our component-based analysis, we want to identify components that have a high stockout risk by performing one single run experiment. In the simulation, we keep track of the number of stockouts per components. Based on this statistic, we can identify the components that cause lines to stand still.

The single run experiment is executed with *Input schedule 3* as input schedule and *layout 1* as input setting. Input schedule 3 is the input schedule in which only one job (the most capacity demanding job) is scheduled per line, for the whole working day.
The following material supply setting is used as input.

Table 30: Input material supply setting for the component-based analysis

Number of tugger trains	*Buffer level line 1*	*Buffer level line 2*	*Buffer level line 3*	*Buffer level line 4*	*Buffer level line 5*	*Buffer level line 6*	*Buffer level line 7*	*Buffer level line 8*	*Buffer level line 9*	*Buffer level line 10*
5	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*

After running, we find the experiment to have an average line utilization of 86.31%. The target utilizations that we set of 97% and 99% for our regular scenarios, are not reached. In other words, there had to be component stockouts to cause the line utilization to be low. In chapter 6.3.1, we highlight which components where most prolific in causing stockouts.

6.3.1 Components with higher stockouts risk

For every line, we have identified which components caused stockouts. All lines except line 5 and line 7 had to deal with component stockouts.

Line 1 – Job ?

Components	**Kanban size**	**Bin type**	**BOM quantity**	**Max stock**	**Mean cycle time**	**Nr. Of stockouts**
Component ?	?	Container	1	99	?	18
Component ?	?	Container	1	99	?	18

With both components experiencing 18 stockouts, these two components are the main reason that line 1 is underutilized.
The Kanban size and bin spaces to store the component at the line are too small, in order to replenish the component in time. The time in which replenishments need to be fulfilled is short, due to the job's small mean cycle time.

Line 2 – Job ?

Components	Kanban size	Bin type	BOM quantity	Max stock	Mean cycle time	Nr. Of stockouts
Component ?	?	Container	1	75	?	28

This component managed to be out of stock 28 times. The reason for this is the same as for the vulnerable components of line 1.

Line 3 – Job ?

Components	Kanban size	Bin type	BOM quantity	Max stock	Mean cycle time	Nr. Of stockouts
Component ?	?	One meter box	1	40	?	8

This component was out of stock 8 times. The problem with *one meter box* bin types, is that at buffer level 3 the first Kanban card is released when there is only 1 bin remaining (since there fit only 2 bins in the bin rack). When the Kanban size is only 20, this turned out to be too small of a number, which led to stockouts.

Line ? – Job ?

Components	Kanban size	Bin type	BOM quantity	Max stock	Mean cycle time	Nr. Of stockouts
Component ?	?	Container	1	45	?	21

With 21 stockouts, the component being out of stock was a regular occurrence. The main reason is the small Kanban size in combination with a mean cycle time of only 30 seconds.

Line ? – Job ?

Components	Kanban size	Bin type	BOM quantity	Max stock	Mean cycle time	Nr. Of stockouts
Component ?	?	*End box*	1	**140**	?	6
Component ?	?	One meter box	1	**120**	?	5

The *end box* component was in total 6 times out of stock. Due to its low mean cycle time, the component could not be replenished in time. Kanban cards were released when 140*0.33=42 components were in the bin rack. Similarly, as we found with the component *Verpakking* at line 3, the component *ONDERD.PIJP PVC 125X932MM WIT* suffers 5 stockouts due there only being 2 bin places in the *One meter box* bin rack.

Line ? – Job ?

Components	Kanban size	Bin type	BOM quantity	Max stock	Mean cycle time	Nr. Of stockouts
Component ?	?	End box	1	140	?	8

Similarly to what we encountered at line 6, this component could not be replenished in time due to the timing of its Kanban card being released and its low mean cycle time.

Line ? – Job ?

Components	Kanban size	Bin type	BOM quantity	Max stock	Mean cycle time	Nr. Of stockouts
Component ?	?	End box	1	140	?	8
Component ?	?	Quarter meter box	1	80	?	7

Even though *quarter meter box* bin types have 4 bin places in the buffer rack at buffer level 3, the Kanban size and low cycle time combination still led to stock outs.

Line ? – Job ?

Components	Kanban size	Bin type	BOM quantity	Max stock	Mean cycle time	Nr. Of stockouts
Component ?	?	Container	1	30	?	46

During the simulation run, this component was an astonishing 46 times out of stock. The Kanban size of this component is simply way too small.

6.4 Conclusion

In this chapter, we have presented and analysed the results from the regular scenarios, the sensitivity analysis, and the component-based analysis.
From the regular scenario's results, we can conclude that:

- Having 4 to 5 tugger trains is for most regular scenarios cost-efficient.
- Adopting level schedules, in which tugger train capacity needed is spread evenly over the day, leads to costs savings when compared to unlevelled schedules.
- Implementing layout 2, where the assembly lines are closer positioned to the supermarkets as opposed to layout 1, saves costs over layout 1.
- Incorporating Large product of Line X jobs in the schedule increases the pressure on the material supply system significantly. Additional tugger trains are needed to relieve the pressure.

We conclude that there are three reasons to use (multiple) tugger trains:

- spread the handling time amongst tugger trains
- be more responsive in picking bins
- spread capacity over multiple tugger trains

The low wagon capacity usage in the regular scenarios indicates that the deployment of multiple tugger trains is primarily done to spread handling times and to be more responsive with respect to component demand.

In the sensitivity analysis, we have changed various fixed input parameters of regular scenario 7. One of the most interesting findings is that costs can be saved significantly if the bin type and Kanban size of container components with a Kanban size < 20, is changed to a larger bin type (quarter meter box format) with its Kanban size doubled.
We have also seen that a small reduction in cycle time (10%) or a small increase in handling times (10%) lead to significant increases in costs of respectively 34.49% and 18.79%. An increase of 10% in handling times yields a cost saving of 20.05%. It should be noted that our analysis was only focussed on costs incurred by the material supply system. Obviously, a reduction in cycle times yields to a higher output of the assembly processes, which improves productivity. However, we do not consider this side of the coin in our analysis.

From the component-based analysis we can deduce that container bins and one meter box bins with relatively small Kanban sizes have a high stockout risk.
End box components are also subject to stockouts. These stockouts may be caused by the fact that only one end box can be picked per tugger train and/or that the number of components left in the bin at the line is too small (0.33*140=46).

7 Conclusion and recommendations

In this final chapter, we conclude this thesis project, and we give recommendations to Ubbink.
First, we summarize our main findings, and we answer the main research question in Section 7.1.
Next, we provide Ubbink with recommendations, focussed on the arrangement of Ubbink's material supply system. We also put emphasis on how the recommendations can be implemented. We finish off by discussing the limitations of the research, what could be done in future research and how this thesis has contributed practically, as well as scientifically.

7.1 Research conclusion

In this section, we answer the main research question. Our main research question was formulated as follows:

> *How should the material supply at Ubbink's LCIA lines be arranged at a tactical level?*

We started this thesis assignment with the idea that Ubbink wants to implement a new material supply system. The system would incorporate new LCIA lines which incorporate bin storage racks at the line. These bins are filled with components, whose are used in assembly. Tugger trains are used to transport empty bins and to replenish the lines with full bins. The full bins are picked from one of the three Kanban supermarkets.

Although the strategic decision to implement a new material supply system has already been made, there is still a lot unclear at a tactical level. It is difficult to foresee the impact on the material supply system when it incorporates 10+ LCIA lines. For example, nobody at Ubbink can foresee how much tugger trains are needed or how large the bin space should be.

Additionally, a number of tactical cornerstones of the material supply system are undecided, as its effect or influence on the required material supply setting (number of tugger trains and buffer levels) or costs is unknown. To this end, we examine various scenarios that are branched on input schedule, the target average line utilization and the layout choice.

The scenarios have been solved to (near) optimality by using a SA heuristic, giving us for each scenario a fitting material supply setting. The findings are presented in chapter 6. In the paragraphs below, we present the most important conclusions from our findings.

Material supply setting

Most scenarios outcomes show that it is sufficient to incorporate 4 or 5 tugger trains in the material supply setting. Exceptions are scenarios that are solved against a 99% minimal average line utilization, that either incorporate Large product of Line X jobs and/or which input schedule is unlevelled.

We reason that there are three reasons to use (multiple) tugger trains:

- spread the handling time amongst tugger trains
- be more responsive in picking bins
- spread capacity over multiple tugger trains

The low wagon capacity usage in the regular scenarios indicates that the deployment of multiple tugger trains is primarily done to spread handling times and to be more responsive with respect to component demand.

Level scheduling

We have proven that scenarios incorporating levelled schedules are more cost efficient than their counterparts with the same but unlevelled schedule.
However, it depends on the input schedule how big of a difference level scheduling can make. The most significant cost savings can be observed when comparing scenarios incorporating input schedule 4 with scenarios that incorporate its levelled counterpart, input schedule 7. IS4 is the opposite of a level schedule, as 4 jobs are scheduled on every line, and they are sequenced from high to low tugger train capacity. IS7 is the level schedule of IS4. When comparing the material supply settings of scenarios considering IS4 and scenarios considering IS7, we see that level scheduling can save up to two tugger trains in addition to buffer space on average.
On the other hand, we have seen that level scheduling makes only a small cost difference when comparing scenarios incorporating input schedule 1 with scenarios incorporating the level schedule of input schedule 1, input schedule 5. In the previous paragraph, we reasoned that tugger trains are primarily deployed to spread handling times over multiple trains. This may explain why levelling capacity, which is focussed on spreading tugger train capacity, does not necessarily yield big cost savings. To this end, level scheduling could be applied more effectively if its objective is focussed on minimizing the variation in handling time needed during the day, as opposed to minimizing the variation in handling time needed during the day.

Target average line utilization

We have gathered outcomes for similar scenarios that were solved against either a 97% or a 99% minimum average line utilization.
We observe that significant savings are made if 2% of the average line utilization is given up. When all cost differences are considered between the 97%-scenarios and its counterpart 99%-scenarios, we see that they vary between €? and €?. In other words. Up to two tugger trains and/or multiple buffer levels can be saved if Ubbink is willing to give up 2% on the average line utilization. However, whether this decision is cost effective, considering its implications as the productivity decreases, is up to Ubbink to decide.

Layout

We have gathered outcomes for similar scenarios that were solved with either incorporating layout 1 and layout 2. The difference between the two layouts lies in the distance between the supermarkets and the assembly lines.
As expected, we have shown that scenarios that incorporate layout 2 yield significant cost savings compared to similar scenarios that incorporate layout 1. The extent to which costs can be saved is scenario dependent.

Large product of Line X-jobs

We have run multiple similar scenarios with similar input schedules, which only deviate from each other with respect to what is scheduled at line 3; either Large product of Line X jobs are not scheduled or Large product of Line X jobs are scheduled.
We conclude that the Large product of Line X jobs apply heavy pressure on the material supply system, as the cost comparison between the similar scenarios show differences of about €700.-. In other words, we can conclude that extra buffer space as well as extra supply capacity is needed to host the assembly process of the Large product of Line X.

7.2 Recommendations

In this section, we follow up on chapter 7.1, *Research conclusion*. The aim is to give clear recommendations upon which Ubbink could take further action.

Recommendation 1 – Level scheduling

We have shown level scheduling to be cost-effective, hence we recommend its implementation.
In order to make it work, Ubbink should determine per job what its tugger train capacity per hour is (similar as in Appendix 3). When constructing an assembly schedule, estimations (as accurate as possible) need to be made about how long the jobs takes. For every assembly line, this information needs to be given as input to the Excel sheet that is input to Level scheduling model (see Appendix 6). By running the Python script, we get our level schedule in an Excel file.
However, as we already mentioned in the Conclusion section, level scheduling could be applied more effectively if its objective is focussed on minimizing the variation in handling time needed during the day, as opposed to minimizing the variation in required tugger train capacity during the day. Therefore, **we recommend Ubbink to introduce job attributes that describe the amount of handling that is needed for a job, per time unit.** These attributes could be used to create level schedules with respect to the execution of handling actions.

Recommendation 2 - Layout

We have shown that costs can be saved if the assembly lines are positioned as in layout 2, as opposed to layout 1.
It is incorporated in the design of LCIA lines to makes them easy to move from one place to another. The current departments that are located in layout 2, do not consist out of any material which would make it difficult to move it to another place. Hence, it should not be much of struggle to make move the lines to another place.

Recommendation 3 – Component-based analysis

In our component-based analysis, we identified components that have a high stockout risk. A number of those components had the properties to have *Container* as its bin type and to have a low Kanban size. In combination with relatively low cycle times, this component acts as a bottleneck which leads to stockouts.

Comparing scenario 31 (*Sensitivity analysis, chapters 6.3 and 6.4*) with scenario 7 showed that we can prevent component stockouts. If we put components with *Container* as bin type that have a Kanban size of below 20, in a bin (*Quarter meter box*) twice as large, we can double its Kanban size. As a result, less replenishments need to be carried out for this component type. In other words, we could reduce the number of tugger trains and/or the buffer space needed by making this change.

Since not every component is made to be put in a box, we recommend Ubbink to buy container crates twice the size of a *container* bin, such that the size of these new *container* crates complies with the size of a *Quarter meter box*.

Recommendation 4 – Number of tugger trains

Most material supply settings of the regular scenarios we solved incorporate 4 to 5 tugger trains. Assuming that the planners try to spread total job demand somewhat evenly over the working days of the week and level scheduling is applied, it is expected that five tugger trains are sufficient to fulfil line demand during a normal working day.

In our model, we did not take line breakdowns and components being unavailable into account. If we would have taken this into account, it would have relieved the pressure on the material supply system. In other words, we would have found material supply settings with lower or equal costs (and fewer tugger trains and lower buffer levels).

On the other hand, it is unclear what percentage of time tugger trains may be subject to breakdowns. However, we can imagine that it is needed to have at least 1 or 2 tugger train front parts ready as a reserve. Additionally, when there is peak demand, 4 to 5 tugger trains may not a sufficient number to satisfy the target average line utilization.

All in all, we cannot pin down on one number and simply make a statement like: you have to invest in X tugger trains, and it will be all right. When we consider line breakdowns, component unavailability, tugger train breakdowns and peak demand, **we estimate the right number of tugger trains to possess is in the region of 6 or 7.**

Recommendation 5 – Buffer levels

For every scenario that we have solved, we found a material supply setting consisting of ten buffer levels. It became clear that if layout 2 and level scheduling are applied, the standard buffer level suffices for most assembly lines. In some scenarios, buffer level 2 is even sufficient for some lines. A few scenarios incorporate lines that have buffer level 4.

Since the material supply settings that we have found for our scenarios consider buffer levels at line level (instead of job or component level), we cannot give clear recommendations on buffer levels. However, the results indicate that it differs per component and per scenario what the right buffer level is. To this end, **it may be wise to further investigate how much bin places there should be in a rack per component and to choose a number of bin places which is on the safe side for a large majority of possible scenarios.**

Recommendation 6 – Kanban cards

During our time at Ubbink, we got to experience the starting phase of the new material supply system. Based on what we saw, we feel like we can make recommendations to improve the functioning of the system.

Our first recommendation regards the detachment of Kanban cards. Currently, the Kanban card is clamped to the bin and needs to be detached by using force physical force. After detachment, the Kanban card, which is rather large, is put in a basket together with the other Kanban cards. The empty bin is placed on a tugger train wagon.
The problem here is that detaching the Kanban card is time consuming, as well as that it is difficult for the tugger train driver to know what components need to be picked if he has +5 large Kanban cards in his basket. He simply does not have an overview and has to rely on his memory.

We think that it would be better to introduce scannable bar codes instead of physical Kanban cards, which can be scanned with an electronical device. This electronical device can register all the components bins that are picked, make an overview of this information. In the overview, it may be a possible to add warehouse locations on where to pick the full bin again.

Recommendation 7 – Line design

As we have seen in our simulation and in Appendix 2, there are jobs with 10+ components as input. With this many components as input, it seems that it is very difficult to see where the empty bins are located at assembly lines itself. **To this end, I would propose an electronical board at the line, which contains an overview of empty bins and available Kanban cards.**

Recommendation 8 – Dimensions

The tugger train driver told us that it is not that easy to drive with the tugger train through the plant. Either the wagons are too wide, or the paths are too narrow, or it is a combination of both. Anyways, in the future the tugger trains will need space to manoeuvre and to pass each other. **So, changes need to be made with respect to tugger train wagon design or the paths in the plant.**

Also, there will be occurrences in which multiple tugger trains queue behind each other. There needs to be space for this to be possible. To this end, **we recommend to design supermarket 3 such that it can host more than one tugger train at a time, as this is the busiest station.** It may even be possible to serve multiple tugger trains in supermarket 3 fat the same time, which would reduce the percentage of time tugger trains are blocked at significantly.

Recommendation 9 – Tasks of the tugger train driver

In the starting phase of the system, we have observed what the tugger train driver is actually doing. By watching what he did it came to light that he executes some handling actions, of which we think it may be better that someone else executes it (such taking a plastic sheet out of the bin, put it away, to only after this has been done, load the bin on the wagon). In the starting phase, there is no problem with this as there is no huge pressure on the material supply system. However, when more lines are operational, I think it is key if the tugger train can execute his job quickly without difficulties. **The more unnecessary movements are executed by the tugger train driver, the more tugger trains, and buffer space Ubbink is going to need.**

Recommendation 10 – Bin rack accessibility

In a recent observation in the Ubbink, we saw that not every bin rack was easily accessible by the tugger train. As a consequence, the tugger train driver needs to walk more than ten meters to load full bins and to pick up empty bins. This costs time and it is inconvenient for the tugger train driver.

In the starting phase, you may be able to get away with this and it may even be unavoidable sometimes. **Nevertheless, I would highly recommended making the bin racks as accessible as possible, so the tugger train driver can get close to it.**

7.3 Limitations

We did not include every component in our analysis. As earlier discussed in chapter 5.1.2, a few components were not suited for transportation with tugger trains. These components have been excluded from the model, as we consider them to fall outside our scope. An example of such components are Ubiflex rolls and aluminium tubes.

All the 20 different handling times that were input to the model have been measured and estimated. A handling time is decided on the basis of a small number of time measurements, in combination with an educated

estimation. With educated estimation, we mean that we have considered how the action would be executed on average, if the future material supply system is fully operational.
Admittedly, this approach may have resulted in some handling times not being correct. However, there is no data available from which we could calculate the handling times. Still, we feel that the deviation between the real handling time and our estimation is rather small.

The model that we developed were not focussed on the dimensions of tugger trains themselves. Hence, it is not clear how much tugger trains can actually drive in Ubbink's plant before it gets overloaded. To this end, we recommended in the previous section to either widen the paths in the current plant.

In the calculation of the average line utilization, we gave equal weight to every assembly line. It would have been fairer if we would have looked at the jobs that are executed on the line and base our weights on that. I am sure there is some kind of hierarchy between all the different assembly jobs. However, we did not do that.

7.4 Practical and scientific contribution

In this section, we explain how this thesis assignment contributed both practically and scientifically.

7.4.1 Practical contribution

With this research we showed how a material supply system incorporating tugger trains, in a Kanban controlled environment, can be modelled. Additionally, it is easy to modify model inputs. So, the model could still be used in the future to run new scenarios with new input parameters.

It may be difficult for companies to express surface space in terms of value, or in other words, money. To this end, the methodology followed in the paragraph *Buffer costs* in chapter 5.2.1 could give others an idea on how to approach this issue. What we did was using profit data per department to calculate its value per square meter.

It may be a common problem for manufacturing companies to deal with the trade-off between buffer space and tugger train cost. With the Simulated Annealing algorithm incorporated in the material supply system model, we have shown how we can find a good balance in this trade-off, while still satisfying a target average line utilization.

Apart from solving various scenarios to near optimal solutions, our model can easily be understood by other stakeholders, such as management, as the material supply system is visual. As a result, it may be easier for management to accept the results and to follow up on the recommendations given.

7.4.2 Scientific contribution

The main scientific contribution of this thesis is the development of the material supply system model. The model's main purpose is to find material supply settings (tugger trains and buffer levels) that yield (close to) minimal costs for a certain scenario branched on input schedule, layout, and minimum average line utilization. We do not recall literature sources that developed a model with this purpose.

Our level scheduling model, with a focus of levelling supply capacity, could be unique. In our literature study, we found literature problems that used a similar objective as we implemented in our model, such as Output Rate Variation Problem (ORVP). However, the focus of the ORVP is on minimizing the variation in output of

production processes in particular. In our model, the focus was to level component demand, expressed in terms of supply capacity.
The methodology, in which every job is given an attribute value (tugger train capacity per hour in our case) to determine its demand of supply capacity is as far as we know unique.

7.5 Future research

In the future, it may be possible to gather data about changeover times, handling times etc. and use this as input to the model. As a result, experiments can be carried out with the new input, which could support tactical decision making.

We have assumed components to be always available, but this is not realistic. Components being unavailable is a regular occurrence at Ubbink. Gathering and processing data about component availability could be useful to provide the model with new inputs.

The scope of the model could also be extended by adding failure distributions about line breakdowns and tugger train breakdowns into the model.

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Appendix

Appendix 1 – Material flows in Ubbink plant

Flow 1:

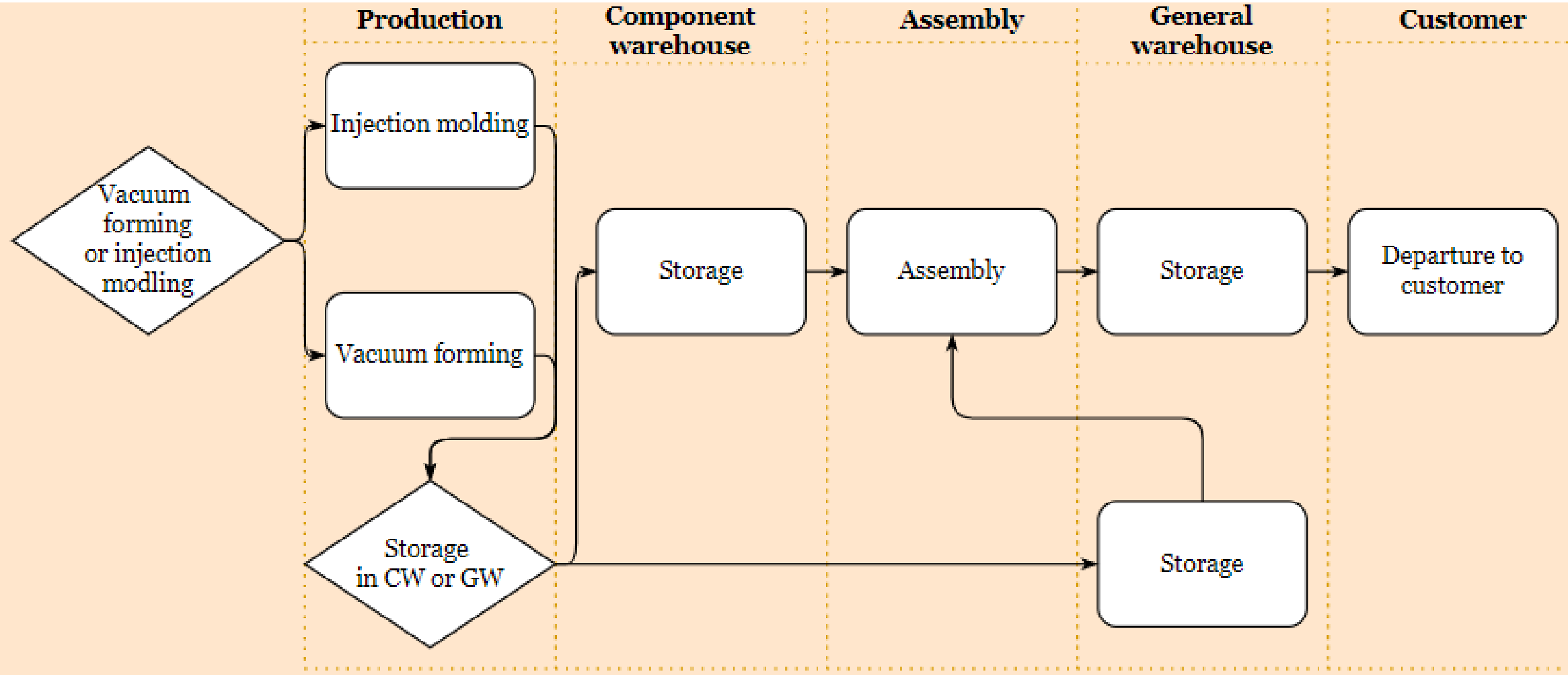


Figure 40: Flow 1 (Material flow)

Flow 2:

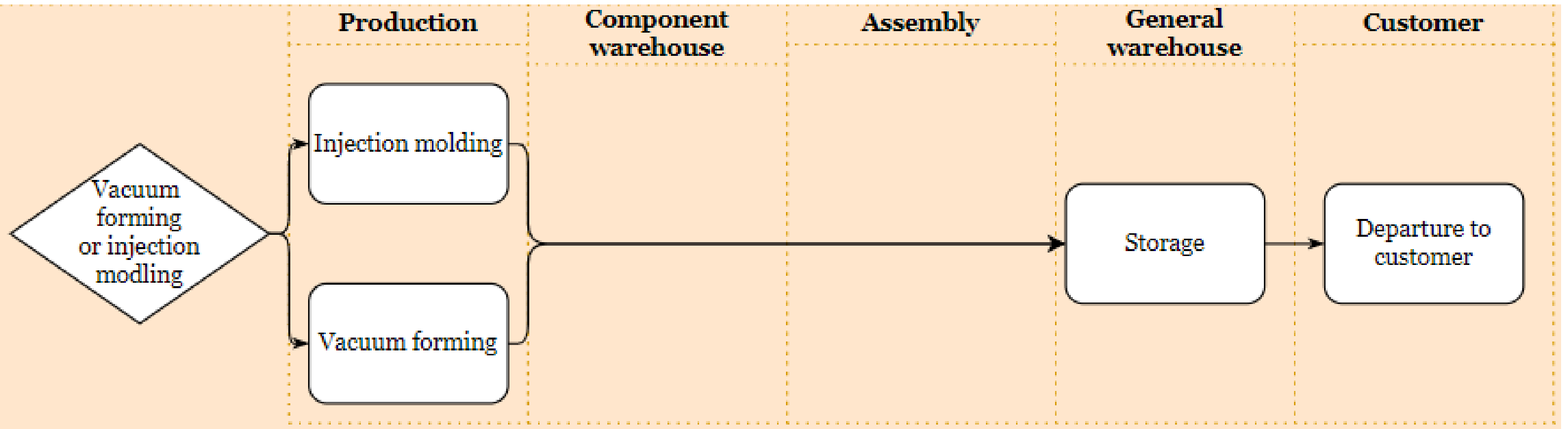


Figure 41: Flow 2 (Material flow)

Flow 3:

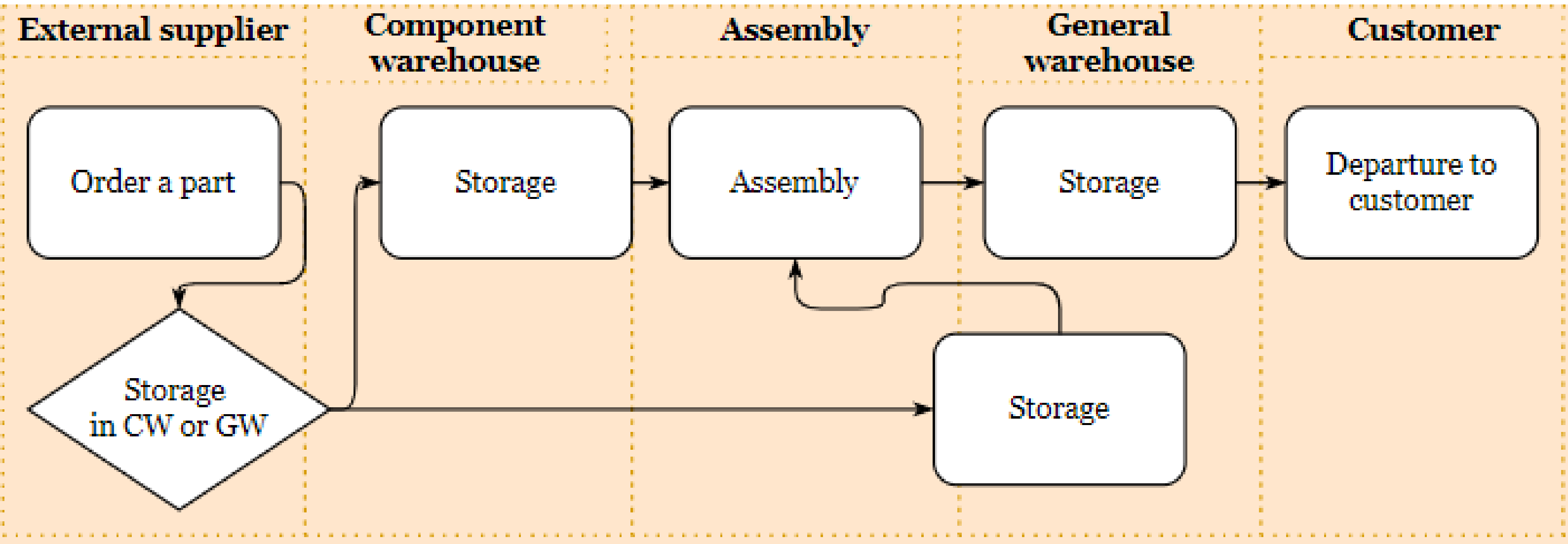


Figure 42: Flow 3 (Material flow)

Flow 4:

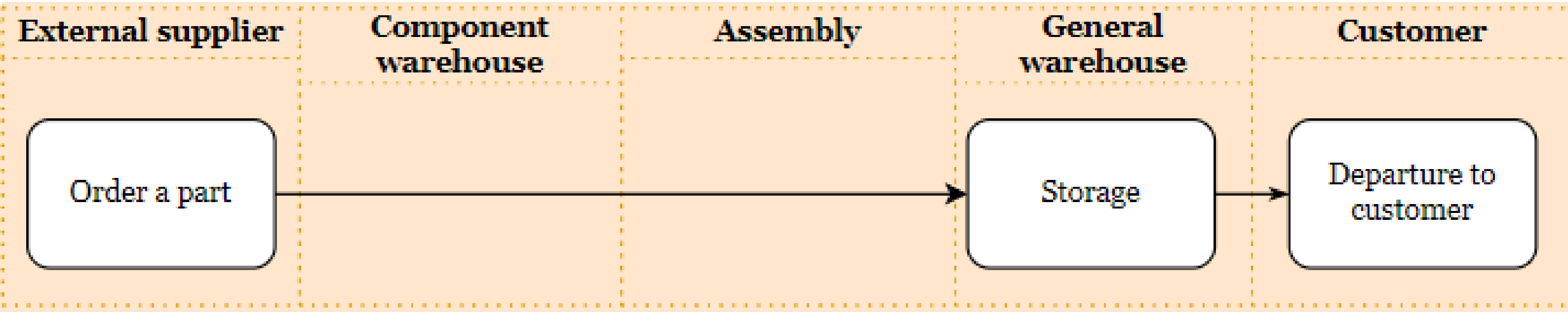


Figure 43: Flow 4 (Material flow)

Appendix 2 – BOM data

Confidential

Appendix 3 – Example calculation of parameter *tugger train capacity per hour*

At this point, we have not explained how tugger train capacity per hour ($TC_{a,j}$) is actually determined. Every job j that is scheduled on a line a has its own attribute T*ugger train capacity/hour.* The value of this parameter depends on a couple of factors: Kanban sizes (Appendix 2) of its components, the assembly cycle times of the product (Appendix 2) and the bin types of the components (Appendix 2).

There are three different wagons behind a tugger train:
Wagon 1 carries 3 bin types: *container*s, *quarter meter boxes* and half meter boxes. The wagon contains 32 *container*s places, which equals 16 *quarter meter box* places or 8 half meter box places.
Wagon 2 carries a chest in which final box (*end box*) components can be delivered to replenish the lines.
Wagon 3 carries only *one meter boxes*, for which it has two places available.

Table 32: Bin type capacities

Bin type	Capacity needed
Container	1/32 wagon
Quarter meter box	1/16 wagon
Half meter box	1/8 wagon
One meter box	½ wagon
Final box	1 wagon

Table 31: Wagon type capacities

Wagon	Bin carries	Bin capacity
Wagon 1	Containers, quarter meter boxes, half meter boxes	32 containers, or 16 quarter meter boxes, or 8 half meter boxes
Wagon 2	Final box chest	One final box component
Wagon 3	One meter boxes	2 one meter boxes

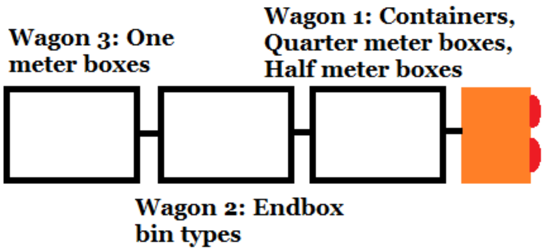


Figure 44: Wagon types of the tugger train

Because we know what wagons are behind a tugger train, and how much bin capacity they have, we know how much wagon capacity is needed for one bin type. Because we also know the cycle times of the jobs and the Kanban size of its components (how much of the component fits in the bin), we estimate which bins types and how many bins are needed per hour to replenish a certain product. Because we know the wagon capacity needed to transport one bin as well, we derive the total wagon capacity per hour.
Summarizing, the tugger train capacity per the *tugger train capacity per hour* (TC_j) is calculated as follows:

$$TC_j = \sum_{c_j=1}^{C_j} \frac{\frac{3600}{x_j} * b_{c,j}}{y_c} * WC_{bin_c} * \frac{1}{3}$$

Where:

TC_j	Tugger train capacity per hour of job *j*
C_j	Set of components of job *j*
$b_{c,j}$	Number of components *c* required for one product of job *j*
x_j	Cycle time of job *j*
y_j	Number of components *c* in one bin
WC_{bin_c}	Wagon capacity needed for bins of components with type *c*

For every product that we take as input in our level scheduling model, we calculate the *tugger train capacity per hour* ($TC_{a,j}$). Appendix 2 shows the *tugger train capacity per hour* values, per line and per job.
As an example, we present two tables; the first table shows the BOM information of the product *?* of Line ?. The second table shows how the *tugger train capacity per hour* is calculated for this product.

Table 34: BOM data – Job ?

Job J?	BOM qty	Kanban Size	Cycle time	Packaging	Supermarket
?	1	?	?	End box	3
?	1	?	?	Half meter box	3
?	1	?	?	Container	3
?	1	?	?	Container	2

?	1	?	?	Half meter box	1

$$Nr. of\ products\ produced\ per\ hour\ = \frac{3600}{Cycle\ Time} = \frac{3600}{18} = 200$$

$$Nr. of\ bins\ needed\ per\ hour\ = \frac{Nr. of\ products\ produced\ per\ hour}{KanbanSize} * BomQTY$$

$$Tugger\ train\ capacity\ per\ hour\ = \frac{Nr. of\ bins\ needed\ per\ hour * Wagon\ capacity\ needed\ per\ bin}{3}$$

Table 35: Tugger train capacity per hour calculation - EXT 80/125 L500 PP/PL CL3

Job ?	Wagon capacity needed per bin	Nr. of bins needed per hour	Wagon capacity per hour
?	1	1.429	0.476
?	0.125	3.333	0.139
?	0.03125	3.364	0.038
?	0.03125	0.2	0.002
?	0.125	6.25	0.260
			0.915

Appendix 4 – Level scheduling model: swap operator and measuring the objective in the simulated annealing heuristic

In this example we illustrate how we measure the objective of a schedule after swapping operations have been carried out.

In this example, we consider three assembly lines. Every assembly line has a number of jobs that need to be executed during the working day. Here, a working day lasts eight hours.

Every product or job has an attribute called tugger train capacity per hour. Table 46 shows the jobs that are assigned to the assembly lines and the corresponding tugger train capacity per hour per job. The duration of a job is expressed in hours.

Table 36: 3-line assembly schedule - example

Line 1			Line 2			Line 3		
Article	Tc/h	Duration	Article	Tc/h	Duration	Article	Tc/h	Duration
1A	40	1	2A	20	2	3A	25	4
1B	20	3	2B	60	2	3B	70	4
1C	90	2	2C	90	4			
1D	20	1						
1E	10	1						

Below, the assembly schedule is worked out further, such that in every time bucket a job is scheduled. Here, the time buckets are taken in hours as all job durations are integer. The quadratic differences (d_s) per hour are given by $d_s = (y - \sum_{a=1}^{10} w_{a,s})^2$. Subsequently, the objective function value is given by $\sum_{s=1}^{S} d_s$.

Table 37: 3-line assembly schedule (jobs assigned per time bucket) - example

Line 1		Line 2		Line 3		Total transport capacity usage per step size		Quadratic differences per hour	
1A	40	2A	20	3B	70	130		189,0625	
1C	90	2A	20	3B	70	180		32400	
1C	90	2C	90	3B	70	250		62500	
1B	20	2C	90	3B	70	180		32400	
1B	20	2B	60	3A	25	105		11025	
1B	20	2B	60	3A	25	105		11025	
1E	10	2B	60	3A	25	95		9025	
1D	20	2B	60	3A	25	105		11025	
						Average	143,75	Objective; sum of quadratic differences	169589,1

When we would change the assembly sequence of line 1 by swapping 1B and 1C in the sequence and change the sequence of line 2 by swapping 2A and 2C, we get a new objective function value of 141064.1 (Figure X). Compared to the objective value (169589,1) of the table above, this is an improvement.

Table 38: 3-line assembly schedule (after 1 SWAP operation) - example

Line 1		Line 2		Line 3		Total transport capacity usage per step size		Quadratic differences per hour	
1A	40	2C	90	3B	70	200		3164,063	
1B	20	2C	90	3B	70	180		32400	
1B	20	2A	20	3B	70	110		12100	
1B	20	2A	20	3B	70	110		12100	
1C	90	2B	60	3A	25	175		30625	
1C	90	2B	60	3A	25	175		30625	
1E	10	2B	60	3A	25	95		9025	
1D	20	2B	60	3A	25	105		11025	
						Average	143,75	Objective; sum of quadratic differences	141064,1

Appendix 5 – Level scheduling model: acceptance ratio plots

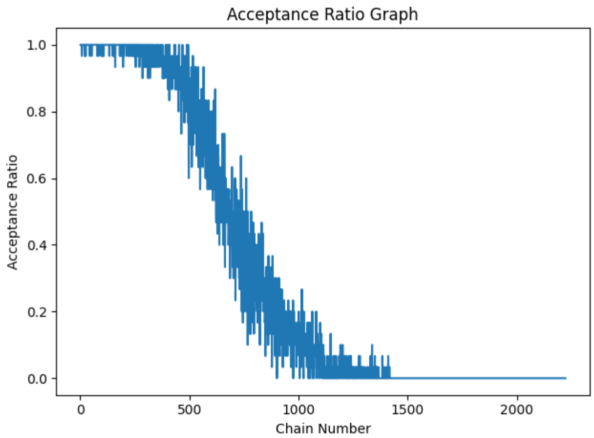


Figure 45: Acceptance ratio SA1 algorithm

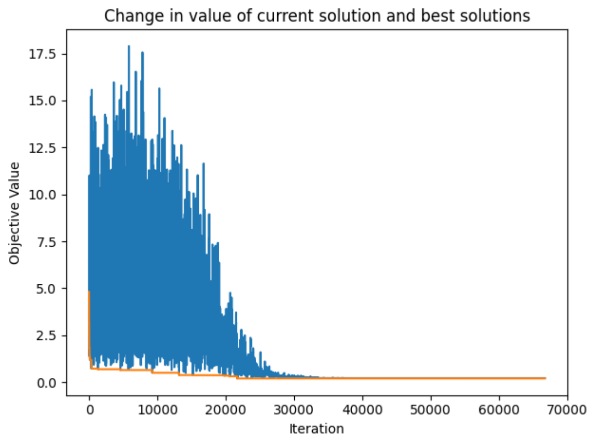


Figure 46: Current and best solution SA1 algorithm

Appendix 6 – Level scheduling model: application usage

To run the application, one should change inputs in excel file “LevelSchedulingModel.xlsx”.
Figure 46 shows the input fields (in the green and blue rectangles).

First, one should enter the input fields in the blue rectangle. In the first row, the number of lines has to be entered. This number is pretty much fixed to 10 in this assignment. If one was to alter this number, other changes have to made in the file as well.
The second row in the blue rectangle represents the time length of a time bucket. In figure 46, this is 0,25 hours (or 15 minutes). This input field should always be entered in hours.
The last row in the blue rectangle is updated after the second row is filled in.

The input fields in the green rectangle have to be filled for every assembly line.
In the first input column, the article name (or job, or product name) should be entered. In this example, we simply chose “1A”, “1B”, etc.
In the second column, the transport capacity per hour of the corresponding product should be entered.
In the third column, one has to indicate how long the job takes. One should note that when there are 32 time buckets in an 8 hour workday (as is the case in figure 46), every time bucket represents 15 minutes. One should also enter the duration of a job in the amount of time buckets that job takes to be executed.

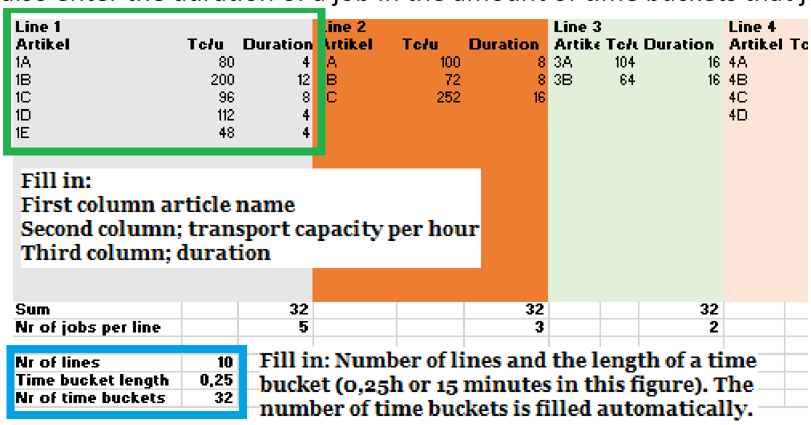
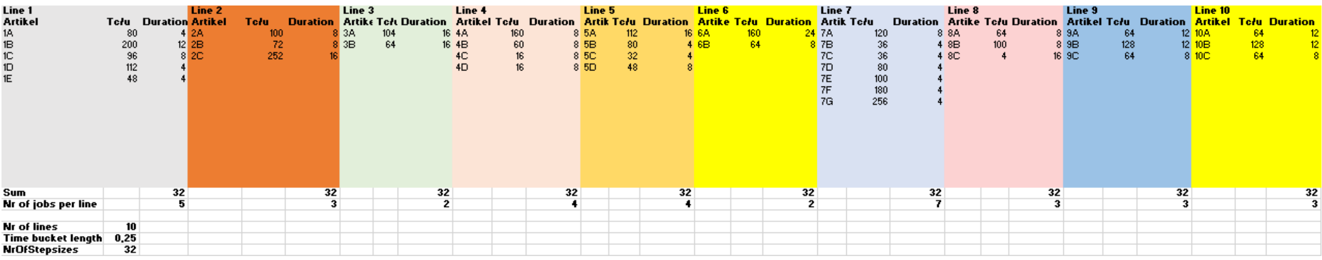


Figure 47: Input fields of the level scheduling application (LevelSchedulingModel.xlsx)



Line 1			Line 2			Line 3			Line 4			Line 5		
Artikel	Tc/u	Duration	Artikel	Tc/u	Duration	Artike	Tc/t	Duration	Artikel	Tc/u	Duration	Artik	Tc/u	Duration
1A	80	4	2A	100	8	3A	104	16	4A	160	8	5A	112	16
1B	200	12	2B	72	8	3B	64	16	4B	60	8	5B	80	4
1C	96	8	2C	252	16				4C	16	8	5C	32	4
1D	112	4							4D	16	8	5D	48	8
1E	48	4												
Sum		32			32			32			32			32
Nr of jobs per line		5			3			2			4			4
Nr of lines	10													
Time bucket length	0,25													
NrOfStepsizes	32													

Line 6			Line 7			Line 8			Line 9			Line 10		
Artike	Tc/u	Duration	Artik	Tc/u	Duration	Artike	Tc/u	Duration	Artikel	Tc/u	Duration	Artikel	Tc/u	Duration
6A	160	24	7A	120	8	8A	64	8	9A	64	12	10A	64	12
6B	64	8	7B	36	4	8B	100	8	9B	128	12	10B	128	12
			7C	36	4	8C	4	16	9C	64	8	10C	64	8
			7D	80	4									
			7E	100	4									
			7F	180	4									
			7G	256	4									
		32			32			32			32			32
		2			7			3			3			3

Figure 48: All ten lines and their input fields (LevelSchedulingModel.xlsx)

When all the input fields are filled in, one can run the program by accessing Python project *LevelSchedulingModel/main.py* and clicking on the run button. Figure 48 shows where the run buttons can be found in the Python file.

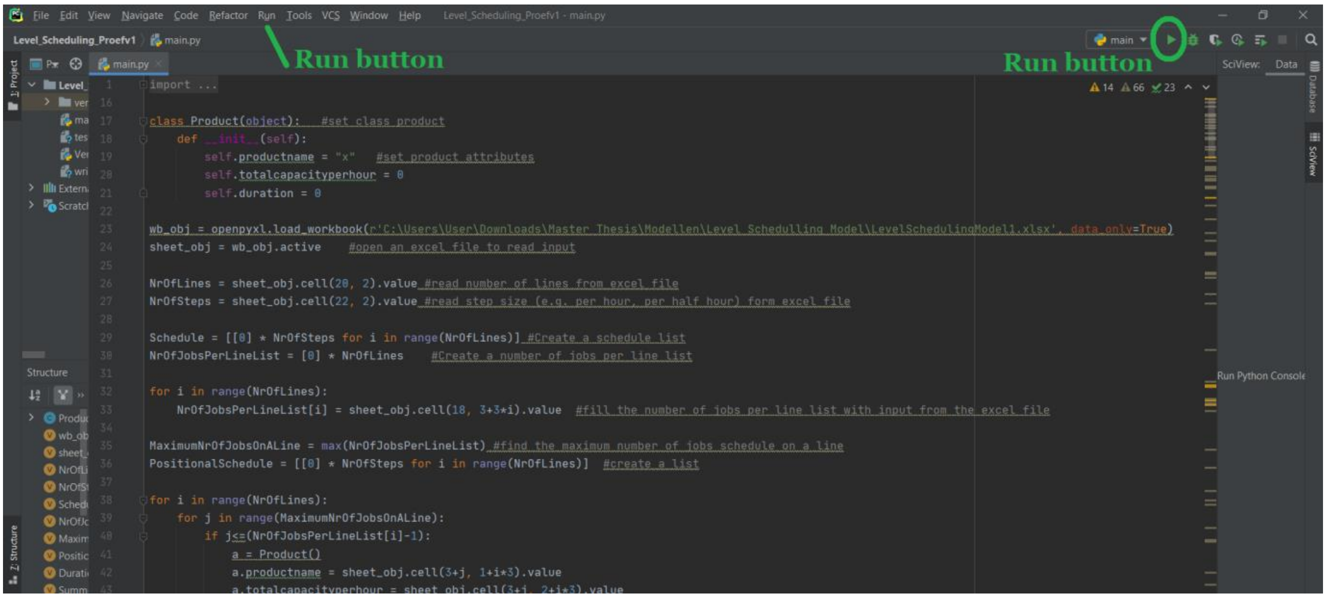


Figure 49: Python file, from which the level scheduling model has to be started

The outcome of the level scheduling model is written to excel file "OutcomeModel.xlsx". This Excel file shows the level schedule as shown in figure 49. In the figure 49, we see a collective assembly schedule for 10 assembly lines. Here, time buckets of length 0,25 hour were considered. Hence, there are (8/0,25=) 32 rows in the schedule since we consider 8 hour working days.

1D	1	112	2C	4	252	3A	4	104	4D	2	16	5C	1	32	6B	2	64	7A	2	120	8B	2	100	9B	3	128	10A	3	64
1E	1	48	2C	4	252	3A	4	104	4D	2	16	5A	4	112	6B	2	64	7A	2	120	8B	2	100	9B	3	128	10A	3	64
1A	1	80	2C	4	252	3A	4	104	4B	2	60	5A	4	112	6A	6	160	7C	1	36	8C	4	4	9B	3	128	10A	3	64
1C	2	96	2C	4	252	3A	4	104	4B	2	60	5A	4	112	6A	6	160	7B	1	36	8C	4	4	9C	2	64	10B	3	128
1C	2	96	2A	2	100	3B	4	64	4C	2	16	5A	4	112	6A	6	160	7G	1	256	8C	4	4	9C	2	64	10B	3	128
1B	3	200	2A	2	100	3B	4	64	4C	2	16	5B	1	80	6A	6	160	7F	1	180	8C	4	4	9A	3	64	10B	3	128
1B	3	200	2B	2	72	3B	4	64	4A	2	160	5D	2	48	6A	6	160	7D	1	80	8A	2	64	9A	3	64	10C	2	64
1B	3	200	2B	2	72	3B	4	64	4A	2	160	5D	2	48	6A	6	160	7E	1	100	8A	2	64	9A	3	64	10C	2	64
1D	2	112	2A	4	100	3B	8	64	4B	4	60	5A	8	112	6A	12	160	7G	2	256	8C	8	4	9C	4	64	10C	4	64
1D	2	112	2A	4	100	3B	8	64	4B	4	60	5A	8	112	6A	12	160	7G	2	256	8C	8	4	9C	4	64	10C	4	64
1B	6	200	2A	4	100	3B	8	64	4B	4	60	5A	8	112	6A	12	160	7B	2	36	8C	8	4	9B	6	128	10B	6	128
1B	6	200	2A	4	100	3B	8	64	4B	4	60	5A	8	112	6A	12	160	7B	2	36	8C	8	4	9B	6	128	10B	6	128
1B	6	200	2B	4	72	3B	8	64	4A	4	160	5A	8	112	6B	4	64	7D	2	80	8C	8	4	9B	6	128	10B	6	128
1B	6	200	2B	4	72	3B	8	64	4A	4	160	5A	8	112	6B	4	64	7D	2	80	8C	8	4	9B	6	128	10B	6	128
1B	6	200	2B	4	72	3B	8	64	4A	4	160	5C	2	32	6B	4	64	7F	2	180	8C	8	4	9B	6	128	10B	6	128
1B	6	200	2B	4	72	3B	8	64	4A	4	160	5C	2	32	6B	4	64	7F	2	180	8C	8	4	9B	6	128	10B	6	128
1C	8	96	2C	16	252	3B	16	64	4B	8	60	5A	16	112	6A	24	160	7A	8	120	8C	16	4	9C	8	64	10C	8	64
1C	8	96	2C	16	252	3B	16	64	4B	8	60	5A	16	112	6A	24	160	7A	8	120	8C	16	4	9C	8	64	10C	8	64
1C	8	96	2C	16	252	3B	16	64	4B	8	60	5A	16	112	6A	24	160	7A	8	120	8C	16	4	9C	8	64	10C	8	64
1C	8	96	2C	16	252	3B	16	64	4B	8	60	5A	16	112	6A	24	160	7A	8	120	8C	16	4	9C	8	64	10C	8	64
1B	12	200	2C	16	252	3B	16	64	4B	8	60	5D	8	48	6A	24	160	7C	4	36	8C	16	4	9A	12	64	10B	12	128
1B	12	200	2C	16	252	3B	16	64	4B	8	60	5D	8	48	6A	24	160	7C	4	36	8C	16	4	9A	12	64	10B	12	128
1B	12	200	2C	16	252	3B	16	64	4B	8	60	5D	8	48	6A	24	160	7C	4	36	8C	16	4	9A	12	64	10B	12	128
1B	12	200	2C	16	252	3B	16	64	4B	8	60	5D	8	48	6A	24	160	7C	4	36	8C	16	4	9A	12	64	10B	12	128
1B	12	200	2A	8	100	3B	16	64	4A	8	160	5D	8	48	6B	8	64	7D	4	80	8B	8	100	9A	12	64	10B	12	128
1B	12	200	2A	8	100	3B	16	64	4A	8	160	5D	8	48	6B	8	64	7D	4	80	8B	8	100	9A	12	64	10B	12	128
1B	12	200	2A	8	100	3B	16	64	4A	8	160	5D	8	48	6B	8	64	7D	4	80	8B	8	100	9A	12	64	10B	12	128
1B	12	200	2A	8	100	3B	16	64	4A	8	160	5D	8	48	6B	8	64	7D	4	80	8B	8	100	9A	12	64	10B	12	128
1B	12	200	2A	8	100	3B	16	64	4A	8	160	5B	4	80	6B	8	64	7B	4	36	8B	8	100	9A	12	64	10B	12	128
1B	12	200	2A	8	100	3B	16	64	4A	8	160	5B	4	80	6B	8	64	7B	4	36	8B	8	100	9A	12	64	10B	12	128
1B	12	200	2A	8	100	3B	16	64	4A	8	160	5B	4	80	6B	8	64	7B	4	36	8B	8	100	9A	12	64	10B	12	128
1B	12	200	2A	8	100	3B	16	64	4A	8	160	5B	4	80	6B	8	64	7B	4	36	8B	8	100	9A	12	64	10B	12	128

Figure 50: Outcome schedule (10 assembly lines, 32 time buckets); "OutcomeModel.xlsx"

Appendix 7 – Simulation model; an example of a total bin rack space calculation

Table 39: Bin rack space calculation; material supply system model

Job J	Kanbansize	Packaging	Standard buffer level; bin rack space (m²) **	Extra buffer level; extra bin rack space (m²)
?	?	Quarter meter box	1.95	1.95/4=0485
?	?	Container	1.1	1.1/3=0.3657
?	?	Container	1.1	1.1/3=0.3657
?	?	End box	2.76	-
>	?	Container	-	-
?	?	Container	-	-
Totals			**6.91**	**1.23**

** It should be noted that we have chosen to exclude the components bins with a Kanban size bigger than or equal to 1000 for the calculation of columns *Total bin rack space in m^2 considering the standard buffer level SBL* and *Surface area needed for an increase in buffer level in m^2 (BA_a)*. Although we have listed these components to have a bin type, they are probably not kept in bin racks in a real life scenario, since these components are quite small. Therefore, we feel like we should not include them here.

Appendix 8 – Simulation model: input schedules

The sequence that jobs are listed is the sequence in which they are scheduled to be executed.

Input schedule 1 – Random jobs for all lines

Line 1

Job	Tc/h	Duration
BND 60/100 87° PP/PL CL1	0,25	3
BND 80/125 45° PP/PL CL3	0,35	11
BND 60/100 45° PP/PL CL1(2)	0,19	18

Line 2

Job	Tc/h	Duration
BND 60/100 87° T120 PP/PL PF	0,24	13
BND 80/125 45° PP/PL CL3	0,35	8
BND 80/125 87° PP/PL CL3	0,35	11

Line 3

Job	Tc/h	Duration
ONTL.PAN UB ZW&ADAPT.RVT200 PS	0,52	9
PAN 214 UB 25-45° BLK	0,50	23

Line 4

Job	Tc/h	Duration
PAN 166 UL 25-45° NTL	0,40	4
PAN 166 UB 25-45° BLK	0,41	3
PAN 166 UB 35-55° BLK	0,51	25

Line 5

Job	Tc/h	Duration
PAN 131 UL 25-45° NTL +S	0,20	8
Dachziegel DN125 25-45°schwarz	0,35	9
PAN 131 UB 25-45° BLK +S	0,21	15

Line 6

Job	Tc/h	Duration
EXT 80/125 L1000 ALU/PL PF1	1,04	9
EXT 60/100 T120 L500 PP/PL CL1	0,75	3
EXT 60/100 T120 L250 PP/PL CL1	0,39	10
EXT 60/100 T120 L1000PP/PL CL1	1,00	4
EXT 60/100 T120 L250 PP/PL PF	0,39	6

Line 7

Job	Tc/h	Duration
MVENT 131 L750 BLK	0,59	28
VTUB 110 L780 BLK	0,39	2
RIOOLONTL. 110 VD 300/400 ZW	0,35	2

Line 8

Job	Tc/h	Duration
EXT 80/125 L500 PP/PL CL3	0,92	13
EXT 60/100 T120 L500 PP/PL CL1	0,75	12
EXT 80/125 L250 PP/PL CL3	0,48	4
EXT 60/100 T120 L1000PP/PL CL1	1,00	3

Line 9

Job	Tc/h	Duration
MDV-K 80/125 ALU BLK +BND 21"	1,00	4
MDV 60/100 PP L750 T120 WHT	1,17	19
MDV-K 80/125 PPs BLK +BND 21"	1,49	3
MDV-K 80/125 PPs BLK +BND 12"	1,16	6

Line 10

Job	Tc/h	Duration
ROLUX 5G 60-100 PP T120 BLK	1,35	10
RLX4 80/125 AL/PL L965 T200BLK	1,31	10
MULTIVENT 5V L1225	1,54	12

Figure 51: Input schedule 1 - Random jobs for all lines; material supply system model

Input schedule 2 – Random jobs for all lines (input schedule 1) + Large product of Line X on line 3 only

Line 1

Artikel	Tc/h	Duration
BND 60/100 87° PP/PL CL1	0,25	3
BND 80/125 45° PP/PL CL3	0,35	11
BND 60/100 45° PP/PL CL1(2)	0,19	18

Line 2

Artikel	Tc/h	Duration
BND 60/100 87° T120 PP/PL PF	0,24	13
BND 80/125 45° PP/PL CL3	0,35	8
BND 80/125 87° PP/PL CL3	0,35	11

Line 3

Artikel	Tc/h	Duration
Ventus hellend dak D200-180	2,60	16
Ventus plat dak D200-180	2,01	16

Line 4

Artikel	Tc/h	Duration
PAN 166 UL 25-45° NTL	0,40	4
PAN 166 UB 25-45° BLK	0,41	3
PAN 166 UB 35-55° BLK	0,51	25

Line 5			Line 6			Line 7		
Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration
PAN 131 UL 25-45° NTL +S	0,20	8	EXT 80/125 L1000 ALU/PL PF1	1,04	9	MVENT 131 L750 BLK	0,59	28
Dachziegel DN125 25-45°schwarz	0,35	9	EXT 60/100 T120 L500 PP/PL CL1	0,75	3	VTUB 110 L780 BLK	0,39	2
PAN 131 UB 25-45° BLK +S	0,21	15	EXT 60/100 T120 L250 PP/PL CL1	0,39	10	RIOOLONTL. 110 VD 300/400 ZW	0,35	2
			EXT 60/100 T120 L1000PP/PL CL1	1,00	4			
			EXT 60/100 T120 L250 PP/PL PF	0,39	6			

Line 8			Line 9			Line 10		
Job	Tc/h	Duration	Job	Tc/h	Duration	Job	Tc/h	Duration
EXT 80/125 L500 PP/PL CL3	0,92	13	MDV-K 80/125 ALU BLK +BND 21"	1,00	4	ROLUX 5G 60-100 PP T120 BLK	1,35	10
EXT 60/100 T120 L500 PP/PL CL1	0,75	12	MDV 60/100 PP L750 T120 WHT	1,17	19	RLX4 80/125 AL/PL L965 T200BLK	1,31	10
EXT 80/125 L250 PP/PL CL3	0,48	4	MDV-K 80/125 PPs BLK +BND 21"	1,49	3	MULTIVENT 5V L1225	1,54	12
EXT 60/100 T120 L1000PP/PL CL1	1,00	3	MDV-K 80/125 PPs BLK +BND 12"	1,16	6			

Figure 52: Input schedule 2 – Random jobs for all lines (input schedule 1) + Large product of Line X on line X only; material supply system model

Input schedule 3 – per line only the job that demands the most tugger train capacity

Line 1			Line 2			Line 3			Line 4		
Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration
BND 80/125 45° PP/PL CL3	0,35	32	BND 80/125 87° PP/PL CL3	0,48	32	Ventus hellend dak D200-180	2,60	32	PAN 166 UB 35-55° BLK	0,51	32

Line 5			Line 6			Line 7		
Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration
Dachziegel DN125 25-45°schwarz	0,35	32	EXT 80/125 L1000 ALU/PL PF1	1,04	32	MVENT 131 L980 BLK	0,61	32

Line 8			Line 9			Line 10		
Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration
EXT 80/125 L1000 PP/PL CL3	1,31	32	MDV-K 80/125 PPs BLK +BND 21"	1,49	32	RLX5 80-80 PP L1284 T120 BLK	2,11	32

Figure 53: Input schedule 3 – per line only the job that demands the most tugger train capacity; material supply system model

Input schedule 4 – the 4 most tugger train capacity demanding jobs per line, in sequence from most capacity demanding job to the least capacity demanding job

Line 1			Line 2			Line 3			Line 4		
Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Durat
BND 80/125 45° PP/PL CL3	0,35	8	BND 80/125 87° PP/PL CL3	0,35	8	Ventus hellend dak D200-180	2,60	8	PAN 166 UB 35-55° BLK	0,51	
BND 60/100 87° PP/PL CL1	0,25	8	BND 80/125 45° PP/PL CL3	0,35	8	Ventus plat dak D200-180	2,01	8	PAN 131 UB 15-55° BLK	0,45	
BND 60/100 87° T120 PP/PL PF	0,24	8	BND 60/100 87° PP/PL CL1	0,25	8	ONTL.PAN UB ZW&ADAPT.RVT200 PS	0,52	8	PAN 166 UB 25-45° BLK	0,41	
BND 60/100 45° PP/PL CL1(2)	0,19	8	BND 60/100 87° T120 PP/PL PF	0,24	8	ONTL.UB NR+ADAPT.RVT200 R PS	0,52	8	PAN 166 UL 25-45° NTL	0,40	

Line 5			Line 6			Line 7		
Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration
Dachziegel DN125 25-45°schwarz	0,35	8	EXT 80/125 L1000 ALU/PL PF1	1,04	8	MVENT 131 L980 BLK	0,61	8
Dachziegel DN125 25-45° rot	0,35	8	EXT 60/100 T120 L1000PP/PL CL1	1,00	8	VTUB 131 L1020 BLK	0,59	8
PAN 131 UB 25-45° BLK +S	0,21	8	EXT 60/100 T120 L500 PP/PL CL1	0,75	8	MVENT 131 L750 BLK	0,59	8
PAN 131 UL 25-45° NTL +S	0,20	8	EXT 60/100 T120 L250 PP/PL CL1	0,39	8	VTUB 110 L780 BLK	0,39	8

Line 8			Line 9			Line 10		
Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration
EXT 80/125 L1000 PP/PL CL3	1,31	8	MDV-K 80/125 PPs BLK +BND 21"	1,49	8	RLX5 80-80 PP L1284 T120 BLK	2,11	8
EXT 60/100 T120 L1000PP/PL CL1	1,00	8	MDV 60/100 PP L750 T120 WHT	1,17	8	RLX5 80/125 PP L1174 T120 TER	1,80	8
EXT 80/125 L500 PP/PL CL3	0,92	8	MDV-K 80/125 PPs BLK +BND 12"	1,16	8	MULTIVENT 5V L1225	1,54	8
EXT 60/100 T120 L500 PP/PL CL1	0,75	8	MDV-K 80/125 ALU BLK +BND 21"	1,00	8	ROLUX 5G 60-100 PP T120 BLK	1,35	8

Figure 54: Input schedule 4 – the 4 most tugger train capacity demanding jobs per line, in sequence from most capacity demanding job to the least capacity demanding job; material supply system model

Input schedule 5 – Level schedule of input schedule 1

Line 1

Artikel	Tc/h	Duration
BND 80/125 45° PP/PL CL3	0,35	11
BND 60/100 87° PP/PL CL1	0,25	3
BND 60/100 45° PP/PL CL1(2)	0,19	18

Line 2

Artikel	Tc/h	Duration
BND 80/125 87° PP/PL CL3	0,35	11
BND 80/125 45° PP/PL CL3	0,35	8
BND 60/100 87° T120 PP/PL PF	0,24	13

Line 3

Artikel	Tc/h	Duration
ONTL.PAN UB ZW&ADAPT.RVT200 PS	0,52	9
PAN 214 UB 25-45° BLK	0,50	23

Line 4

Artikel	Tc/h	Duration
PAN 166 UL 25-45° NTL	0,40	4
PAN 166 UB 35-55° BLK	0,51	25
PAN 166 UB 25-45° BLK	0,41	3

Line 5

Artikel	Tc/h	Duration
Dachziegel DN125 25-45°schwarz	0,35	9
PAN 131 UB 25-45° BLK +S	0,21	15
PAN 131 UL 25-45° NTL +S	0,20	8

Line 6

Artikel	Tc/h	Duration
EXT 60/100 T120 L1000PP/PL CL1	1,00	4
EXT 60/100 T120 L250 PP/PL PF	0,39	6
EXT 60/100 T120 L250 PP/PL CL1	0,39	10
EXT 60/100 T120 L500 PP/PL CL1	0,75	3
EXT 80/125 L1000 ALU/PL PF1	1,04	9

Line 7

Artikel	Tc/h	Duration
MVENT 131 L750 BLK	0,59	28
VTUB 110 L780 BLK	0,39	2
RIOOLONTL. 110 VD 300/400 ZW	0,35	2

Line 8

Artikel	Tc/h	Duration
EXT 80/125 L250 PP/PL CL3	0,48	4
EXT 80/125 L500 PP/PL CL3	0,92	13
EXT 60/100 T120 L1000PP/PL CL1	1,00	3
EXT 60/100 T120 L500 PP/PL CL1	0,75	12

Line 9

Artikel	Tc/h	Duration
MDV-K 80/125 ALU BLK +BND 21"	1,00	4
MDV 60/100 PP L750 T120 WHT	1,17	19
MDV-K 80/125 PPs BLK +BND 12"	1,17	6
MDV-K 80/125 PPs BLK +BND 21"	1,16	3

Line 10

Artikel	Tc/h	Duration
ROLUX 5G 60-100 PP T120 BLK	1,35	10
MULTIVENT 5V L1225	1,54	12
RLX4 80/125 AL/PL L965 T200BLK	1,31	10

Figure 55: Input schedule 5 – Level schedule of input schedule 1; material supply system model

Input schedule 6 – Level schedule of input schedule 2

Line 1

Artikel	Tc/h	Duration
BND 60/100 45° PP/PL CL1(2)	0,19	18
BND 60/100 87° PP/PL CL1	0,25	3
BND 80/125 45° PP/PL CL3	0,35	11

Line 2

Artikel	Tc/h	Duration
BND 80/125 87° PP/PL CL3	0,35	11
BND 60/100 87° T120 PP/PL PF	0,24	13
BND 80/125 45° PP/PL CL3	0,35	8

Line 3

Artikel	Tc/h	Duration
Ventus hellend dak D200-180	2,60	16
Ventus plat dak D200-180	2,01	16

Line 4

Artikel	Tc/h	Duration
PAN 166 UB 25-45° BLK	0,41	3
PAN 166 UB 35-55° BLK	0,51	25
PAN 166 UL 25-45° NTL	0,40	4

Line 5

Artikel	Tc/h	Duration
PAN 131 UB 25-45° BLK +S	0,21	15
PAN 131 UL 25-45° NTL +S	0,20	8
Dachziegel DN125 25-45°schwarz	0,35	9

Line 6

Artikel	Tc/h	Duration
EXT 60/100 T120 L250 PP/PL PF	0,39	9
EXT 60/100 T120 L250 PP/PL CL1	0,39	10
EXT 60/100 T120 L1000PP/PL CL1	1,00	4
EXT 80/125 L1000 ALU/PL PF1	1,04	9
EXT 60/100 T120 L500 PP/PL CL1	0,75	3

Line 7

Artikel	Tc/h	Duration
RIOOLONTL. 110 VD 300/400 ZW	0,35	2
VTUB 110 L780 BLK	0,39	2
MVENT 131 L750 BLK	0,59	28

Line 8

Artikel	Tc/h	Duration
EXT 80/125 L500 PP/PL CL3	0,92	13
EXT 60/100 T120 L500 PP/PL CL1	0,75	12
EXT 80/125 L250 PP/PL CL3	0,48	4
EXT 60/100 T120 L1000PP/PL CL1	1,00	3

Line 9

Artikel	Tc/h	Duration
MDV-K 80/125 PPs BLK +BND 21"	1,49	3
MDV-K 80/125 PPs BLK +BND 12"	1,16	6
MDV-K 80/125 ALU BLK +BND 21"	1,00	4
MDV 60/100 PP L750 T120 WHT	1,17	19

Line 10

Artikel	Tc/h	Duration
ROLUX 5G 60-100 PP T120 BLK	1,35	10
MULTIVENT 5V L1225	1,54	12
RLX4 80/125 AL/PL L965 T200BLK	1,31	10

Figure 56: Input schedule 6 – Level schedule of input schedule 2; material supply system model

Input schedule 7 – Level schedule of input schedule 4

Line 1

Artikel	Tc/h	Duration
BND 60/100 87° T120 PP/PL PF	0,24	8
BND 80/125 45° PP/PL CL3	0,35	8
BND 60/100 45° PP/PL CL1(2)	0,19	8
BND 60/100 87° PP/PL CL1	0,25	8

Line 2

Artikel	Tc/h	Duration
BND 60/100 87° PP/PL CL1	0,25	8
BND 80/125 45° PP/PL CL3	0,35	8
BND 80/125 87° PP/PL CL3	0,35	8
BND 60/100 87° T120 PP/PL PF	0,24	8

Line 3

Artikel	Tc/h	Duration
Ventus hellend dak D200-180	2,60	8
ONTL.UB NR+ADAPT.RVT200 R PS	0,52	8
Ventus plat dak D200-180	2,01	8
ONTL.PAN UB ZW&ADAPT.RVT200 PS	0,52	8

Line 4

Artikel	Tc/h	Duration
PAN 166 UB 25-45° BLK	0,41	8
PAN 131 UB 15-55° BLK	0,45	8
PAN 166 UL 25-45° NTL	0,40	8
PAN 166 UB 35-55° BLK	0,51	8

Line 5			Line 6			Line 7		
Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration
Dachziegel DN125 25-45°schwarz	0,35	8	EXT 60/100 T120 L250 PP/PL CL1	0,39	8	MVENT 131 L750 BLK	0,59	8
Dachziegel DN125 25-45° rot	0,35	8	EXT 80/125 L1000 ALU/PL PF1	1,04	8	VTUB 131 L1020 BLK	0,59	8
PAN 131 UL 25-45° NTL +S	0,20	8	EXT 60/100 T120 L500 PP/PL CL1	0,75	8	VTUB 110 L780 BLK	0,39	8
PAN 131 UB 25-45° BLK +S	0,21	8	EXT 60/100 T120 L1000PP/PL CL1	1,00	8	MVENT 131 L980 BLK	0,61	8

Line 8			Line 9			Line 10		
Artikel	Tc/h	Duration	Artikel	Tc/h	Duration	Artikel	Tc/h	Duration
EXT 60/100 T120 L500 PP/PL CL1	0,75	8	MDV-K 80/125 ALU BLK +BND 21"	1,00	8	ROLUX 5G 60-100 PP T120 BLK	1,35	8
EXT 60/100 T120 L1000PP/PL CL1	1,00	8	MDV 60/100 PP L750 T120 WHT	1,17	8	RLX5 80-80 PP L1284 T120 BLK	2,11	8
EXT 80/125 L500 PP/PL CL3	0,92	8	MDV-K 80/125 PPs BLK +BND 12"	1,16	8	MULTIVENT 5V L1225	1,54	8
EXT 80/125 L1000 PP/PL CL3	1,31	8	MDV-K 80/125 PPs BLK +BND 21"	1,49	8	RLX5 80/125 PP L1174 T120 TER	1,80	8

Figure 57: Input schedule 7 – Level schedule of input schedule 4; material supply system model

Appendix 9 – Simulation model: neighbourhood operator Simulated Annealing

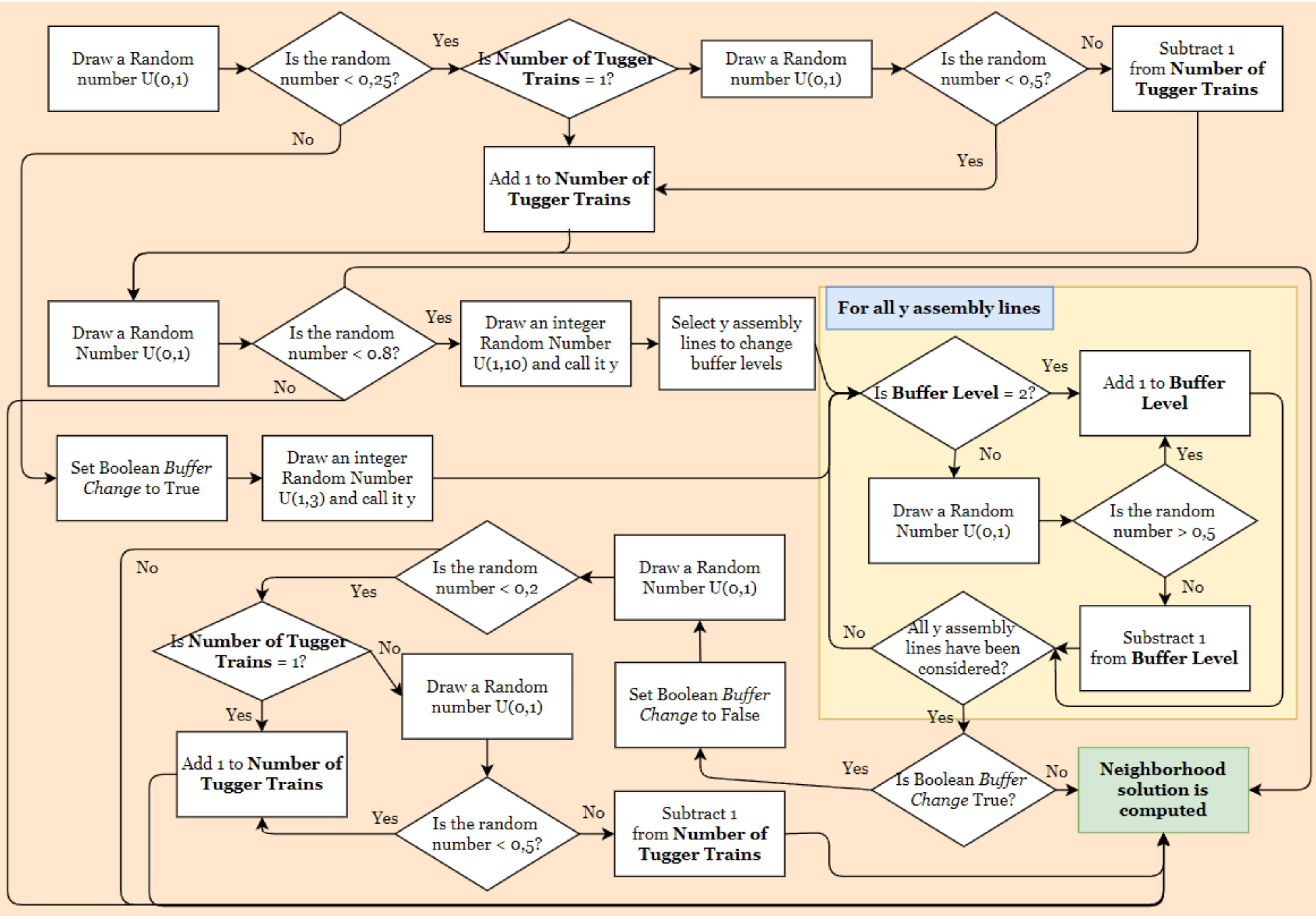


Figure 58: Neighbourhood operator SA2 algorithm; material supply system model

Appendix 10 – Simulation model: determining the number of replications

Input schedule 7 with the following setting of decision variables (see below):

Table 40: Input material supply setting - input schedule 7 - 1; material supply system model

Nr of tugger trains	Buffer level line 1	Buffer level line 2	Buffer level line 3	Buffer level line 4	Buffer level line 5	Buffer level line 6	Buffer level line 7	Buffer level line 8	Buffer level line 9	Buffer level line 10
2	2	2	3	2	2	2	2	2	2	2

Input schedule 7

n	KPI	Mean	Var	Tvalue	Error	Left side of CI	Right side of CI
1	0,7283						
2	0,7091	0,7187	0,000183882	12,706	0,1695	0,709105253	0,728282401
3	0,7096	0,7157	0,00011953	4,3027	0,0379	0,70934913	0,721973432
4	0,7256	0,7181	0,000104351	3,1824	0,0226	0,713036843	0,723252098
5	0,7131	0,7171	8,33293E-05	2,7764	0,0158	0,713055537	0,721220304
6	0,7341	0,72	0,000114449	2,5706	0,0156	0,715592548	0,724327493
7	0,7393	0,7227	0,000149027	2,4469	0,0156	0,718114474	0,727342586
8	0,7261	0,7232	0,00012918	2,3646	0,0131	0,719134783	0,727171562
9	0,704	0,721	0,000153715	2,306	0,0132	0,716894344	0,725159799
10	0,7187	0,7208	0,000137188	2,2622	0,0116	0,717088045	0,724495835
11	0,7168	0,7204	0,000124912	2,2281	0,0104	0,717059939	0,723799577
12	0,7201	0,7204	0,000113564	2,201	0,0094	0,717328745	0,723481362
13	0,7188	0,7203	0,000104306	2,1788	0,0086	0,717446565	0,723111748
14	0,7302	0,721	0,000103256	2,1604	0,0081	0,718269135	0,723700687
15	0,7076	0,7201	0,0001079	2,1448	0,008	0,71740773	0,722771806
16	0,7161	0,7198	0,000101701	2,1314	0,0075	0,717319329	0,722361669
17	0,7243	0,7201	9,65356E-05	2,1199	0,007	0,717722229	0,722488178
18	0,7131	0,7197	9,35765E-05	2,1098	0,0067	0,717436453	0,721996581
19	0,722	0,7198	8,86422E-05	2,1009	0,0063	0,717674535	0,721994432
20	0,7129	0,7195	8,63536E-05	2,093	0,006	0,717411847	0,721567654
21	0,7168	0,7194	8,2393E-05	2,086	0,0057	0,717378581	0,721340134
22	0,7244	0,7196	7,96271E-05	2,0796	0,0055	0,717686262	0,721491213
23	0,7097	0,7192	8,02403E-05	2,0739	0,0054	0,717291942	0,72102756
24	0,7334	0,7198	8,51947E-05	2,0687	0,0054	0,717868789	0,72163696
25	0,7307	0,7202	8,64604E-05	2,0639	0,0053	0,718332076	0,72205144
26	0,7194	0,7202	8,30245E-05	2,0595	0,0051	0,718375378	0,72194931
27	**0,72**	**0,72**	**7,98327E-05**	**2,056**	**0,005**	**0,71845025**	**0,7218893**

Figure 59: Determining number of replications – input schedule 7 - 1; material supply system model

Input schedule 7 with the following setting of decision variables (see below):

Table 41: Input material supply setting - input schedule 7 - 2; material supply system model

Nr of tugger trains	Buffer level line 1	Buffer level line 2	Buffer level line 3	Buffer level line 4	Buffer level line 5	Buffer level line 6	Buffer level line 7	Buffer level line 8	Buffer level line 9	Buffer level line 10
3	3	3	4	3	3	3	3	3	3	3

Input schedule 7							
n	KPI	Mean	Var	Tvalue	Error	Left side of CI	Right side of CI
1	0,8985						
2	0,924	0,9113	0,000323597	12,706	0,1774	0,89854917	0,9239892
3	0,9121	0,9115	0,000162004	4,3027	0,0347	0,90418192	0,91887901
4	0,9105	0,9113	0,000108257	3,1824	0,0182	0,90607558	0,91648026
5	0,9087	0,9108	8,25406E-05	2,7764	0,0124	0,90669577	0,91482181
6	0,9321	0,9143	0,000142188	2,5706	0,0137	0,90945339	0,91918952
7	0,9106	0,9138	0,000120418	2,4469	0,0111	0,90964907	0,91794426
8	0,8997	0,912	0,000127915	2,3646	0,0104	0,90804086	0,91603821
9	0,8908	0,9097	0,000162163	2,306	0,0108	0,90543214	0,9139217
10	0,9216	0,9109	0,000158296	2,2622	0,0099	0,90688784	0,91484513
11	0,9211	0,9118	0,000152076	2,2281	0,0091	0,90808294	0,91551936
12	0,9262	0,913	0,000155465	2,201	0,0087	0,9093995	0,91659823
13	0,9032	0,9122	0,000149838	2,1788	0,0081	0,90885308	0,91564306
14	0,9038	0,9116	0,000143434	2,1604	0,0076	0,90844237	0,91484402
15	0,9018	0,911	0,000139585	2,1448	0,0072	0,90793967	0,91404071
16	0,9199	0,9115	0,000135269	2,1314	0,0068	0,90864103	0,9144563
17	0,9172	0,9119	0,000128706	2,1199	0,0064	0,90913068	0,91463376
18	0,9165	0,9121	0,000122322	2,1098	0,006	0,90953208	0,91474577
19	0,9068	0,9119	0,000117017	2,1009	0,0057	0,90937713	0,9143405
20	0,9184	0,9122	0,000113002	2,093	0,0055	0,90980923	0,91456321
21	0,9114	0,9121	0,000107384	2,086	0,0052	0,90988576	0,91440839
22	**0,912**	**0,912**	**0,0001023**	**2,08**	**0,005**	**0,910004**	**0,914316**

Figure 60: Determining number of replications – input schedule 7 - 2; material supply system model

Input schedule 7 with the following setting of decision variables (see below):

Table 42: Input material supply setting - input schedule 7 - 3; material supply system model

Nr of tugger trains	Buffer level line 1	Buffer level line 2	Buffer level line 3	Buffer level line 4	Buffer level line 5	Buffer level line 6	Buffer level line 7	Buffer level line 8	Buffer level line 9	Buffer level line 10
4	4	4	5	4	4	4	4	4	4	4

Input schedule 7							
n	KPI	Mean	Var	Tvalue	Error	Left side of CI	Right side of CI
1	0,983						
2	0,9789	0,9809	8,51711E-06	12,706	0,0267	0,978884872	0,983012126
3	0,9767	0,9795	1,02191E-05	4,3027	0,0081	0,977693308	0,981384578
4	0,9812	0,98	7,50416E-06	3,1824	**0,004**	0,978585017	0,98132439

Figure 61: Determining number of replications – input schedule 7 - 3; material supply system model

Appendix 11 – Simulation model: regular scenarios

Table 43: Simulation model; regular scenarios; material supply system model

Positioning of the LCIA lines in the plant	Input schedule	Target average line utilization
Lay out 1	Input schedule 1	99%
Lay out 1	Input schedule 2	99%
Lay out 1	Input schedule 3	99%
Lay out 1	Input schedule 4	99%
Lay out 1	Input schedule 5	99%
Lay out 1	Input schedule 6	99%
Lay out 1	Input schedule 7	99%
Lay out 1	Input schedule 1	95%
Lay out 1	Input schedule 2	95%
Lay out 1	Input schedule 3	95%
Lay out 1	Input schedule 4	95%
Lay out 1	Input schedule 5	95%
Lay out 1	Input schedule 6	95%
Lay out 1	Input schedule 7	95%
Lay out 2	Input schedule 1	99%
Lay out 2	Input schedule 2	99%
Lay out 2	Input schedule 3	99%
Lay out 2	Input schedule 4	99%
Lay out 2	Input schedule 5	99%
Lay out 2	Input schedule 6	99%
Lay out 2	Input schedule 7	99%
Lay out 2	Input schedule 1	95%
Lay out 2	Input schedule 2	95%
Lay out 2	Input schedule 3	95%
Lay out 2	Input schedule 4	95%
Lay out 2	Input schedule 5	95%
Lay out 2	Input schedule 6	95%
Lay out 2	Input schedule 7	95%

Appendix 12 – Simulation model: model usage

Model usage

The model contains many methods and tables, that together make sure that the model runs correctly. For most of these methods and tables, we do not recommend users to change its contents. Being able to understand the model code takes a lot of time, let alone change the modelling behaviour succesfully by changes modelling contents.

However, we have incorporated input fields in the model that can be changed easily by users. In figure 61, all fields that could be changed by users are encircled in dark green. The most importnant outputs are also marked in figure 61.

After every replication, the average line utilization per line is shown in table *LineStatistics*. In the table *ResultsReplications*, the input setting (number of tugger trains and buffer levels) and its corresponding performance indicator values are written down.
After every experiment, the input setting (number of tugger trains and buffer levels) and its corresponding performance indicator values are written down in table *ExpSetting*. Here, the performance indicators are taken as averages over all replications.

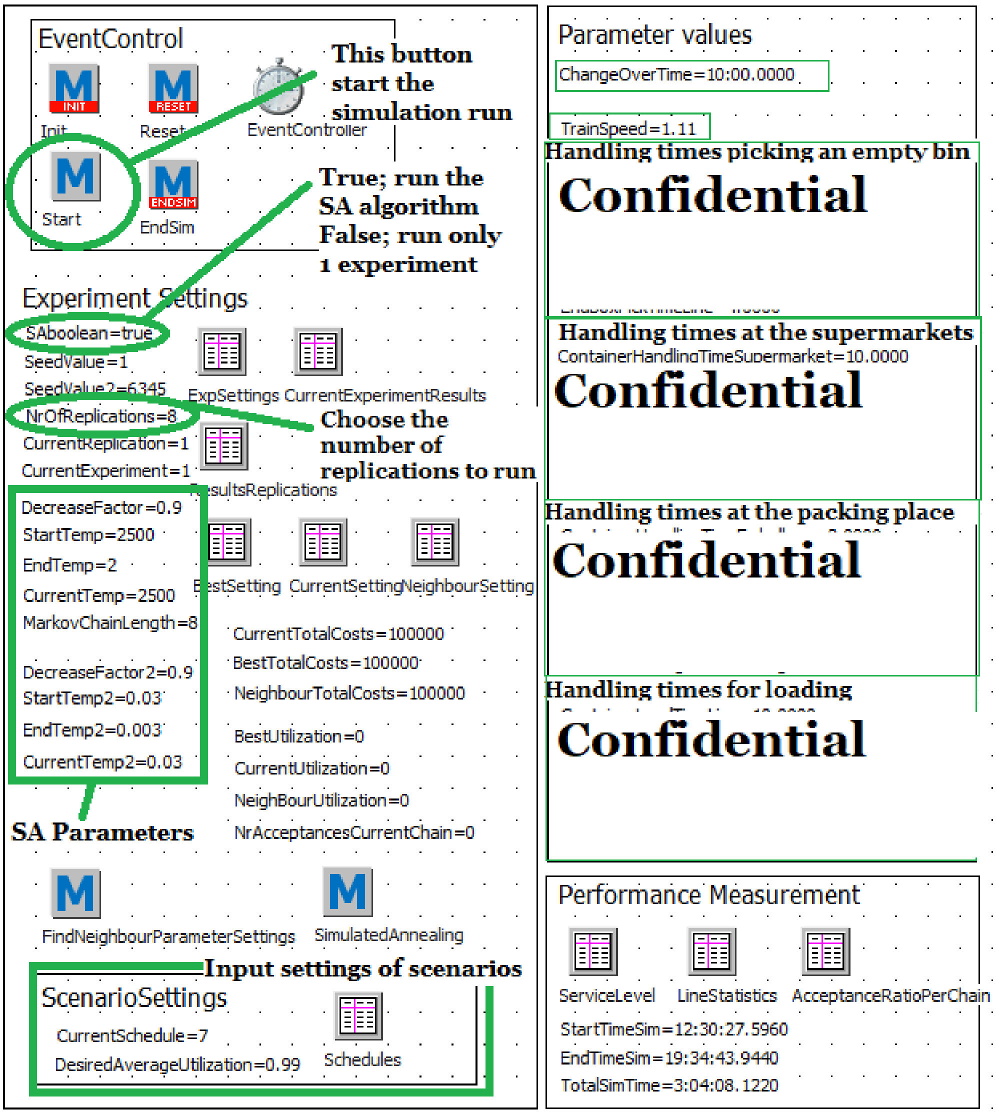


Figure 62: Marked with green colours are the input fields that may be changed; material supply system model (Simulation model)

Simulation logic; methods

Lastly, we want to discuss briefly what is actually happening in the model. For a normal user, only the start button needs to be pressed, after which the model starts running. While the model is running, the user can see tugger trains are moving around, trains stopping at supermarkets to pick component bins, trains stopping at lines to load bins/take empty bins and their Kanban cards, etc.

However, there are various methods and tables that pass information to each other to facilitate the behaviour of all objects or entities that are part the material supply system. Most of these methods and tables are depicted in figure 62 below. Appendix 13 shows how the different methods communicate with each other to emulate the behaviour of the material supply system.

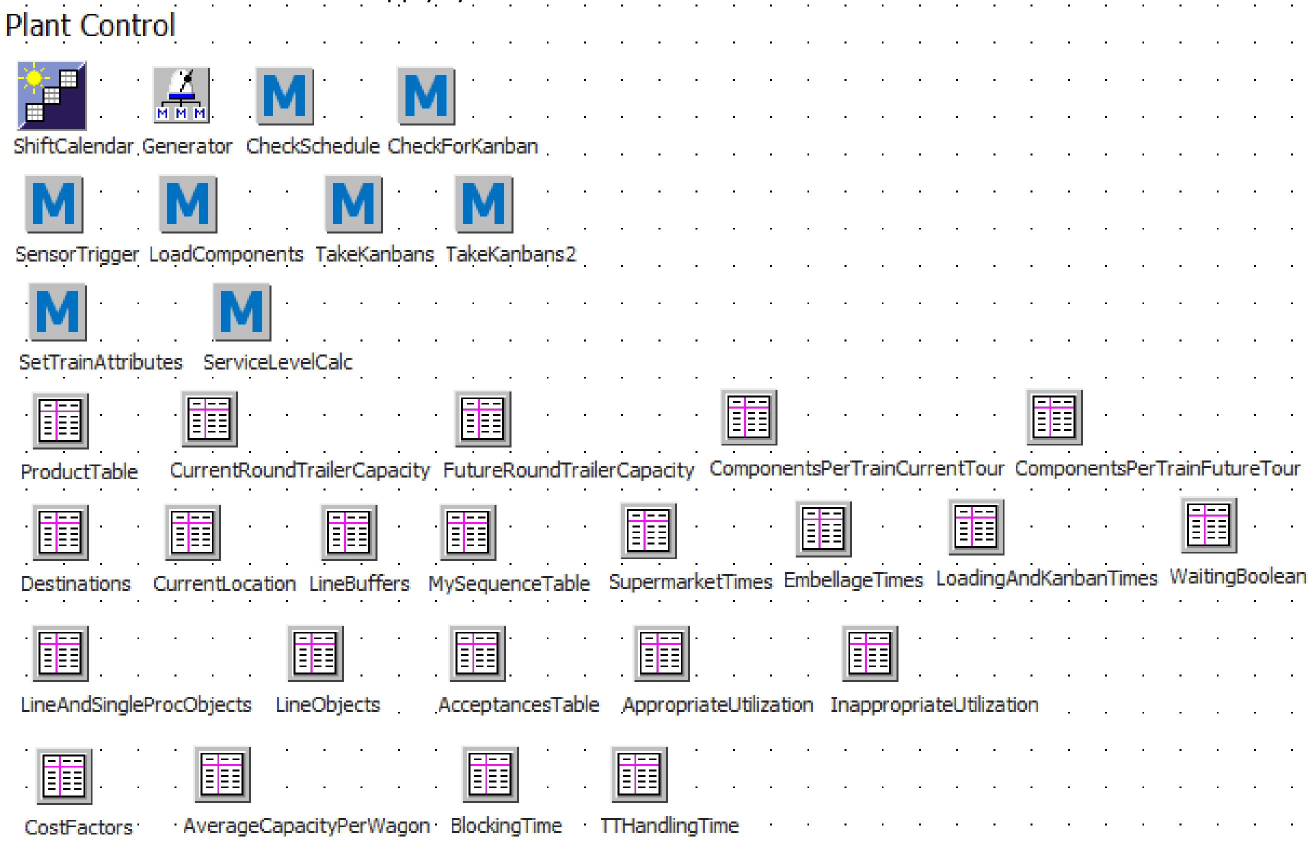


Figure 63: Methods and tables facilitating the behaviour of the material supply system model (simulation model)

Appendix 13 – Simulation model: model logic

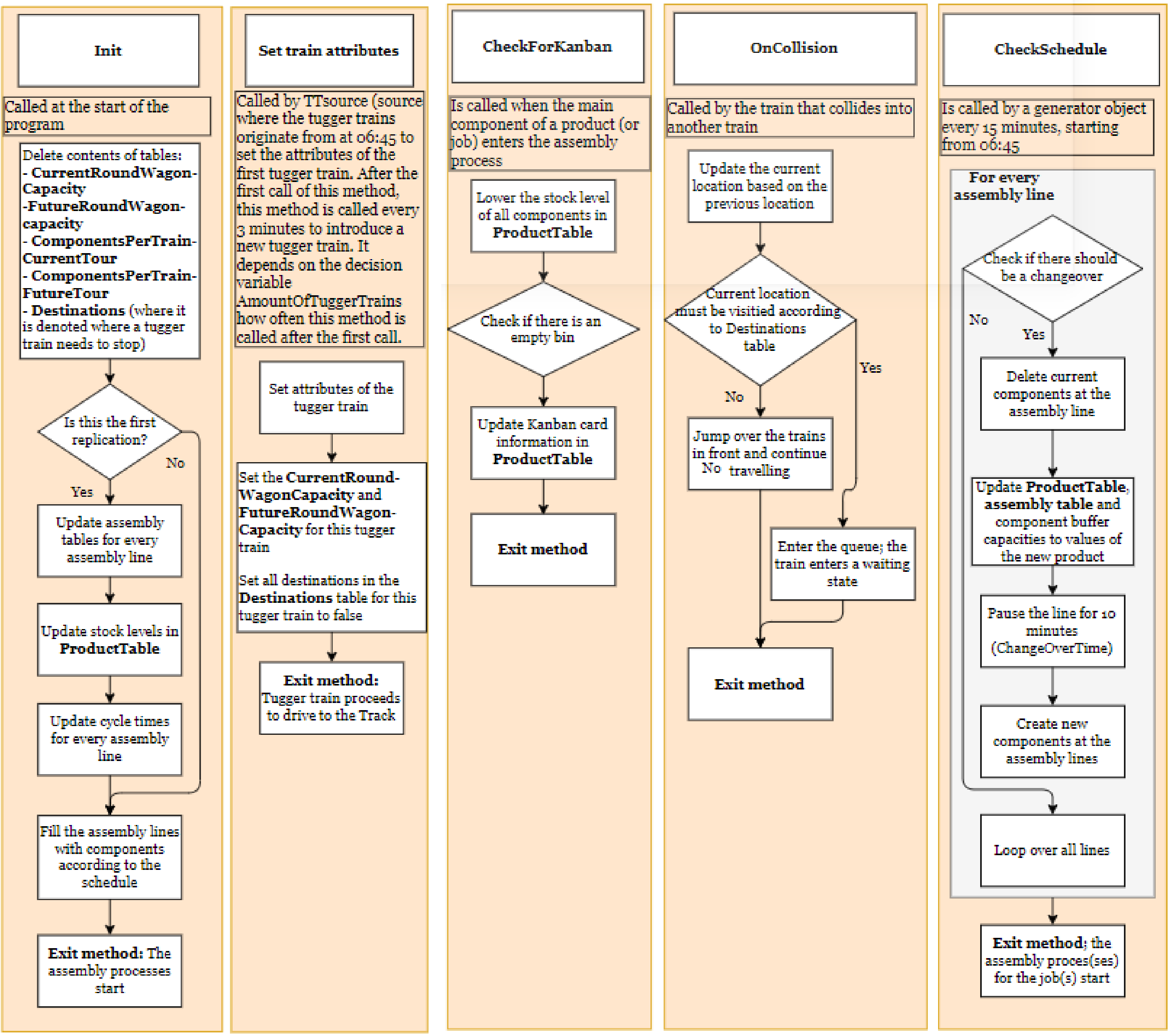
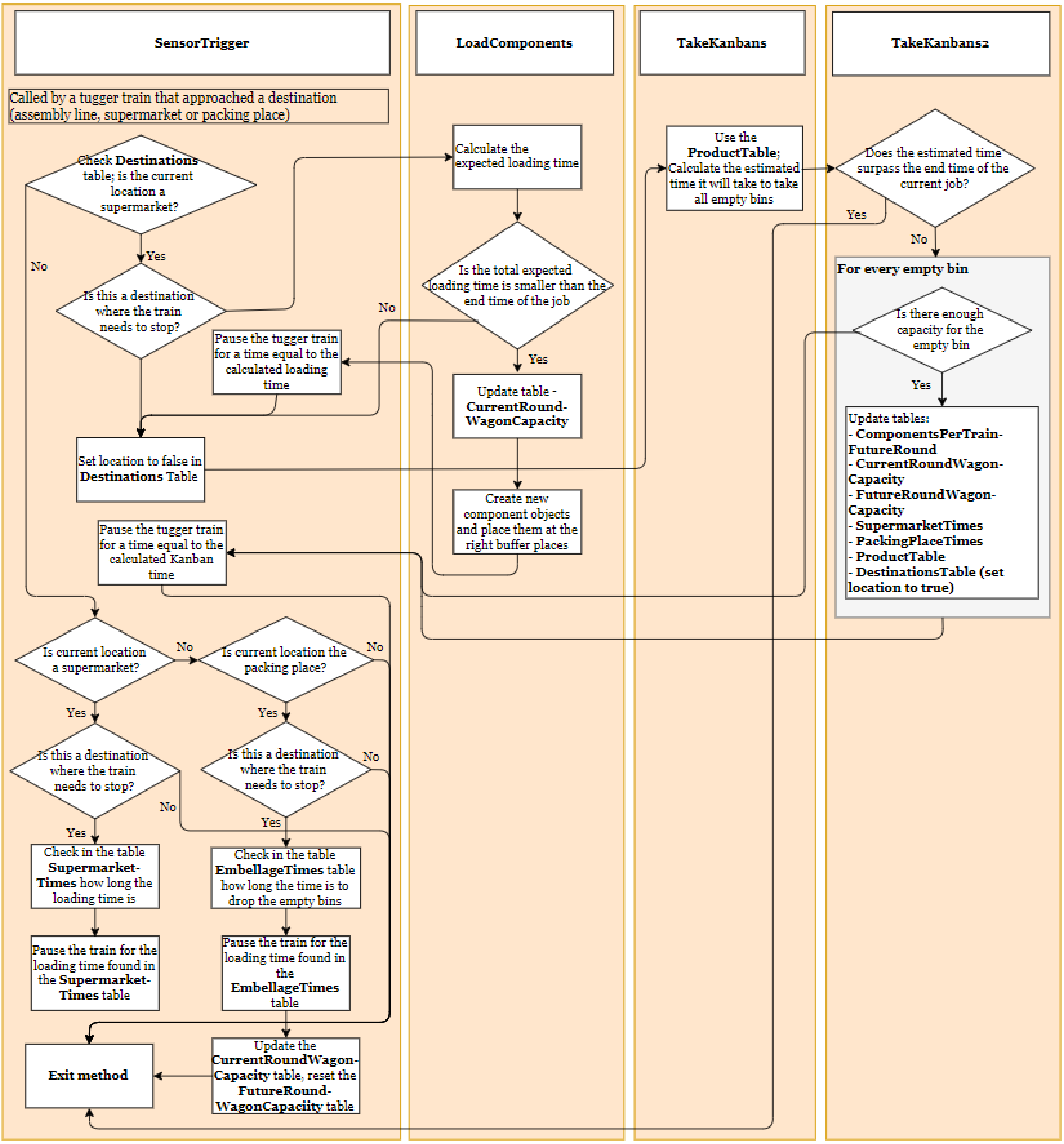


Figure 64: Model logic (material supply system model, simulation model)



Appendix 14 – Regular scenario results

Results; material supply settings and key performance indicators per regular scenario

For every regular scenario that we have ran, we notated the model outcomes. Table 55 shows per scenario the material supply setting that is found and the corresponding key performance indicators.

Table 44: The outcomes per scenarios for the regular scenarios (Material supply system model, simulation model)

Scena rio	Layout	Input schedule	Target avg. line utilization	Costs (€)	Material supply setting**	Avg. line utilization
Sc. 1	Lay out 1	IS 1	99%	Confidential	Confidential	99.08%
Sc. 2	Lay out 1	IS 2	99%	Confidential	Confidential	99.34%
Sc. 3	Lay out 1	IS 3	99%			
Sc. 4	Lay out 1	IS 4	99%	Confidential	Confidential	99.01%
Sc. 5	Lay out 1	IS 5	99%	Confidential	Confidential	99.10%
Sc. 6	Lay out 1	IS 6	99%	Confidential	Confidential	99.24%
Sc. 7	Lay out 1	IS 7	99%	Confidential	Confidential	99,10%
Sc. 8	Lay out 1	IS 1	97%	Confidential	Confidential	97.27%
Sc. 9	Lay out 1	IS 2	97%	Confidential	Confidential	97.30%
Sc. 10	Lay out 1	IS 3	97%			
Sc. 11	Lay out 1	IS 4	97%	Confidential	Confidential	97.11%
Sc. 12	Lay out 1	IS 5	97%	Confidential	Confidential	97.33%
Sc. 13	Lay out 1	IS 6	97%	Confidential	Confidential	97.71%
Sc. 14	Lay out 1	IS 7	97%	Confidential	Confidential	97.28%
Sc. 15	Lay out 2	IS 1	99%	Confidential	Confidential	99.04%
Sc. 16	Lay out 2	IS 2	99%	Confidential	Confidential	99.00%
Sc. 17	Lay out 2	IS 3	99%			
Sc. 18	Lay out 2	IS 4	99%	Confidential	Confidential	99.13%
Sc. 19	Lay out 2	IS 5	99%	Confidential	Confidential	99.09%
Sc. 20	Lay out 2	IS 6	99%	Confidential	Confidential	99.17%
Sc. 21	Lay out 2	IS 7	99%	Confidential	Confidential	99.09%
Sc. 22	Lay out 2	IS 1	97%	Confidential	Confidential	97.51%
Sc. 23	Lay out 2	IS 2	97%	Confidential	Confidential	97,03%
Sc. 24	Lay out 2	IS 3	97%			
Sc. 25	Lay out 2	IS 4	97%	Confidential	Confidential	97.05%
Sc. 26	Lay out 2	IS 5	97%	Confidential	Confidential	97.07%
Sc. 27	Lay out 2	IS 6	97%	Confidential	Confidential	97.52%
Sc. 28	Lay out 2	IS 7	97%	Confidential	Confidential	97.09%

**

Number of tugger trains	Buffer level line 1	Buffer level line 2	Buffer level line 3	Buffer level line 4	Buffer level line 5	Buffer level line 6	Buffer level line 7	Buffer level line 8	Buffer level line 9	Buffer level line 10

One can observe that no results are gathered for scenarios 3, 10, 17 and 24. The reason for this lies in the fact that we observed these scenarios to be overloaded by tugger trains.
We could have computed solutions for the scenarios. However, results with 10+ tugger trains in the material supply setting are infeasible. Hence, there was no point in running the scenarios knowing we would find an infeasible solution.

Results; tugger train driver behaviour per scenario

For every regular scenario for which we have found a fitting material supply setting, we have tracked tugger train behaviour performance indicators. The values of the performance indicators are stated in Table 56.

Table 45: Tugger train behaviour in percentages for the regular scenarios (Material supply system model, simulation model)

	Blocked	Handling					Driving
Scenario	Perc. of time train is blocked (per train)	Perc. of time at packing place (per train)	Perc. of time loading empty bins/picking Kanban cards (per train)	Perc of time loading full bins to bin racks (per train)	Perc. of time at the SM (per train)	Total perc. of time handling (per train)	Perc. of time driving (per train)
Sc. 1	10%	3%	10%	13%	13%	**39%**	51%
Sc. 2	17%	2%	9%	15%	14%	**40%**	43%
Sc. 3	0%						
Sc. 4	16%	2%	7%	11%	10%	**30%**	54%
Sc. 5	10%	3%	10%	13%	13%	**38%**	52%
Sc. 6	17%	2%	9%	15%	13%	**40%**	43%
Sc. 7	15%	3%	10%	15%	14%	**42%**	43%
Sc. 8	11%	3%	12%	16%	15%	**47%**	42%
Sc. 9	16%	3%	11%	18%	16%	**47%**	37%
Sc. 10	0%						
Sc. 11	14%	2%	9%	14%	13%	**38%**	48%
Sc. 12	12%	3%	12%	16%	15%	**46%**	42%
Sc. 13	16%	3%	11%	18%	16%	**47%**	37%
Sc. 14	14%	3%	10%	15%	14%	**41%**	45%
Sc. 15	12%	3%	12%	17%	16%	**48%**	40%
Sc. 16	18%	3%	11%	19%	16%	**48%**	34%
Sc. 17	0%						
Sc. 18	16%	2%	7%	11%	10%	**31%**	53%
Sc. 19	11%	3%	12%	17%	16%	**48%**	41%
Sc. 20	18%	3%	11%	18%	16%	**48%**	34%
Sc. 21	16%	3%	10%	15%	14%	**42%**	42%
Sc. 22	11%	3%	12%	16%	15%	**47%**	42%
Sc. 23	17%	3%	11%	19%	16%	**48%**	35%
Sc. 24	0%						
Sc. 25	14%	3%	10%	15%	14%	**41%**	45%
Sc. 26	11%	3%	12%	16%	15%	**47%**	42%
Sc. 27	17%	3%	13%	22%	18%	**58%**	25%
Sc. 28	14%	3%	10%	15%	14%	**41%**	45%

Results; wagon capacity usage per scenario

For every regular scenario for which we have found a fitting material supply setting, we have also tracked the capacity usage of the wagons. Table 57 shows how the capacity of the wagons was used on average, per tugger train, at the start of a tour.

Table 46: Wagon capacity usage per scenario (Material supply system model, simulation model)

Scenario	Layout	Input schedule	Target avg. line utilization	Wagon 1 average capacity usage	Wagon 2 average capacity usage	Wagon 3 average capacity usage
Sc. 1	Lay out 1	IS 1	99%	8%	11%	6%
Sc. 2	Lay out 1	IS 2	99%	8%	10%	14%
Sc. 3	Lay out 1	IS 3	99%			
Sc. 4	Lay out 1	IS 4	99%	6%	6%	7%
Sc. 5	Lay out 1	IS 5	99%	8%	11%	6%
Sc. 6	Lay out 1	IS 6	99%	8%	9%	14%
Sc. 7	Lay out 1	IS 7	99%	10%	10%	12%
Sc. 8	Lay out 1	IS 1	97%	12%	16%	8%
Sc. 9	Lay out 1	IS 2	97%	11%	12%	19%

Sc. 10	Lay out 1	IS 3	97%			
Sc. 11	Lay out 1	IS 4	97%	9%	10%	12%
Sc. 12	Lay out 1	IS 5	97%	12%	16%	8%
Sc. 13	Lay out 1	IS 6	97%	12%	13%	19%
Sc. 14	Lay out 1	IS 7	97%	9%	10%	12%
Sc. 15	Lay out 2	IS 1	99%	10%	13%	7%
Sc. 16	Lay out 2	IS 2	99%	9%	11%	15%
Sc. 17	Lay out 2	IS 3	99%			
Sc. 18	Lay out 2	IS 4	99%	4%	5%	5%
Sc. 19	Lay out 2	IS 5	99%	9%	12%	6%
Sc. 20	Lay out 2	IS 6	99%	9%	11%	16%
Sc. 21	Lay out 2	IS 7	99%	7%	8%	9%
Sc. 22	Lay out 2	IS 1	97%	9%	12%	6%
Sc. 23	Lay out 2	IS 2	97%	9%	10%	15%
Sc. 24	Lay out 2	IS 3	97%			
Sc. 25	Lay out 2	IS 4	97%	7%	8%	8%
Sc. 26	Lay out 2	IS 5	97%	9%	12%	6%
Sc. 27	Lay out 2	IS 6	97%	15%	17%	26%
Sc. 28	Lay out 2	IS 7	97%	7%	8%	7%

Appendix 15 – Sensitivity analysis results

As in chapter 6.1, we present the results of solving the additional scenarios by solving it with the SA2 heuristic in three tables.
Table 58 shows which material supply settings and the corresponding key performance indicators we have found for each scenario.
Table 59 shows per scenario what tugger train behaviour was measured considering the best material supply setting that was found
Table 60 shows our findings about how the capacity of the tugger train wagons was used in each of our regular scenarios. The results consider the material supply setting that is shown in Table 58 to be an input.
Table 61 shows the outcome of regular scenario 7, which we can use to compare the results of the additional scenarios with that are part of the sensitivity analysis.

Table 47: Outcomes of the sensitivity analysis (Material supply system model, simulation model)

Scenario	Layout	Input schedule	Target avg. line utilization	Costs (€)	Material supply setting**	Avg. line utilization	Scenario change
Sc. 29	Lay out 1	IS 7	99%	Confidential	Confidential	99.11%	**Changeover times** of 5 minutes
Sc. 30	Lay out 1	IS 7	99%	Confidential	Confidential	99.16%	**Tugger train speed** * 1.5
Sc. 31	Lay out 1	IS 7	99%	Confidential	Confidential	99.40%	**Kanban sizes of components with container as bin type** that were smaller than 20, are doubled and its bin type is changed to quarter meter box
Sc. 32	Lay out 1	IS 7	99%	Confidential	Confidential	99.07%	**Cycle times** are reduced by 10%
Sc. 33	Lay out 1	IS 7	99%	Confidential	Confidential	99.13%	**Handling times** are reduced by 10%
Sc. 34	Lay out 1	IS 7	99%	Confidential	Confidential	99.01%	**Handling times** are increased by 10%

**

Number of tugger trains	Buffer level line 1	Buffer level line 2	Buffer level line 3	Buffer level line 4	Buffer level line 5	Buffer level line 6	Buffer level line 7	Buffer level line 8	Buffer level line 9	Buffer level line 10

Table 48: Tugger train behaviour in percentages – sensitivity analysis (Material supply system model, simulation model)

Blocked	Handling	Driving

Scenario	Perc. of time train is blocked (per train)	Perc. of time at packing place (per train)	Perc. of time loading empty bins/picking Kanban cards (per train)	Perc of time loading full bins to bin racks (per train)	Perc. of time at the SM (per train)	Total perc. of time handling (per train)	Perc. of time driving (per train)
Sc. 29	16%	2%	9%	14%	12%	**37%**	47%
Sc. 30	16%	3%	10%	16%	14%	**43%**	41%
Sc. 31	14%	2%	9%	14%	14%	**40%**	46%
Sc. 32	20%	2%	8%	12%	11%	**34%**	46%
Sc. 33	13%	2%	9%	14%	13%	**38%**	49%
Sc. 34	19%	2%	8%	12%	11%	**33%**	52%

Table 49: Wagon capacity usage– sensitivity analysis (Material supply system model, simulation model)

Scenario	Layout	Input schedule	Target avg. line utilization	Wagon 1 average capacity usage	Wagon 2 average capacity usage	Wagon 3 average capacity usage
Sc. 29	Lay out 1	Input schedule 7	99%	8%	9%	9%
Sc. 30	Lay out 1	Input schedule 7	99%	7%	8%	8%
Sc. 31	Lay out 1	Input schedule 7	99%	9%	10%	12%
Sc. 32	Lay out 1	Input schedule 7	99%	7%	9%	9%
Sc. 33	Lay out 1	Input schedule 7	99%	9%	10%	11%
Sc. 34	Lay out 1	Input schedule 7	99%	6%	7%	8%

Table 50: Outcome of scenario 7 (Material supply system model, simulation model)

Scenario	Layout	Input schedule	Target avg. line utilization	Costs (€)	Material supply setting**	Avg. line utilization
Sc. 7	Lay out 1	IS 7	99%	Confidential	Confidential	99,10%