FUTURE FLAMCO

A scenario-based simulation approach for smart intralogistics

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Flamco
aalberts hydronic flow control

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Preface

What a journey it was! Coming back from Karlsruhe and finishing my bachelors like Speedy Gonzalez, I did not know what to do next. Desperately wanting to make the 'right' choice, and knowing a lot of friends still studied in Enschede, I took off and started the Masters Industrial Engineering and Management. With dad a few days in the hospital, I found a nice room in a house with nice people. The new journey had started.

The first year went by really fast, making sure I enjoyed student life and got my points, as I was lucky enough to be rewarded with a scholarship of Flamco, an Aalberts Industries company. I will never forget the long days at the IEBIS table, which became an unwritten law as we sat there every day, studying, drinking delicious Stress coffee and tea, and above all, messing around with each other and the people passing by.

After an exciting summer trip to and through Mexico, it was Christmas before I knew it, which meant that I needed to start preparing my thesis. While I had the Aalberts scholarship, Jeroen van der Scheer, Supply Chain Manager at Flamco, had already showed me various places of Flamco's daily operations. Hence, it was a no-brainer to give him a call and discuss the possibilities.

Together, we formulated an assignment, in which I was going to review the internal logistics of the factory in Bunschoten, potentially able to also add something to a future Flamco somewhere else. In February, I started travelling to Bunschoten three times a week, leaving each time bed around 5:15. It absorbed my life, but I had great fun! A special thanks goes to my company supervisors Jeroen van der Scheer, Theo Kroon, and Ruurd Hartman, for creating this opportunity and helping me along the way with valuable comments. In addition, I thank my colleagues at Flamco for the nice time I had with you guys. It was a real pleasure.

Besides Flamco, I was of course still two days at the university. During that time, I did not only discuss life with Herr dr. Reinoud Joosten, I also received excellent support and guidance from my first supervisor Martijn Mes. It was already nice when I worked for him as a student assistant, but also during my master thesis, I could always knock on his door to ask a few questions. I really appreciate it that he read, more than once, every single word of my thesis, thereby providing useful feedback and being a good sparring partner. Thanks a lot Martijn! By the same token, I would also like to express my gratitude to my second supervisor Peter Schuur, who took the initiative to visit Flamco together with Martijn Mes, and helped improving my thesis the Schuur-ious way, energetic and creative.

Last, but certainly not the least, I would like to thank my girlfriend, family, and friends for their continuous support. I felt really loved and backed up - especially during the times I really needed to unleash the fury of graduating (haha!) -, but also during those days that writing a thesis did not have any importance at all...

So, this journey has come to an end, and a new journey will start soon!

Leaves me with saying that I hope you enjoy your reading; and keep in mind: *"De beste raad is voorraad!"*

Bunschoten-Spakenburg, October 2018,

Willem Wisselink

aalberts hydronic flow control

Flamco

Management Summary

Aalberts Hydronic Flow Control is the part of Aalberts Industries that provides customers with solutions for their boiler room - the place responsible for the heating and/or cooling of a building. As today the heating of buildings mainly happens through closed systems containing (warm) water, there is a need to control the pressure in such systems. That is where Flamco comes in, delivering the expansion vessels to do so.

In Bunschoten, The Netherlands, stands a Flamco factory that produces these expansion vessels and other boiler room equipment – mainly make-to-stock. Considering the fact that, as a starter, every Dutch household needs an expansion vessel and only 24 fit on one Euro pallet, the total transportation workload is considerable. Not only on the roads outside, but also inside the factory (i.e., intralogistics). As Flamco did not know what the magnitude and performance of their intralogistics was, this became the main problem to solve in our research.

In addition, not only water expands, Flamco grows as well. To cope with the increasing customer demand, Flamco wants to expand their production capacity. However, at the current production location in Bunschoten, there is no room to expand. As a result, a new facility will be built in greenfield. Evidently, there is a need for decision support here, especially when it comes to layout planning and dimensioning of the new facility. Hence, providing insight into what can be expected in terms of intralogistics when production lines start working more shifts, a new production line is added, or supply of materials is done less in advance, is important.

As a result, our main research became:

"What is the current intralogistics performance, what does a smart organisation of intralogistics related processes look like in a future business environment, and what performance can be expected from it?"

To answer this question, we first analysed the current situation at Flamco. As intralogistics is at the heart of everything, it comprised quite some processes and materials, from raw materials to planning to production to finished goods. Even though, it was sometimes hard to get hands on data, the analysis resulted in, amongst other things, the Sankey diagram from Figure 1.

Next, we performed a literature study to provide some scientific background on the problem and identify possible solution methods. The concepts of Smart Industry were not overlooked, as Flamco realises that automating processes could certainly add value to their business.

Discrete-event simulation was chosen as a method to fill up the gap in (performance) data on intralogistics. An extensive simulation model was created in Siemens Plant Simulation, taking up almost half our research time and enabling the simulation of the current situation as well as a foreseeable future situation, with numerous model parameters to vary.

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Figure 1: Sankey diagram of the average daily pallet flows of finished goods

We validated the production system, which generates the demand for the intralogistics, using the weekly production numbers. We simulated the exact production planning of 2017 and compared the weekly production output with the production output that was realised in 2017. We discussed the results with the management of Flamco, after which we concluded that the model was valid.

In the experiments we conducted, we found that in the current situation, the average number of pallets transported weekly is just above x, with peaks to y. We also found that this workload is fairly evenly spread over the days and shifts.

Spreading the workload over the production lines, we see that *Bandvatenlijn* (BVL) is dominating, followed by the *Middelgrote vaten lijn* (MGV) and *Original Equipment Manufacturer lijn* (OEM). This also has its influence on the vehicles supplying the different production lines. Currently, there are three vehicles that are dedicated to one specific production line (also working the same shifts), and one multifunctional vehicle helping out all lines, but only during the dayshift. It is surprising to see that this fourth and last vehicle still performs ±20% of the total work, and hence, proves its usefulness levelling the workload for the other vehicles when new production batches are released and materials need to be brought into the factory all at once. The use of different priority rules to prioritise transportation tasks does not really have an influence on the utilisation of the different vehicles. The driving distance and speed does, making the underlying assumptions vital.

When looking at the type of goods, the pallets with finished goods account for around x% of the total workload, thereby dominating the incoming and return stream of goods. Hence, Flamco should mainly focus on efficiently organising the stream of finished goods, e.g., by placing - in a new factory layout - the end of production lines close to the entrance of a finished goods warehouse or cross-docking area.

Still, with y% of the workload remaining, it is worth looking at the intralogistics related to the raw materials. Here we see, across all production lines, that steel and diaphragms are the largest streams in terms of amount of pallets transported. Note that in terms of volume, e.g., carton may be a larger stream. As an example, for the BVL, we yearly transport x pallets of finished goods, for which we supply the production floor with a total of 11000 raw material pallets, i.e., 3100 pallets of steel, 2000 pallets of clamping rings, 3600 pallets of diaphragms, and 2300 pallets of carton. But this is not all, there are various other materials that need to be supplied to (and retrieved empty from) the production in order to run a production line. Figure 2 gives an overview; note that air and nitrogen do not induce any transport, but cause the finished goods stream to be much larger than the raw material stream.

Figure 2: Sankey diagram current situation BVL

Apart from the intralogistics workload, we also investigated the space requirements on the production floor. Today, Flamco continuously supplies the production with materials that are expected to be used between now and 24 hours from now, a so-called *SupplyInAdvanceTime* of 24 hours. We found that in- or decreasing the *SupplyInAdvanceTime* has a large impact on the average amount of pallets present at the different places along a production line. For example, for the BVL, doubling the *SupplyInAdvanceTime* to 48h means an increase of 80% in the average amount of pallets present in the material buffers at the production line. Supplying just 1 hour in advance, would leave the BVL still with on average 15 pallets. Note that when one looks at the maximum number of pallets instead of the average, the number of pallets is increased by a factor 2-3, i.e., compared to the average. This should certainly be taken into consideration when dimensioning a new facility and layout.

Then, we also conducted experiments for a future situation, in which the factory layout is different. And, production capacity was expanded (through working more shifts and adding a new production line). The findings were similar compared to the current situation, even though the numbers grew bigger of course. The weekly average intralogistics workload grew from x to y transports per week, a z% increase. The average daily workload is still quite stable, just under x pallets a day. The total space requirements for material buffers grew with 50% to almost 300 pallets, mainly due to a newly added production line.

To conclude, we recommend Flamco to:

- Take our estimations of travel frequencies (from origin to destination) as input for their Facility Layout Problem. See Figure 3 for a quick overview. When solving the layout problem, one should aim for a situation where the end of the production lines are close to the finished goods warehouse. Organising the stream of finished goods efficiently should get priority over the stream of raw materials (respectively x% versus y% of the total intralogistics workload). Furthermore, based on the choice of *SupplyInAdvanceTime*, one should take into account the spaces required for material buffers.

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Figure 3: Sankey diagram (complete overview of the expected future situation)

- Choose a *SupplyInAdvanceTime* between 12 and 24 hours. Choosing a *SupplyInAdvanceTime* below 12 hours yields a situation where one potentially needs more vehicles to supply production, whereas the decrease in material buffer space becomes smaller and smaller, see also Table 1. Choosing a *SupplyInAdvanceTime* of 24 hours is a scenario, in which one could deliver production only during the dayshift, as material is available for the next 24 hours of production. This has advantages in terms of control, as problems related to intralogistics are often related to purchasing or supply chain, people that only work the normal office hours during day time.

Table 1: Overview of space requirements for different SupplyInAdvanceTimes

SupplyInAdvanceTime / **Space requirements (in no. of pallets)**		**48h**	**24h**	**12h**	**6h**	**1h**
Current situation	Avg	278	196	153	133	116
Current situation	Max	1123	839	688	627	561
Future situation	Avg	418	292	223	189	162
Future situation	Max	1636	1188	960	878	777

- Take our estimations of intralogistics workload as a starting point to critically reflect and thereafter optimise the intralogistics capacity. The percentage of time a vehicle drives with a load is now estimated to be 25% or less. Pooling of resources (so, stop with dedicated vehicles) might add value in this context, because in a situation with no dedicated vehicles the first available vehicle will simply do the job. One will then also quickly recognise when the i^{th} vehicle only waits for jobs, making it easier to choose the right vehicle fleet size. If one wants to use our simulation model for this, one should at least address the assumptions made for driving distance and speed. One should use a tailored distance metric, taking into account the feasible driving lanes in between production lines. The average driving speed should be measured in practice.

- Take a look at the practical suggestions we made in Chapter 7. These suggestions have little to do with our scenario-based simulation, but could certainly add value to the business. Our major concern is the reliability of the production lines. In 2017, the downtime percentages for the BVL, MGV, and OEM were respectively x%, y% and z%. This not only means a lot of lost production time, it also means that there a quite a lot of disturbances in production, and the production planning needs to be changed frequently due to unpredictable output. One way to improve this, which is also in line with the concepts of Smart Industry, is placing sensors on the different stations at the production lines to automatically register, e.g., processing times, OEE data, et cetera. Structurally analysing the resulting data could provide valuable suggestions about where to start first at a certain production line when improving (i.e., resolving bottlenecks).

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Lists

This master dissertation should, to a large extent, be understandable for the general public. However, some educational background, (practical) experience, or affinity with the subject, field of study, and/or used software is assumed in some parts of the report. As a result, jargon is sometimes used to express and explain things. To account for this, we provide every novice yet interested reader with a series of lists and a number of extensive appendices to further explain and elaborate on the important (specialised) parts of the report. The List of Abbreviations clarifies all abbreviations used in the report. The List of Figures and the List of Tables provide overviews of all figures and tables used in the report. The specific software and related jargon, variables, and model parameters are explained in the thesis itself and/or in the additional appendices.

List of Abbreviations

Abbreviation	Description (in English)
AGV	Automated Guided Vehicle
AH	Air Half, filled with nitrogen
AI	Aalberts Industries N.V.
Air+Dirt	Job shop-alike production line producing degassing and dirt separation equipment
AS/RS	Automatic Storage and Retrieval System, mostly used in a (high-bay) warehouse
AWL	Finishing station of a production line: including quality testing, packing, etc.
B2B	Business-to-Business
B2C	Business-to-Consumer
BI	Business Intelligence
BOM	Bill of Materials
BVL	Production line standard consumer vessels, 8-80 liter
CI	Confidence Interval
CPS	Cyber Physical System
CT	Cycle Time
DES	Discrete Event Simulation
DM	Data mining
DOE	Design of Experiments
DTL	Deep drawing machine for vessel halves
EBITDA	Earnings Before Interest Taxes Depreciation and Amortization
ERP	Enterprise Resource Planning
FG	Finished goods, e.g., expansion vessels
FG WH	Finished goods warehouse
FLP	Facility Layout Problem
FMS	Flexible Manufacturing System
FTE	Full Time Equivalent (1 employee, 40 hours a week)
HVAC	Heating, Ventilation and Air Conditioning

IGWH	See RM WH
IoT	Internet of Things
JIS	Just In Sequence
JIT	Just In Time
KPI	Key Performance Indicator
KW	Production line clamping rings
MAS	Multi Agent System
MES	Manufacturing Execution System
MGV	Production line large and medium-sized vessels, 100-1000 liter
MHS	Material Handling System
MHSD	Material Handling System Design
MPSM	Managerial Problem Solving Method
MRP	Material Requirements Planning
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OEE	Overall Equipment Effectiveness (Availability x Speed x Quality)
OEM	Production line OEM vessels, 2-12 liter, use inside boilers
OEM	Original Equipment Manufacturer
OFAT	One factor at a time
P/D-point	Pickup and Delivery point, which in practice represents an area
PLC	Programmable Logic Controller (used to control a machine)
PM	Product Management department
R&D	Research and Development department
RM	Raw materials, e.g., steel and diaphragms
RM WH	Warehouse or temporary storage location for Raw Materials
RNL	Welding machine: joins mantles and covers by means of a weld
RQ	Research question
RSL	Production line discs
S&OP	Sales and Operations Planning
SAP	Enterprise Resource Planning Software
SHA	Systematic Handling Analysis
Smart Industry	Dutch term for the German Industrie 4.0 concept
SME	Small and Medium Enterprise
SMED	Single Minute Exchange of Die
TH	Throughput
VLM	Plate of steel
VR	Virtual Reality
WH	Water Half, filled with water once used
WIP	Work In Process
WMS	Warehouse Management System
WN	Water Nipple, connection between piping and vessel

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1 Introduction

In the framework of completing my Master's study in Industrial Engineering and Management at the University of Twente, this research is performed on the internal logistics processes of Flamco's largest production facility located in Bunschoten, the Netherlands. The main focus lies on the intralogistics associated with the production floor. In a broad attempt to give insight in and improve processes, making them sustainable towards the future, automation and the concepts of Smart Industry are not overlooked. The backbone of the research consists of quantitative analyses performed in Siemens Plant Simulation (i.e., discrete event simulation) and Microsoft Excel (i.e., data analysis).

In the remaining of this chapter, we introduce the company and the research project. We also motivate why we do research in the particular area of material handling. Furthermore, we define the research problem and its scope, list the research objectives and come up with research questions tailored to cover all important aspects of the problem at hand.

1.1 Company background

In this section, we provide some background information on Flamco as a business.

The Flamco Group, or Flamco Holding B.V., is part of the business unit Climate Control within Aalberts Industries N.V., which is listed at the Amsterdam stock exchange. The business unit Climate Control, of which a large part is taken up by the Flamco Holding B.V., showed a total revenue of approximately five hundred million euros in 2016. In the same year, the operating profit (EBITDA) of the Climate Control division came out around fifty-four million euros (Aalberts Industries N.V., 2016).

Flamco is involved with the development, manufacturing and sales of hydronic systems – for Heating, Ventilation and Air Conditioning (HVAC). Most common is the expansion vessel – a product, which is used to keep a stable pressure in a closed water heating system. It can be found in almost every Dutch household right next to or within the central heating boiler. The famous red expansion vessel was originally developed after the Second World War by Flamco director Johan Wormmeester, who saw the opportunity and came up with the innovative idea to produce an expansion vessel using the available, and therefore cheap, moulds of a saucepan. As of today, this is still the leading product design.

The company sells its HVAC solutions in roughly seventy countries. Markets being served are related to commercial and residential buildings as well as sustainable energy. The head office of the Flamco Group is located in Bunschoten, the Netherlands. Besides the head office, there are another twelve sales offices around the globe. Production facilities are located in both Europe and China. To give an illustration, the manufacturing plant in Bunschoten, The Netherlands is responsible for the mass production of most expansion vessels, whereas a smaller factory in Wijhe, The Netherlands is concerned with, amongst other things, the assembly of more complex expansion automats. The facility in China manufactures all products related to fixing technology, i.e., rails, clips and other mounting material, for installing HVAC systems and hanging pipes.

Figure 4: Example of products that Flamco delivers worldwide

Besides Figure 4, which gives a visual impression of the product portfolio, a list of products Flamco offers (Flamco Flexcon B.V., 2018), can be found underneath:

- Expansion vessels, expansion and refill automats for heating and cooling.
- Safety valves, pressure gauges, connection groups and other appendages.
- Storage vessels, boilers and expansion vessels for hot water systems.
- Equipment for deaeration and dirt separation.
- T-plus fittings for rapid expansion of existing systems.
- Valves and fittings for solar systems.
- Rail, clips, brackets and other mounting material for installing, and hanging pipes.

In order to sustain its position as A-brand, Flamco sticks to top-quality products. However, at Flamco, quality is not restricted to products. Quality is also the focus when providing additional (technical) services, and smooth operations and logistics. The latter is also the topic of this research.

1.2 Project background

In this section, we give some background information on the project, addressing also the current business environment, dynamics and outlook.

Today, Flamco's largest manufacturing facility is located at its headquarters in Bunschoten, The Netherlands. In recent years Flamco has been growing substantially and this sales trend upwards is expected to sustain in the coming years. Therefore, Flamco is preparing to expand its current production capacity. Logically, such changes require adaptation of the current manufacturing environment. For this "brownfield" factory redesign, a concept layout plan has been developed.

In addition, as the situation in Bunschoten cannot be sustained for 5 more years, plans to build a new facility are now also developed. In this so-called "greenfield" situation, it is evident that there is more freedom in terms of factory layout and control. However, management prefers to stick to the concept layout originally created for the plant in Bunschoten. Nevertheless, as size, dimensions, et cetera, are not determined yet, there is still the freedom to shape the inbound and outbound flows respectively to and from the facility. Evidently, this has a major impact on the organisation of the material handling processes.

Next to the planned capacity expansion and the uncertainty related to the facility location, Flamco aims to continuously improve its operations, which naturally includes manufacturing and logistics. In this area the German *Industrie 4.0* initiative, also referred to as Smart Industry, Industry 4.0 or the Industrial Internet, receives a lot of attention lately (Hofmann & Rüsch, 2017). In short, it is all about so-called *Connected Factories*, in which machines, people, information systems, and so on, are all connected to the internet. As such, they are all able to communicate with each other in real-time and on the basis of synchronised data. This would not only prevent a lot of miscommunication, it also provides us with countless opportunities to integrate processes and collaborate not only more, but also more efficiently - with and without human interference. Also, the Internet of Things (IoT) and other concepts related to process automation and digitalisation are starting to gain more and more traction in industry. Flamco recognises this development. Because some change in operations, induced by the previously mentioned factors, is inevitable, it is now the time to look for a new smart and dynamic manufacturing and logistics environment that could incorporate more automation and digitalisation if that turns out to be beneficial, i.e., if the benefits outweigh the costs - now or at a future point in time.

In recent years, also many researchers have pointed out that - due to the increasingly dynamic conditions within manufacturing systems – processes should have the ability to anticipate or respond in real-time to changes in production. This also means that issues like the level of automation, reconfigurable systems and equipment, maximum throughput and cost effectiveness need to be addressed. All in all, the goal is to strive for operations featuring a high degree of (process) flexibility, short response times and the ability to adapt smoothly to more and more frequent changes in the manufacturing environment (Güller, Hegmanns, & Kuhn, 2016).

1.3 Problem description

In this section, we sketch a relevant subset of the business problem(s) Flamco faces at this moment and elaborate on the important factors of influence, which need to be addressed in order to work towards a solution.

In the previous section, we mentioned that Flamco finds itself in a situation with quite a lot of uncertainty related to their largest manufacturing site. A situation in which there evidently is a need for decision support (tools) to be able to make well-founded (strategic) business decisions.

Some strategic decisions have already been made; as mentioned in the previous section, a concept layout plan for the future (redesigned) facility has already been established. However, a Material Handling System Design (MHSD), which complies with this new layout, still misses. Such a design should also anticipate future changes, i.e., growing demand, a larger mix of products, a higher degree of process automation, and so on. Furthermore, as new facilities are generally built for a considerable period, say at least 15 years, a smart factory redesign cannot ignore changed market conditions ten years from now. Therefore, it is now also the time to think of what the concepts related to Smart Industry could add to the business. Yet, everybody talks about Smart Industry, but adapting to it and integrating it into daily operations seems to be much harder.

Due to the fact that the internal logistics processes form the heart of the manufacturing operations at Flamco, one cannot risk doing it the wrong way, i.e., ineffectively and inefficiently. Logically, management feels that some sort of decision support could in this case definitely be beneficial.

Hence, the main research question is how we can redesign Flamco's internal logistics processes in such a way that it is not only done more effectively and efficiently, but that it is also future-minded, i.e., tries to integrate the concepts of Smart Industry.

Note

As we often refer to Flamco's internal logistics processes, or *intralogistics*, it is useful to state a clear definition.

Intralogistics *"Intralogistics is about the organisation, control, execution and optimisation of the internal material flows, the flows of information, as well as the handling operations performed in industry, commerce and public institutions."* Verband Deutscher Maschinen- und Anlagenbau (VDMA)

Note that intralogistics is closely related to the broader concept of material handling systems. Common definitions of material handling are listed below.

Material handling *"The art and science of moving, storing, protecting and controlling material."* (Tompkins, White, Bozer, & Tanchoco, 2010)

Material handling *"The movement, protection, storage and control of materials and products throughout the process of their manufacture and distribution, consumption and disposal."* Material Handling Industry of America (MHIA)

To avoid any confusion, we mainly focus this research on intralogistics and leave out a large part of the issues related to permanent storage, protection and control of material. It is the material movement that counts. However, the terms intralogistics and material handling may be used interchangeably in the remaining of this report. When we refer to *Smart Intralogistics*, we mean that intralogistics are designed following the principles of Smart Industry. This does not necessarily mean that Smart Intralogistics are indeed smart, i.e., more effective and efficient than the current intralogistics at Flamco.

A logical next step, deepening our problem identification, is to try and grasp the magnitude and complexity of the problem by identifying important factors of influence for Flamco's intralogistics. This is done by means of a mind map, which is an individual brainstorming method with the focus on the quantity of 'ideas' rather than the quality. According to Higgins (1996), it is a great technique to generate ideas around a main problem. The mind map is displayed in Figure 5. It is hereby important to realise that when one starts reorganising a factory (operation), one inevitably touches on many aspects of the system such that also a lot of improvement opportunities (e.g., layouts, processes, protocols, et cetera) come to mind. Therefore, it is also important to make a wise and informed choice in terms of research direction, i.e., on which improvement potential to focus.

Looking at Figure 5, one can immediately see that the intralogistics is the spider in the web called operations. By moving all the different goods physically through the plant, it is the connecting factor. As the production lines are the main customers of intralogistics, intralogistics itself depends on what happens there. Machine breakdowns and setups are examples of events that directly influence the intralogistics workload. That a 'good' material handling system should unify processes and deliver quality - in time and on many aspects - was also emphasised by Tompkins et al. (2010). They state that a perfect material handling system provides

- the right amount
- of the right material
- in the right condition
- at the right place
- in the right position and orientation
- in the right sequence
- at the right cost
- by making use of the right method(s)
- at the right point in time

The mind map and the nine bullet points both illustrate the complexity that comes with intralogistics. However, as we have limited resources to do research and are facing the dynamics of real-life, it is impossible to design a perfect material handling system. Nevertheless, this research should provide a first answer on how to smartly organise intralogistics of the (new) factory. To this end, the continuously changing stream of goods in the factory, consisting of, e.g., Raw Materials (RM), Work In Progress (WIP), and Finished Goods (FG), should be described and quantified in order to find a suitable solution.

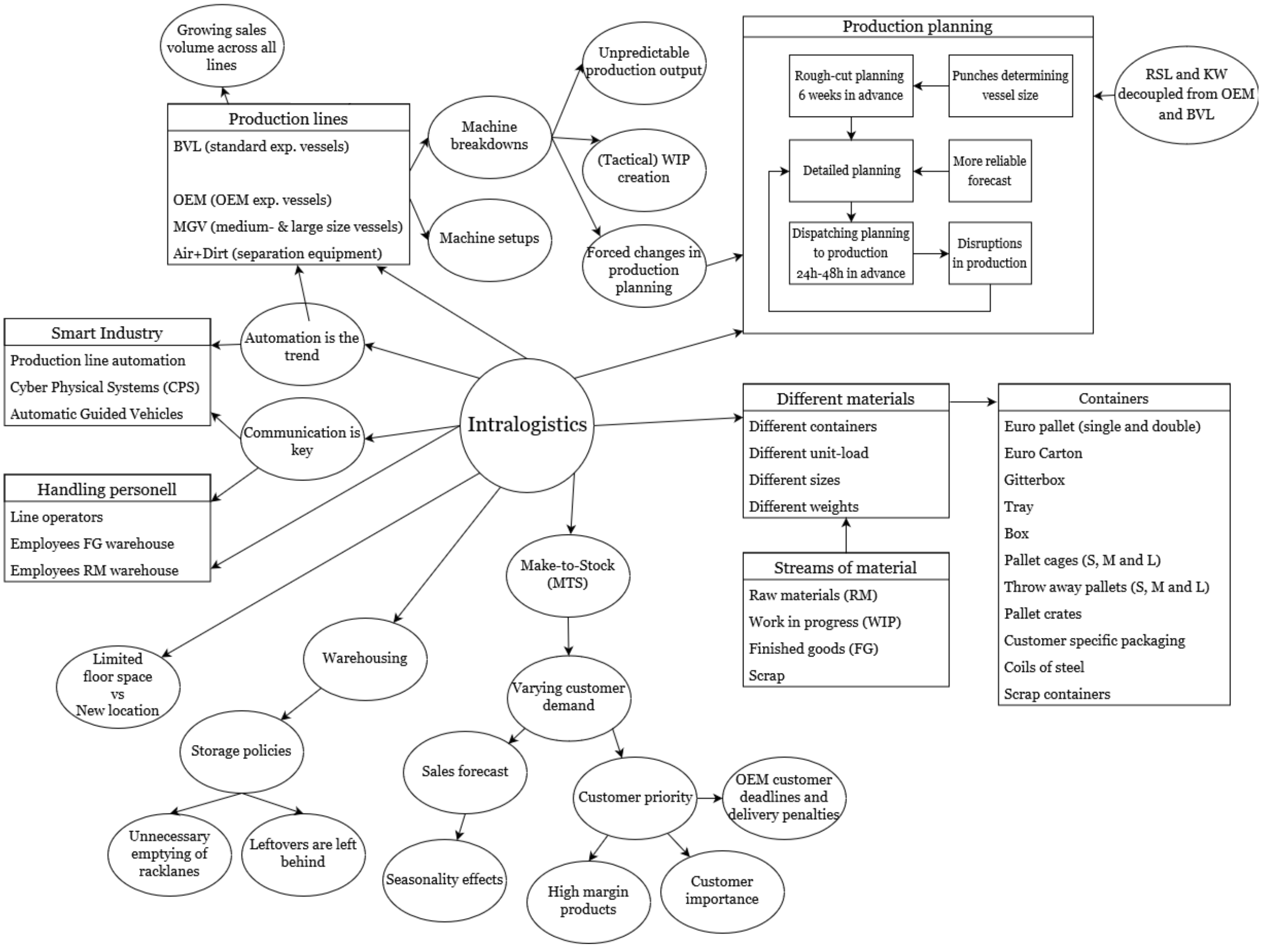

Figure 5: Mind map intralogistics Flamco Bunschoten

1.4 Research objectives and scope

In this section, we set our research goals and define a research scope that is attainable given our resources.

In short, the research objective is to come up with a model that not only provides valuable insight in the current intralogistics of Flamco, but also provides valuable suggestions for *Smart Intralogistics* in a future factory. We thereby assume that Flamco will continue to automate their processes and will sooner or later incorporate at least some principles of Smart Industry.

As this research focuses on intralogistics, the relation between production (planning) and material handling workload is investigated. All inbound and outbound supply chain activities are ignored, i.e., those activities (e.g., purchasing materials, inventory management, and shipping goods) are assumed to function smoothly. Also, the condition of materials is assumed to be always perfect, i.e., no quality deficiencies, driving accidents, and so on.

The production system is analysed and modelled in a high level of detail (i.e., often on the level of a single article), as it is the main determinant of what the intralogistics system should deliver in terms of supporting activities. When it then comes to the materials that are transported through the intralogistics system, we only focus on the large streams of goods, i.e., the dominating RMs and the FGs. WIP outside the production lines itself (e.g., vessel halves) is excluded from the model, because the amounts are rather small and one could question the necessity. Nevertheless, WIP, together with RM leftovers, exists within the factory and needs to be temporarily stored somewhere. In this context, storage policies become extra important. However, our first focus is on the magnitude of the internal transportation needs and corresponding buffering spaces within the plant. Thereafter, smart storage policies might come in handy.

In terms of Smart Industry, we focus on simulation, the concept of Cyber Physical Systems (CPS), machine-to-machine communication, and collaborative robots (AGV to AGV). Systematic data collection, in function of future big data analysis, and adding sensors (IoT) in the manufacturing process is something that could also yield improvements, but in this regard we restrict ourselves to suggestions and recommendations.

For the standardisation of processes, which we may already assume in our model later on, we mainly rely on common sense, rather than choosing a continuous improvement paradigm like Lean, Six Sigma or World Class Manufacturing. Of course, we use a structured approach to build up a logical argument (based on common sense) and test the hypothesis using simulation.

1.5 Research questions

In this section, we formulate research questions that will help us tackle the problem posed.

In order to provide a solution to the problem as described in the previous sections, it is helpful to split the problem in different parts and assign research questions to each of them. We discuss our research approach and methodologies used to answer our research questions (RQs) in the next chapter, i.e., Chapter 2.

Hence, the main research question is how we can redesign Flamco's internal logistics processes in such a way that it is not only done more effectively and efficiently, but that it is also future-minded, i.e., tries to integrate the concepts of Smart Industry.

The main research problem can be formulated as follows:

"What is the current intralogistics performance, what does a smart organisation of intralogistics related processes look like in a future business environment, and what performance can be expected from it?"

Research questions that help us in providing a solution to the main research problem are denoted below.

Question 1: How does the current production facility in Bunschoten operate and what is the role of intralogistics in the daily operations?

- How is the current production facility organised in terms of layout?
- Which final products are produced on which production lines? Do they show a demand pattern?
- Which resources, i.e., raw materials and personnel, are needed to produce the different final products?
- How is the purchase and supply of raw materials organised? How is the production planning organised?
- What is the current degree of standardisation within the factory operations?
- How is the production floor organised? Where are the pickup and delivery points (P/D-points) for raw materials and finished goods located? What are the streams of goods to and from the P/D-points?
- Are there Key Performance Indicators (KPIs) in place that measure intralogistics performance?

Question 2: What theory does the scientific literature offer when it comes to intralogistics in a Smart Industry context?

- What is Facilities Planning and how does intralogistics fit in this area of research and design?
- What does the Smart Industry concept mean and what are the implications for a manufacturing environment?
- What framework(s), method(s) and algorithm(s) could we use to enhance intralogistics?

Question 3: How to apply the theory to Flamco's intralogistics?

- How to apply the chosen framework(s), method(s) and algorithm(s) in the context of redesigning Flamco's intralogistics?

- How to incorporate the concept of Smart Industry?

Question 4: How to construct a model that can quantify both the (expected) performance of the current intralogistics and the new *Smart Intralogistics*?

- How do we model the factory operations and the associated material handling processes?
- What are the scenarios and interventions that we are going to investigate?
  - ✓ *Scenarios:* what customer demand do we face? What factory layout do we use? Et cetera.
  - ✓ *Interventions:* what could be good strategies (resource pooling, routing, job prioritisation, etc.) for AGVs performing the intralogistics?
- What input do we need for the model?
- What are (experimental) factors that should be made dynamic in the model? And how do we realise this?
- How could we make the model easily adjustable and scalable in order to cope with continuously changing plans for a new factory?
- What output does result from the model?
- How do we verify and validate the model?
- How do we establish credibility and trust in the model?

Question 5: What performance can be expected of the *Smart Intralogistics* compared to the current way of working?

- What are the main causes of difference between the old system and the new scenarios?
- How does the distribution of the intralogistics workload look over time in the current situation? And in possible new situations?
- How much capacity (no. of forklifts or AGVs or else) is needed to deal with all handling at the busiest moment? And on average?
- What is the interaction between production lines and other parts of the factory?
- How do the trade-offs between supply/retrieve frequency and the needed buffer space at the production line look?
- In what frequency should raw materials be supplied to the production lines?
- In what frequency should finished goods be retrieved from the production lines?
- To which factors is the intralogistics system the most sensitive?

Question 6: How could Flamco implement the new Smart Intralogistics?

- How do we translate the model into a physical system?
- What practical steps are there to take when it comes to implementation of the Smart Intralogistics?

1.6 Research and report outline

In this section, we provide an outline of the report, aiming to properly guide the reader through the report.

To finish the introduction section, we elaborate on the structure of our research and comment on how the rest of this thesis is built up. As mentioned before, Chapter 2 covers the methodology part of this dissertation. Next, in Chapter 3, we start our research with investigating the current practices at Flamco. This corresponds with answering RQ 1. Chapter 3 is followed by a Literature Study in Chapter 4, a review of scientific literature aimed at finding theory that could help in the process of solving the research problem. RQ 2 and RQ 3 are covered in this chapter. In Chapter 5, we work towards an actual solution by developing a simulation model that firstly, gives insight in the current intralogistics performance, and secondly, is able to investigate and test different flavours in Smart Intralogistics. This corresponds with RQ 4. After that, in Chapter 6, we answer RQ 5, i.e., list and discuss the results of different intralogistics scenarios, i.e., what is the intralogistics workload under different circumstances; and which combination of layout and intralogistics strategy is smart to have. We choose a system configuration that is best in the eyes of the stakeholder(s). As we recognise that a solution is only the first step towards actual implementation, we point out some (practical) issues in Chapter 7 that need to be addressed in order to work towards some sort of implementation of the proposed solution. The chapter addresses all sub questions of RQ 6, i.e., the involvement of people, and the translation of the model into a physical system. In the final chapter, we draw up conclusions, address the limitations of our study, provide recommendations for further research and implementation, and discuss possibilities to improve the research or solution quality.

2 Methodology

In this chapter, we first discuss the Managerial Problem Solving Method (MPSM) and the research cycle, as those are approaches that can structure our research on a macro level. Afterwards, we discuss our lower level research approach that should answer the research questions posed.

2.1 Managerial Problem Solving Method (MPSM)

In this section, we discuss a method that should assist in structuring our research.

In order to structure our research, we make use of the Managerial Problem Solving Method (MPSM), as described in (Heerkens & Van Winden, 2012). This method aims to provide a framework to solve any "action" problem in a business environment. An "action" problem is broadly defined as a discrepancy between norm and reality. It makes sidesteps to the research cycle when a "knowledge" problem needs to be solved to be able to proceed with the MPSM. Figure 6 depicts both approaches. In this section, we only describe our research in relation to the two frameworks. For details on how the MPSM and research cycle work in general, we refer to (Heerkens & Van Winden, 2012).

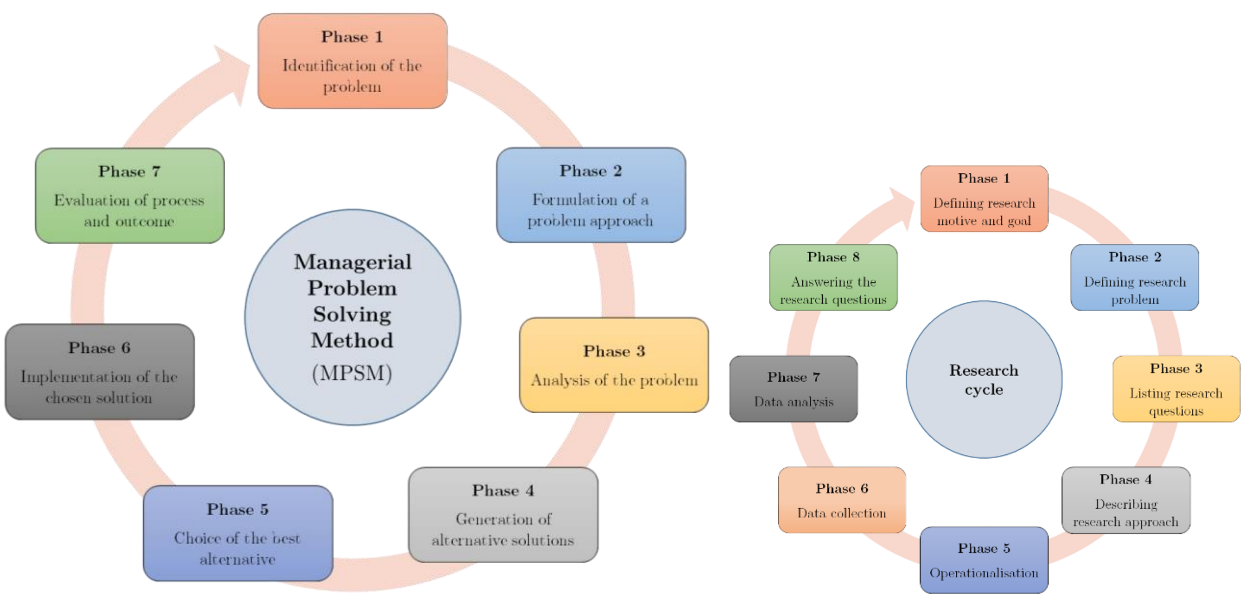

Figure 6: The managerial problem solving method and the research cycle (Heerkens & Van Winden, 2012).

Phase 1 of the MPSM consists of identifying the problem at hand; a large part of this has already been discussed in Chapter 1. The details of the problem result from the case study performed in Chapter 3. In this chapter we obviously formulate a problem and research approach. To be able to do that, we first try to capture the information needs related to the research questions. If knowledge or information is not (directly) available, there is no other option than to enter the research cycle. Stepping through all phases of the research cycle should yield a proper answer to the “knowledge” problem. The “knowledge” problems that were already identified, are listed in Section 1.5. For these questions, a detailed research approach is described in the next section covering all aspects of the research cycle.

2.2 Research approach and methodologies

In this section, a concrete approach per research question is determined and elaborated on briefly.

The first RQ is about Flamco’s current factory operations in Bunschoten. We answer questions related to this subject by means of interviews, personal observations and data analyses. Interviews are being held with the managers responsible for the supply chain, operations and engineering, employees of the planning and purchase department, and with team leaders and operators of the different production lines. The type of interviews range from quick questions to informal coffee machine conversations to more formal meetings. We execute fieldwork in the warehouses and on the production floor, with and without the guidance of a team leader. The work ranges from personal observations to interactively posing questions and asking for information, e.g., about how processes are carried out and what problems are experienced. Also, we attend a product training to be able to distinguish different (raw) materials and final products. The data analysis comprises the analysis of the Bill of Materials (BOM) of (semi) finished products, the production planning files in MS Excel, the sales history and related data from SAP. The goal of this data analyses is to come up with a comprehensive overview of the material flows within the factory.

Answering RQ 1 and all its sub questions yields an overview of the current operations at Flamco Bunschoten as well as more insight in the (average) flow of material throughout the production facility. A Systematic Handling Analysis (SHA), as described in Apple (1972), is performed, which means that all relevant streams of goods are identified and quantified. A translation is made from pieces produced to pallets moved. This not only provides insight in the fast moving goods, but also in the diversity and workload of Flamco’s intralogistics. Combining the different flows to and from the production lines gives an idea where congestion or bottlenecks might occur. Taking a closer look at production and intralogistics processes also helps to focus further research efforts towards the important causes of operations’ inefficiency.

The second and third RQ are about the question how scientific literature can help when researching the topics of intralogistics, Smart Industry and related quantitative methods and algorithms such as simulation. Literature can not only supply relevant information, it could also offer guidance by means of proven methodologies and frameworks. Since time is limited, we will for some topics (e.g., facilities planning and material handling system design) rely on summarizing books and comprehensive reviews that the literature provides us with. As this research mainly focusses on experimenting with a new, Smart Industry based, intralogistics system, we invest more time in reviewing the literature in the research area of Smart Industry as well as in examining relevant (scenario-based) simulation studies.

Answering RQ 2 and 3 provides us with a knowledge foundation, on which we can build our own research.

The fourth and fifth RQ is about creating and evaluating a quantitative model that mimics (a part of) Flamco's production and intralogistics system. We use simulation as a solution methodology, because of the following reasons, which are derived from the more general statements made in Law (2014). One, simulation offers the possibility to simulate a system that does not exist yet, and for which it is known that it is too complex to solve analytically. In this case, both apply. Two, simulation offers the possibility to change and experiment with system parameters, which in real-life would be either too expensive, dangerous, not allowed or taking too long. Three, even though reality is by definition more realistic than a simplified model, it is not repeatable. In contrast, a simulation model is capable of simulating various future scenarios to better predict the future.

We use Siemens Plant Simulation as a simulation tool, because the author is familiar with this software. The simulation model itself is a complex queueing model, of which, as said before, performance can only be evaluated numerically. We perform a simulation study containing all relevant parts, i.e., a conceptual model ("model on paper"), a verificated and validated model implementation in computer software, a set of inputs based on data and valid assumptions, and a (statistically) well-founded experimental design. Important model inputs are the facility layout, the production system, the production planning, the intralogistics system, and a concept defining how an automated intralogistics system - designed following the principles of Smart Industry - should work. We define different scenarios in which crucial model inputs, e.g., the facility layout and the production system, are varied. Furthermore, we define interventions in an attempt to find the smartest way of working (i.e., performing intralogistics) for a given scenario. The experiments, in which scenarios and interventions are combined, form the basis for a thorough what-if analysis. Taking into account the preferences of the stakeholders, we then come up with a suitable advice of how to proceed towards truly smart intralogistics.

For the remaining RQs, a detailed research approach is determined on-the-fly as research progresses.

2.3 Conclusion on methodology

After finishing the first phase of the MPSM, being the problem identification, in Chapter 1, we now discussed a concrete approach to tackle the main problem. In doing so, we also finished the second phase of the MPSM, formulating a problem approach. A summary of the research approach per RQ is as follows. The analysis of the current situation is built upon interviews and observations. The current production system is modelled in simulation software to be able to perform a simulation study. By means of different scenarios and interventions related to factory layout, intralogistics, and demand and production (planning), a thorough what-if analysis is performed. The Smart Industry concept is incorporated by assuming that all production lines are fully automated and supported by Automatic Guided Vehicles (AGVs) supplying raw materials and carrying away finished goods. Finally, based on the stakeholders' preferred KPIs, recommendations are made for a new intralogistics system.

3 Case study

In this chapter, we investigate the current way of working at Flamco Bunschoten. The system as a whole is explained. Next to that, all production lines and processes are discussed. We also elaborate on the planning and control within the manufacturing environment as this forms the connection between the separate processes and is a vital part on which we do research. To finalise, we establish a zero performance of the system, that is, how the system currently performs in terms of effective and efficient intralogistics. Some parts of the system might be discussed rather extensively anticipating on the fact that we model the system in some way afterwards.

3.1 The plant

In this section, we elaborate, on a system level, on the current manufacturing site of Flamco in Bunschoten.

As can be seen in Figure 7, the current production plant at Flamco can be divided in three parts, i.e., two warehousing areas (for incoming and finished goods) and a production area, each indicated by a purple rectangle.

The warehousing area for finished goods consists of a finished goods warehouse and a loading area. The expedition department is responsible for the in-time retrieval of finished goods from the warehouse such that they can be loaded onto a scheduled truck that drives to the customer. This can either be a direct transport to a large (OEM) customer or an indirect transport to a Flamco facility in mostly other European countries.

At the top of the facility, raw materials are brought into the factory. The area indicated as incoming goods represents the doors through which components are supplied to production. Incoming goods are received and stored in hall 15 and 16, which are adjacent to the production halls.

The production area consists of three main production lines:

- Bandvatenlijn (BVL), i.e., a production line that produces standard consumer expansion vessels;
- Middelgrote vaten lijn (MGV), i.e., a production line that produces large and medium sized vessels;
- OEM lijn (OEM), i.e., a production line that produces vessels for companies that produce boilers.

In addition, there are a number of (supporting) production areas:

- Air+Dirt job shop (Air+Dirt), i.e., a production line that manufacturers products for degassing and dirt separation of piping systems (e.g., heating systems, cooling systems, sprinkler installations, et cetera.);
- Rondellensnijlijn (RSL), i.e., a machine that cuts large coils of strip steel into metal discs (in Dutch: *rondellen*), which are then used to produce expansion vessels;
- Klemringenwals (KW), i.e., a machine that produces clamping rings (in Dutch: *klemringen*) from a small coil of strip steel, which are then used to produce expansion vessels;
- Stamping, i.e., an area with stamping machines that produce, e.g., mounting brackets for piping systems. However, this last group of machines is (planned to be) moved to a subsidiary company in Germany, so we do not explain this production area any further.

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Figure 7: Current factory layout Flamco Bunschoten

The most important production line produces the standard consumer expansion vessels (in Dutch: *Bandvatenlijn*, BVL). In Figure 7, it roughly occupies the area indicated in red. For all novices, basically every expansion vessel, whether it is placed in a residential or industrial building, uses the same principle to fulfil its function. The principle is fairly simple. In a closed heating or cooling system, a certain amount of fluid (mostly water, sometimes an anti-freeze mixture of water and up to 30% glycol) circulates with the help of a pump through the boiler/cooler and a bunch of pipes, radiators, et cetera. Due to the heating or cooling of the fluid, the total volume of the fluid varies continuously, i.e., the higher the temperature, the larger the volume. As (steel) pipes are rigid, the volume expansion (in case of heating) is controlled by an expansion vessel. If there would not be a possibility to expand (facilitated by an expansion vessel), the system would collapse. An expansion vessel, as shown in Figure 8, consists of a water side and an air side; the two sides are separated by a non-permeable rubber diaphragm. The water side is connected to the piping system via a so-called water nipple, and hence, can contain water. I.e., water can stand in the rubber cup-shaped diaphragm, see Figure 8. The air side is filled and pressurised with air or nitrogen via an air valve. The fact that the diaphragm is flexible means that it can facilitate the expansion and contraction associated with the volume changes in the system. Figure 8 also clearly shows that the water and air side both have their own vessel half in which the diaphragm can freely move up- and downwards. As the vessel is pressurised, the two vessel halves need to be airtight. To achieve this, the two vessel halves are clamped onto each other using a clamping ring. Figure 9 gives an impression of how an expansion vessel is finally assembled when all input components (e.g., coated vessel halves, clamping ring, and diaphragm) are manufactured. In Figure 10, an impression of the production line is given.

Figure 8: Standard consumer expansion vessel (18 litres)

Figure 9: Impression of the final assembly of a standard consumer expansion vessel

To summarise, the BVL is fed with discs, which are turned into vessel halves that are coated, painted and clamped onto each other using a clamping ring. To fulfil its function as expansion vessel, a diaphragm is placed in between the vessel halves, just before clamping. The obviously non-permeable diaphragm separates the water half from the air half and allows expansion when eventually hot water will raise the pressure in the vessel. Further explanation and more (technical) details on the production processes can be found in Appendix A.

Figure 10: Impression of the Bandvatenlijn (BVL)

Strongly connected to the BVL are the machines that manufacture discs (in Dutch: *Rondellensnijlijn*, RSL) and clamping rings (in Dutch: *Klemringenwals*, KW), as those are two vital inputs to make an expansion vessel (recall Figure 9). In Figure 7, the RSL and KW are referred to as the dark red areas within the BVL area. Figure 17 and Figure 18 give an impression of the in- and output of the two machines.

The second large production line, coloured in blue in Figure 7, is manufacturing medium and large size vessels (in Dutch: *Middelgrote vaten lijn*, MGV). Due to their size, no clamping ring can be used to mount the vessels halves and fix the diaphragm, instead the three vessel parts are welded together. The diaphragm is put between two rings inside the mantle, which are thereafter welded onto the mantle to fix their position. Similar to the

Figure 11: Impression of the Middelgrote vaten lijn (MGV); a) rolling mantles, and b) coating

BVL, vessels are coated and painted, after which they are finished off to fulfil their duty as expansion vessel or automat in for example a large building. See Figure 11 for an impression of two parts of the production line.

Left from the MGV, the Original Equipment Manufacturer (OEM) production line is responsible for producing smaller size expansion vessels that will end up in a boiler of a central heating system. The area for this production line is marked in green in Figure 7. Clamping rings for these vessels are also produced on the KW. An impression of the line is given in Figure 12.

Figure 12: Impression of the almost fully automated Original Equipment Manufacturer line (OEM)

Another production line or area, represented by the violet area in Figure 7, is considerably smaller and manufactures equipment for deaeration and dirt separation instead of expansion vessels. We therefore denote this production line by the abbreviated name Air+Dirt. Air+Dirt products are powder coated in the same machine as where the MGV vessels are treated.

Lastly, there are storage areas reserved for temporary storage of Raw Materials (RM) and Work In Process (WIP), e.g., cartons, wooden boxes, coils and plates of steel, discs, vessel halves and clamping rings are stored here on pallets or in gitterboxes.

The plant is open 24/7. There are three shifts. A dayshift from 7:00 until 15:00, an evening shift from 15:00 until 23:00 and a nightshift from 23:00 until 7:00 (next day). If a production line produces only two out of the three shifts, the dayshift will be from 6:00 until 14:00 and the evening shift from 14:00 until 22:00. Around the clock production is normal during the week. Weekends tend to be free, provided the possibility of working in overtime, which occurs often during high season (October – February). Even though production sometimes goes on in the weekends, goods are only shipped and received during the five working days. Every Wednesday morning there is plant wide scheduled maintenance from 9:00 until 12:00. All production lines stop producing; some operators clean the factory and some assist technical operators performing the necessary maintenance tasks at the machines. To conclude, we show the current capacities per production line in Table 2.

Table 2: Plant capacity overview

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3.2 The demand side

In this section, we discuss the products sold by Flamco's international sales force, thereby focussing on the expansion part of the product portfolio. Also, historical sales figures and demand patterns are discussed.

The demand side of Flamco consists of a worldwide set of customers. Large customers are, e.g., wholesalers and installation companies active in the building industry or OEMs active in the HVAC industry, e.g., producers of boilers. From houses to office buildings to skyscrapers to any other kind of facility, every one of them could potentially make use of Flamco equipment, as any building needs climate control - either heating or cooling or a combination of both. Hence, in any building, existing or to be build, there is potentially a need for Flamco products.

By far, the most important and well-known Flamco product is the expansion vessel. The vessels with the largest sales are those of 18 and 25 litres, which are the common sizes for households in The Netherlands and Germany respectively. These can be viewed in Figure 13. In Germany, it is also common practice that expansion vessels regulate the pressure in sanitary systems. As these vessels are placed in drinking water systems, water may never come to a standstill, as this gives bacteria the chance to grow thereby worsening the water quality. A water standstill is prevented by a plastic propeller-shaped blade.

Figure 13: Dutch 18 litres expansion vessels (red) and German 25 litres expansion vessels (white)

In theory, expansion vessels could be made much smaller for normal households. However, a smaller vessel means more diaphragm movements, which shortens its lifetime. In addition, the lower the system pressure, the safer the system. European safety regulations prescribe a safety valve with a pressure of at most 3 bar; all systems that do not comply with this need to be regularly checked by the authorities. Nevertheless, for small water circuits, smaller expansion vessels exist and are sold by Flamco. Examples are 8 litres vessels and OEM vessels, of which the latter are directly mounted into a boiler; an example can be seen in Figure 14a.

Figure 14: a) an example of an OEM expansion vessels, and b) an example of a large expansion automat

In contrast to small expansion vessels, Flamco also sells products tailored to much larger (industrial) heating and cooling systems. A classic example would be an expansion automat in a cooling system of a large building in the Middle East. In such cases, not only the size of the building matters, also the fact that the expansion automat is placed in a cooling system plays a huge role. As the difference between the outside temperature and the system water temperature is much bigger in heating systems than in cooling systems, one can imagine that cooling down a building one degree Celsius requires much more 'relatively warm' cold water than one would need when heating up that same building one degree. And because more water in the system means more water capable of expanding, one needs a larger expansion vessel or automat. Figure 14b shows such a large expansion vessel that is manufactured on the MGV line, and subsequently turned into an expansion automat in the production facility in Wijhe, The Netherlands.

To give the reader some rough idea about the sales magnitude, Table 3 provides an overview of some important products produced and sold by Flamco (Bunschoten). We already mentioned that Flamco operates in a Business-to-Business (B2B) environment, but most of Flamco's end customers are households, i.e., more like Business-to-Consumer (B2C). Namely, if one's heating system fails on a winter day, one usually wants it fixed by the time it is dark. Logically, similar thoughts are going around in the installers' sector. And hence, even though installers keep a safety inventory of expansion vessels, installers generally do not like to wait for the product they need. As a result, Flamco uses a make-to-stock strategy to guarantee short delivery times.

Table 3: Sales overview

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Having a strategy that aims to keep inventory of every product to keep the customer happy does not necessarily mean that supply always perfectly meets demand. Generally, customer demand is hard to predict. Some products show a clear demand pattern with a seasonality effect, whereas others have so-called lumpy demand curves. Nevertheless, it is claimed that the autumn and winter period are high season and spring and summer are low season, which is logical if you consider the (European) weather conditions. To be more specific, demand is substantially higher from the end of September until the middle of February, even though in recent years the trend seems to be that demand stays longer at a high level, i.e., until the middle of March.

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Figure 15: Demand curve over the past 5 years (BVL)

To support our statements, Figure 15 shows the aggregated demand curve for all BVL expansion vessels produced and shipped in the past 5 years. The seasonality effect is clearly visible. Note that backorders occur on an article level, which means that a positive inventory balance, which is maintained throughout the years, does not necessarily mean a good delivery performance.

Figure 16: Finished goods; impression of the finished goods warehouse in Bunschoten

3.3 The supply side

In this section, we discuss the way materials are sourced within Flamco.

The supply side of Flamco is organised fairly straightforward, which is logical for a medium sized company with relatively straightforward products. A purchasing manager leads a team of (strategic) purchasers that purchase based on the planned production orders and the purchasing requests that are automatically generated by the SAP ERP system, i.e., a MRP II run. The strategic purchasers collaborate with the departments Product Management (PM) and Research and Development (R&D) to make sure new contracts are closed for newly introduced parts that are not yet being purchased. The purchasing department accounts for around x FTE in total. Obvious examples of goods that are purchased regularly are steel and diaphragms. Speeding up supplies is not a common practice; the sales force (and the Customer Service department) is encouraged to respect the earliest delivery date given by SAP when selling products to customers. Of course, this does not always hold and works that way in practice. Actions might be taken when production schedules become infeasible due to a lack of raw materials.

Figure 17: Raw materials; from left to right: steel for discs, mantles and clamping rings

Incoming goods are stored in a raw materials warehouse, which is located in a different hall than, but very close to, the production plant. Within the plant, a significant area is dedicated to the (temporary) storage of raw materials and WIP. Materials that occupy most space are diaphragms, steel, components related to fixing technology and packaging materials. With steel we mean coils, discs, plates, vessel halves, covers, clamping rings, and other smaller and often slow moving supplies. Figure 17 and Figure 18 show some of the materials present in the storage area within the factory.

Figure 18: WIP; from left to right: discs, clamping rings and vessel halves

Raw materials are retrieved by forklift drivers that are either material handling personnel or operators with a license. Supply is self-regulated based on the detailed production planning, which is provided by the production planner. Normally, this detailed production planning is dispatched to production 48 to 24 hours in advance, ignoring of course exceptions and last minute changes. Most important for production to know is when they need to do a setup, i.e., changing vessel size and/or vessel colour. This might be communicated directly to production instead of through the production planning.

Replenishment of goods is done when an employee sees that a pallet or box is (almost) empty. Hence, stock monitoring at production lines is only a matter of visual control. Replenishment quantities are dependent on and mostly equal to the specific unit-load amount. For example, if it is standard to have hundred cartons on a pallet, a pallet of hundred cartons is placed next to the line. No repacking is performed whatsoever.

3.4 The production planning

Now we have discussed what the production floor looks like, where demand originates from, and where materials are sourced, we start explaining the part of operations that Flamco can influence the most, i.e., the production planning. The fact that Flamco can dictate for itself what happens in production means that making changes is easier and process improvements (supported by quantitative evidence) could be directly implemented. Therefore, we expect the research effort to pay off when we address this part extensively. In addition, when one would model the production system, the production planning and process are major model inputs.

Hence, in this section, we elaborate on the production planning process, executed by the production planner of the supply chain department. In the first section, we discuss the planning process in a broad sense. The second section, we zoom in on the actual procedure that is followed by the production planner. The last section discusses the main trigger to produce (and hence, plan production), i.e., Flamco's stock policies – based on customer demand (forecast).

3.4.1 Planning process

Flamco uses a make-to-stock policy. To meet demand as good as possible, the production planning has been split in two parts: a rough-cut production planning and a detailed production planning. The rough-cut production planning has a fixed and rolling planning horizon of six weeks. This means that every week, the rough-cut planning is incremented with one week (i.e., the rough-cut week planning for over six weeks) and communicated via SAP. As illustrated in Figure 19, the rough-cut planning takes all important prerequisites for production into account, i.e., planning history, current stock levels, demand forecasts, available production capacity, availability of raw materials, and major line setups. As a result, this (rough) production schedule can be viewed as the backbone of the actual production planning, which will be dispatched to the production floor in a later stadium. In practice, the rough-cut planning consists of a set of planned production orders in SAP containing a series of final products and their planned production quantities (based on forecast and available capacity). Based on this and the product BOMs, SAP generates so-called purchase requisitions (i.e., suggested purchase orders by SAP that are based on a MRP II run and still need to be manually approved), upon which all raw materials are purchased by the purchasing department.

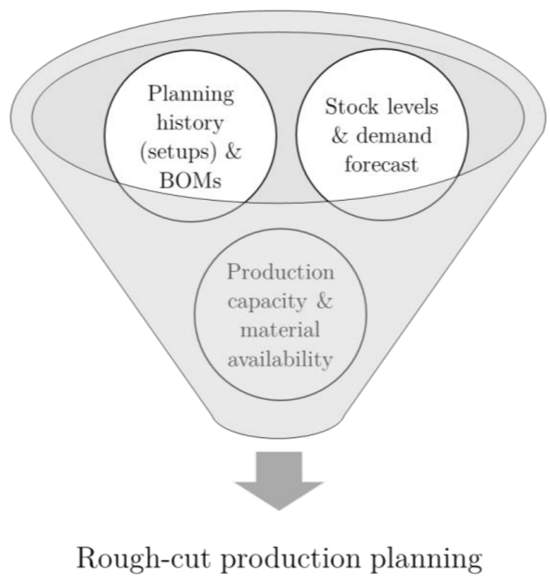

Figure 19: Illustration of the rough-cut planning

Hence, the planning process (for the rough-cut planning) is largely a matter of capacity loading; and in addition, the major line setups are determined. The line setups are mostly related to the expansion vessel size and shape. In a planning context this is important, because setups are time-consuming and many final products share the same size and shape (and hence, also share the same tooling). For the BVL and OEM line, changing the size and shape of the expansion vessel causes a change of punch (in Dutch: *stempel*) or tool, which is needed in the deep drawing machine (in Dutch: *dieptreklijn*, DTL). For the MGV and Air+Dirt line, a different vessel size (often indicated by its diameter) causes a need for changes in the machine settings of the lathe. More information on setups is given in Appendix B.

The fact that many final products share the same size and shape means that they can be clustered in so-called product groups; a list is provided in Table 4. In these product groups, often only the material thickness, colour, carton, accessories, and/or air half pressure, vary over the different articles. Consequently, many (purchased) raw materials are shared amongst final products. Knowing that the rough-cut planning already determined how much will be produced of each product (group), this yields the opportunity to fine-tune the rough-cut planning (on the level of a single article) at the last moment.

Table 4: Overview of product groups per line

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Evidently, the opportunity of fine-tuning the rough-cut schedule is utilised and as a result, a week in advance, the production planner makes a detailed planning. Due to the fact that at this point in time more information about demand realisations is available, the planner can now better estimate for which final products a shortage is likely to occur. This results in a situation where, based on experience, sales information, and limited by recent developments (production standstills, supply delays, etc.) and the choices made six weeks ago (in terms of material thickness, colour, etc.), the planner tweaks the production schedule, such that the expected "optimal" product mix is produced. Once the detailed planning is known, it is communicated with the production team leaders. Also, a copy is dispatched to production at least a day in advance, such that the supply of raw materials and preparation for setups can be started in time.

Important to also point out is the fact that the operational production planning at Flamco is a continuous interplay between the planner and the production floor. When downtime or another unexpected disruption occurs on a production line, it is possible that the planning is adjusted (on-line). Logically, urgent matters with high margin products and important customers receive most attention and are the highest incentive to change the production schedule at the last minute. These changes of course also influence the material handling processes, i.e., supply of raw materials.

3.4.2 Planning procedure

Recall that modelling the production system requires a thorough understanding of the production planning. It might seem that up to this point the planning process, as explained in the previous section, is unstructured, but each planning is subject to planning constraints and (unwritten) planning procedures. Logically, these planning constraints (hard or soft) and procedures - often a result of years of experience - are put in place to structure and guide the planning (process). We discuss the planning procedure for the most important production line (BVL) extensively. For the rest of the lines, we briefly discuss the differences (compared to the BVL), as all planning procedures are rather similar. The story is supported by some planning examples from practice.

Across all production lines, the main planning goal is to create a fixed pattern (rhythm) in producing each product group, especially for the fast moving product groups. The *rhythm* is reflected in the rough-cut planning, which fixes the product groups to be produced six weeks in advance. In line with the *Lean* philosophy, benefits of continuously producing a stable mix of products are, amongst others, frequent restocking of a wide range of articles, improved quality and "peace" in production.

Next to aiming for a *rhythm*, batch sizes should be made large enough to take advantage of the learning curve that is claimed to be present every time one starts producing another article on the line. Due to the fact that setting up the DTL (in case of BVL and OEM) or lathe (in case of MGV and Air+Dirt) is a time consuming and precise job, one wants to continue production for a while once the machine runs smoothly. In addition, as both the DTLs and lathes are at the beginning of their production lines, stopping them normally also brings the rest of the line to a standstill. This is something one obviously wants to avoid. To this end, minimum production quantities are also defined in SAP. However, batch sizes of one article should also not be too large, as customers continuously ask for a variety of expansion vessels.

Having said all this, the fact that each production line has its own technical challenges creates a need for a tailored approach. As a result, each production line (BVL, MGV, OEM and Air+Dirt) has its own set of planning 'rules' tailored to the dynamics of the specific production process.

For the *Bandvatenlijn* (BVL), the planning procedure is as follows:

1. **Determine which product groups are production candidates**
2. **Load the planning (MS Excel) and create planned production orders (SAP) accordingly**
3. **Determine the production sequence**
4. **Determine the detailed planning**

Note that step one, two and three are part of the rough-cut planning, of which an example is given in Table 5. The fourth and last step covers the detailed planning, which is done roughly a week before the planned production date.

The detailed planning is in essence "a plus here and a minus there" in terms of production quantities for final products. The SAP production orders are adjusted accordingly. Evidently, the fine-tuning needs to stay within the boundaries of the raw materials that were anticipated earlier. It could be that, in the recent past, production has not achieved the expected output. In such cases, normally the whole schedule is postponed.

Table 5: Example of a rough-cut production planning for the BVL

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For the *Middelgrote vaten* (MGV), the planning procedure is similar to the BVL. One could argue that the MGV planning is somewhat simpler compared to the BVL, as the number of product groups is smaller, the production capacity is lower and production speed is much lower (due to the size of the vessels). This gives the planner also more time to react if things do not go according to plan.

Generally, the larger the vessel, the slower the production. Some vessels need a flange welded onto it; these so-called *flange vessels* take more time to produce (due to the extra welding step), which is demanding for the operators and also disturbs the flow. Therefore, the maximum number of flange vessels in a batch is set to 70, a value resulting from experience.

For the *Original equipment manufacturer* (OEM) vessels, the planning procedure is also similar to the BVL, except for the fact that OEM vessels generally do not share much raw materials, which decreases opportunities to fine-tune the planning. Fine-tuning here is more a question of when to start and end a batch, as the dynamics of the line are also a bit different compared to the BVL.

As the customers of OEM vessels are (large) manufacturers of boilers, demand is strongly dependent on and dictated by the number of boilers produced and sold. Logically, the rough-cut planning starts with loading these vessels into the planning; thereafter, the others are fit in.

Important to point out is the fact that the OEM line is fully automated and still needs to cope with a wide range of products, i.e., different shapes, dimensions, water nipples, et cetera. This makes the production process rather vulnerable, which is also reflected in the hourly production numbers that are achieved for the different vessels. For the most common vessels, which are produced both frequently and in rather large batches, the production output is considerably higher, as operators get more and more experience in setting up the line and subsequently producing efficiently.

For the *Air+Dirt* products, the first two steps of the planning procedure are similar to the BVL planning; determining the product groups to be produced and the capacity loading. However, after that, other factors come into play. First, the department is organised like a job shop. Second, for some subassemblies production is triggered by a Kanban inventory system. Third, the production itself is allowed to have a high degree of self-organisation. Fourth, Air+Dirt products are coated at the MGV coating line, which means that there needs be room to do so at the MGV line. Hence, the detailed planning is a constant interplay between the production planner and the team leaders of the Air+Dirt and MGV.

3.4.3 Stock policies

The stock policies that Flamco uses strongly influence the production planning. In short, the stock monitoring and replenishment policy are organised as follows. For each final product (a so-called article), a reorder point and safety stock level is determined based on a certain demand forecast. As soon as the SAP ERP system notices that the reorder point is passed, a planned production order is generated. Next, the planner collects all the planned production orders, checks if they fit somewhere in the rough-cut capacity planning, and if so, materialises them by creating production orders in SAP and adding lines to the detailed planning file in MS Excel. Articles that show a planned production order due to real customer demand receive of course priority over articles for which planned production orders are scheduled to replenish safety stock. The lot size to be produced is not always equal to the proposal in SAP. For most articles, an MS Excel file with the sales history of the last five years is consulted to assess if demand is rather stable or lumpy / occasional.

Besides the inventory per article, the total inventory of ready-to-be-shipped expansion vessels is monitored per production line; this is assumed being a good proxy for the inventory levels of individual items. The plant continuously produces a mix of product groups, so the total inventory will probably also cover a large part of the product assortment. Furthermore, it is an unwritten rule in Flamco's business that, even though a delivery appears to be urgent, one most often can stretch out deliveries - let's say for two weeks.

Nevertheless, bottom line is that one should always have a broad selection of products on the shelf. Therefore, Flamco developed over the years an absolute minimum total inventory level for each production line. From experience we know that this point is normally reached somewhere in February, i.e., when high season comes to an end. This also means that during summer inventory is build up to anticipate on the seasonality effect.

3.5 The production

Recall that in the previous section we discussed the planning and control processes and mechanisms extensively. This is not only helpful in understanding what happens in a Flamco factory, it is also key information when modelling or simulating such a system. However, there are more causes to pay attention to. Therefore, in this section, we discuss the remaining yet important issues within production that were not yet covered in the previous sections, i.e., line interaction, downtime, setups and other factors influencing operations.

3.5.1 Interactions between lines

Generally speaking, the production lines are stand-alone, and all production steps are performed in a line process. There are three exceptions in which interaction between lines does occur.

First, the *Rondellensnijlijn* (RSL) cuts discs for the BVL, OEM and MGV line. Based on 14 months of planning history, the division in pallets going from the RSL to a vessel production line is as follows: 87% to BVL, 6% to OEM, and 7% to MGV. Hence, the RSL has a logical location at the beginning of the BVL line - close to the deep drawing machine (DTL) where the discs are eventually used.

Second, the *Klemringenwals* (KW) produces clamping rings for both the BVL and OEM line. Again, based on 14 months of planning history, the division in pallet cages going from the KW to a vessel production line is as follows: 64.5% to BVL and 35.5% to OEM. Paradoxically, in the 14 months before February 2018, the number of clamping rings produced for the OEM was larger than the number of clamping rings produced for the BVL. The explanation for this is that OEM expansion vessels are smaller, and hence, need smaller clamping rings of which larger quantities fit on one pallet cage. Moreover, OEM expansion vessels need two clamping rings per vessel instead of one, which is standard for a BVL expansion vessel.

Third, coating of Air+Dirt and some OEM products is done at the MGV coating line. There are no specific planning instructions in place to fit in the product flow coming from Air+Dirt and OEM. The team leader of MGV simply looks for a suitable moment to fit a batch of those products in, without violating any customer delivery deadlines.

3.5.2 Downtime and setups

Downtime is obviously something one wants to avoid, and hence, Flamco tries to minimise it on all lines. Downtime can occur due to machine failures, setups, and under capacity, which make that planning and maintenance play a crucial role here. Still, it is useful to distinguish between downtime of a machine and downtime of a whole production line, as buffers within a production line could potentially compensate for short breakdowns or temporary speed deficiencies of a single machine. We define *line downtime* as the time that no vessel is coming off a specific production line; this is also what matters most to Flamco. For the OEM and Air+Dirt, the difference between machine downtime and line downtime is nearly zero, because the OEM-line has short cycle times (minutes) and the Air+Dirt is organised like a job shop. The difference becomes significant when one talks about the BVL and MGV line, i.e., cycle times on these lines are significantly longer (hours), mainly due to the time-consuming powder coating process.

As a result, the focus in downtime prevention on the BVL and MGV especially lies on keeping every spindle on the chain conveyor – that guides the vessel (halves) through the powder coating process – occupied with a vessel (half). A series of empty spindles means a gap in the chain conveyor, resulting in a period of no vessels coming off the line some hours after the gap was created. The exact time obviously depends on and corresponds with the processing time of powder coating, which is reflected by the speed of the chain conveyor (the larger the vessel, the slower the chain conveyor). Note that for the MGV, a gap in the chain conveyor could possibly be filled up by a buffer of to-be-coated products coming from Air+Dirt or OEM.

During setups, line downtime is inevitable. To switch from one product to the other, there is always a place in the line where, e.g., machine settings need to be changed, but it might involve more. We elaborate on this in Appendix B, where we also pay attention to the technical origin of different setup activities.

Nevertheless, Flamco continuously searches for ways to decrease line downtime. One method is to try and tactically buffer semi-finished products after the machine that takes the most time to adjust. Then, during a setup, one could add this buffer manually to the line. Normally, buffering is impossible in a balanced line process, but it could be that opportunities to buffer occur due to phased setup activities, a temporarily higher machine speed, machine failures at successive machines, or selectively working in overtime.

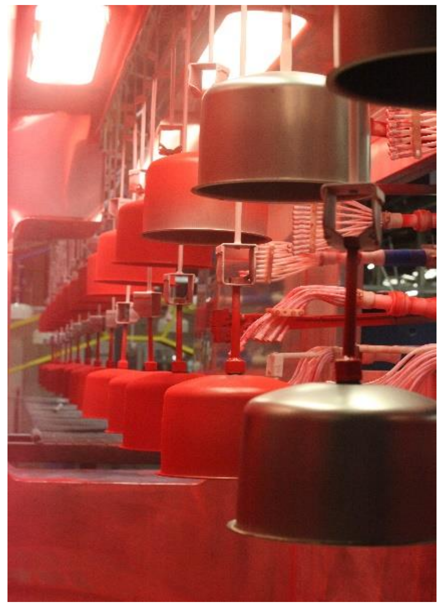

Figure 20: Impression of powder coating process (BVL)

Look for example at the powder coating process of the BVL in Figure 20. One can imagine that the powder coating process for large vessel halves (e.g., 80 ltr) takes longer than for small vessel halves (e.g., 8 ltr). Generally, the smaller the vessel, the larger the hourly production output. As a result, there is a difference in chain conveyor speed when 80 ltr respectively 8 ltr vessel halves are coated, i.e., the speed with 80 ltr vessel halves is lower than with 8 ltr vessel halves. Hence, when changing from 80 ltr to 8 ltr, there is a time period in which the chain conveyor still runs at the speed of 80 ltr vessels, yet all machines preceding the chain conveyor (e.g., deep drawing machine) are changed over to 8 ltr and run at a higher pace. In such a situations, one can either adjust the machine speed or buffer vessel halves outside the line.

As adjusting the deep drawing machine (DTL) is for the BVL the most time consuming activity, it is beneficial to buffer some vessel halves outside the line. A changeover on the DTL takes a factor 3 to 18 times longer than the rest of the setup activities, e.g., due to the fact that a different punch needs to be installed, a welding robot (to weld legs) needs to be configured, or machine settings need to be fine-tuned. Now, a way to reduce the line downtime is to fill the chain conveyor manually with vessel halves, while the DTL is adjusted.

Apart from keeping tactical buffers, one could decrease line downtime by looking at the root cause, i.e., the machine that takes up the largest share in total setup time and the reason it does so. In order to find that machine, one needs to have an overview of the activities that need to be performed during setups and the time they usually take. Note that not all the setup activities are always needed during a setup. Some activities might be only necessary when changing the product group, some might be always needed, i.e., at each change of article. This makes it hard to determine the most critical machine in terms of setup times measured over a period of time. Nevertheless, we address this difficulty in Appendix B.

For now, it is still useful to give a summary of what happened in 2017 on the different production lines in terms of production, downtime, etc. See Table 6. More in-depth analysis can again be found in Appendix B.

Table 6: OEE summary 2017

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3.6 Level of operations' standardisation

Recall that this research is about organising the intralogistics in a smart way, looking also at possibilities to automate processes and incorporate concepts of Smart Industry. It might be then surprising that in this section we point out the lack of standardisation in some parts of the manufacturing operation. Something that obviously raises barriers when it comes to automation and Smart Industry.

The production lines within Flamco Bunschoten can, in most cases, be viewed as transfer lines, in which (prospective) expansion vessels go from one station to the other. In theory, no WIP would be needed in between stations. However, in practice, machines cannot be placed right next to each other, and hence, WIP exists within the line and in between stations to prevent starvation. In situations where blocking of machines might occur (e.g., a successive machine fails), it might be the case that WIP is buffered outside the line. Buffering of semi-finished products happens only for tactical reasons, i.e., to be able to continue producing on (a part of) the line when there is a setup or a machine failure elsewhere.

All production lines are automated to a large extent, which naturally induces standardisation within the production processes. Furthermore, there is a continuous search for further process automation. A recent example is a new robot within the MGV line that automatically hangs an expansion vessel (100 to 1000 litres) onto the chain conveyor, ready to be coated.

When talking about process automation, the hardest production step to automate, is putting the rubber diaphragm between the vessel halves. The elastic character of the rubber makes it hard for a robot arm to properly grab, attach and release the diaphragm. This results in leaking or corroding expansion vessels, as wrongly placed diaphragms allow water to flow in places it is not supposed to flow. Hence, this process will probably remain a manual activity for at least the coming years. Other processes will be more and more automated.

Operators, often employed by an employment agency, are present at production activities that still need to be performed manually. Automated processes are monitored by other operators, which can often monitor multiple machines in parallel. In between their main tasks, operators also perform some of the intralogistics.

In terms of material handling and intralogistics there is very limited standardisation. Handling personnel is supplied with either the production or shipment planning (in- and outbound) and they have to figure out how to get the right material in a timely manner at the right place.

Also, when it comes to unit loads and containers on or in which goods are transported, there is only very limited standardisation. Reasons for this are, amongst others, a lack of information, a lack of coordination and the fact that different actors (e.g., departments, suppliers, et cetera) are involved. This is surprising, because unstandardised packages are generally much harder to handle for machines and robots; and knowing also that machines and robots are designed for a specific (repetitive) task and by definition not as flexible as a human operator. One can imagine that situations in which a machine needs to handle something that is not fully compliant with the specification programmed in the machine could result in speed losses or even machine failures.

In order to illustrate the heterogeneity of containers and corresponding unit loads, Table 7 shows a randomly chosen subset of materials. This heterogeneity obviously complicates the intralogistics, and hence, results in a need for either flexibility or standardisation or both. Automation starts with reliable machines / production lines, which in turn starts with standardised processes.

Table 7: Impression of different materials and corresponding containers and unit loads

Material	Container	Unit load
Coils of steel (discs)	Wooden throw away pallet L	1 roll, 8 a 9 tons
Coils of steel (clamping rings)	Wooden throw away pallet M	1 to 5 rolls, max. 1.5 tons
Discs (BVL and MGV)	Steel pallet	Dependent on thickness of steel
Plates (MGV and OEM)	Wooden throw away pallet L / S	Dependent on the purchasing order (kilos)
Diaphragms	Carton box on Euro pallet (often non-stackable)	Depends on supplier
Cartons	Euro pallet	Depends on carton size and supplier
Expansion vessels BVL	Euro pallet	Depends on expansion vessel size
Expansion vessels MGV	Euro pallet or tailored made wooden cages	Depends on expansion vessel size
Expansion vessels OEM	Pallet cages or customer specific packaging	Depends on customer and expansion vessel size
Scrap metal	Steel container M / L	± 400 kilos / 900 kilos

Last, but not least, the nature of the industry plays a role. Coils of steel are never of the same weight; and it clearly makes a difference if a coil is eight or nine tons of steel. A similar logic applies to other steel products, such as plates, which are purchased externally, but also originate from coils of steel. Hence, the fact that steel is purchased in kilos results in a situation best described in the movie Forest Gump: *"Life is like a box of chocolates, you never know what you're gonna get."*. The fact that coils of steel are hard to handle, makes that it is standard practice to continue production of, e.g., discs, regardless of the production schedule, until the full coil is used.

3.7 Systematic Handling Analysis

Up to this point, we discussed the product, the production system (including details on, e.g., downtime) and the control of the factory (e.g., production planning). We also pointed out that even though Flamco wants to further automate its factory, a certain step in the production process as well as its in- and output needs to be suitable to automate. Nevertheless, regardless of a future factory, we want to know how the system performs today in terms of intralogistics. The method we use to come to a performance is called Systematic Handling Analysis (SHA) and was first introduced by Apple (1972). We provide further scientific context on material handling in Chapter 4. For now, we present the results of our Systematic Handling Analysis (SHA). First, we identify what performance indicators are currently used within Flamco's operations. Second, we discuss the scope of our SHA analysis (in terms of sorts of materials). Third, based on recent historical data, we provide insight into the different material flows and show where currently the most handling of materials takes place. Fourth, we identify the current intralogistics capacity. Fifth and last, we relate the historical material handling workload to the intralogistics capacity to come up with a baseline system performance.

3.7.1 Current performance measurement in Flamco's operations

To date, Flamco measures and keeps track of multiple things in its operations. The 'bottleneck' machine of each production line is linked to an information system that measures the Overall Equipment Effectiveness (OEE). This is basically a ledger in which everything that happens in production is administrated. E.g., at what times the line produced, at what times the line was down due to a setup, or a failure, or maintenance. Also "waiting" for a certain machine is registered when the 'bottleneck' machine is apparently not the bottleneck at those moments in time. The OEE is monitored and discussed during the daily meetings of plant management, supply chain and production. No structural analysis is performed on this data.

Apart from logging what happens in production, Flamco also looks at what happens after. Every week, an overview of the customer backorders is sent to all people that can do something about it, i.e., sales and customer service, supply chain, finance in some cases, and general management. In addition, inventory levels and working capital is monitored by the supply chain manager and the group controller. Evidently, the goals is to minimise backorders, inventory and working capital, while sustaining a good delivery performance. The fact that Aalberts Industries is listed on the Amsterdam Stock Exchange makes that towards the end of the year the importance of low working capital grows, sometimes at the expense of a good delivery performance.

Furthermore, every week Flamco takes stock of how much is products there are produced, how much is shipped to customers, and how much finished goods inventory there is left. Shipments are compared to the budget that was set at the beginning of the year.

To the best of our knowledge, this is what is measured within the production plant and related to supply chain. There is no such thing as a Key Performance Indicator (KPI) for, e.g., intralogistics. Hence, measuring more of the operations' important processes, analysing the resulting data and acting upon it is for sure something that could yield improvements. Note that it is also the exact message broadcasted by the Smart Industry initiative.

3.7.2 SHA scope

On the production floor at Flamco Bunschoten a countless number of different materials can be found. All sorts of (semi) finished expansion vessels, (coated) vessel halves, clamping rings, coils of strip steel, discs of strip steel, plates of strip steel, powder, chemicals, scrap metal, carton, rubber diaphragms, wooden pallets, pallet cages, plastic foil – to name a few. They can be categorised in four categories: raw materials (RM), work in progress (WIP), finished goods (FG), and returns (e.g., empty pallets, scrap metal, et cetera). Addressing each and every material is of course unfeasible, so we focus our research on the materials dominating the material flows (in terms of number of material movements). An overview is provided in Table 8.

Table 8: Overview of materials

Stream of goods		
Category	**In scope**	**Out of scope**
RM	Discs ❖ Discs BVL (in Dutch: Rondellen) ❖ Discs OEM (in Dutch: Platines) ❖ Plates and discs MGV (in Dutch: Vlakke maten en rondellen) Clamping rings Diaphragms Carton Coils of strip steel for Discs	Coils of strip steel for Clamping rings Water nipples Air valves Instruction manuals Accessories Stickers and labels Chemicals for vessel washing Powder for power coating
WIP		Vessel halves
FG	All articles	
Returns	Empty pallets, cages, boxes, etc. Scrap metal	Waste Chemical waste

Note that, before this research project, very little quantitative data was available about the goods flowing through the factory. Hence, also in terms of research effort, it was necessary to smartly choose a scope of materials and gather data accordingly.

3.7.3 Finished goods

In order to quantify the current intralogistics related to finished goods at Flamco Bunschoten, we started a top-down analysis of the production planning history. Looking at the data of all production lines, we found that the largest period for which all lines have historical data is 14 months, i.e., from December 2016 until February 2018. These historical production numbers were combined with other (self-gathered) data to come up with a comprehensive overview of the stream of finished goods that has flown through the factory. In Table 9, one sees the produced quantities, per product group, in both pieces and pallets.

Due to the fact that final products have different physical dimensions, the share that a product group has in the total handling based on pieces deviates from that based on pallets. Noticeable differences between pieces and pallets are present for all production lines. Larger vessels demand more pallets, smaller vessels demand less pallets.

Similar to the BVL line, the MGV line shows a turning point. The explanation also lies in the fact that MGV vessels with a diameter of 790 occupy at least one Euro pallet, whereas vessels with a smaller diameter might be consolidated together on one Euro pallet. Within the Air+Dirt department data was not available nor easy gatherable. Furthermore, as expedition showed that, e.g., 'no. of parts per pallet' are not standardised, we chose to omit the pallet calculation. Nevertheless, a rough estimate can be made by assuming that large diameter products go on one pallet, and, e.g., a DN 65 product is stacked with 4 to 8 on one Euro pallet.

In addition, Figure 21 summarises Table 9 by making a graphical representation, i.e., a Sankey diagram, of the number of pallets per day going from one point in the factory to another.

Table 9: Overview of material flow per product group

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Figure 21: Sankey diagram of the average daily pallet flows of finished goods

3.7.4 Raw materials and returns

Besides the outflow of finished goods, we also have to deal with a product in- and return flow. We view the supplying transport of raw materials (coils, discs, clamping rings, diaphragms, and carton) as a product inflow, whereas scrap metal and empty pallets could be seen as return flows.

Within Flamco, the workload associated with supplying raw materials to the production floor is unknown. Nobody has a quantitative estimate of how many pallets with materials are brought into the factory. In a way, this is understandable, as each final product consumes different raw materials, which are stacked in various quantities onto all kind of different pallets. As a result, one of the main goals of this research is to provide insight in these streams of goods, the relation between product and handling workload and the interaction between lines when it comes to material handling.

There is however an exception. For scrap metal, records are kept, as scrap metal is dropped off at neighbour company Voestalpine Polynorm. Also, coils of steel are picked up there. A trip to Voestalpine Polynorm is estimated to take 20 to 30 minutes, so it is a handling activity worth mentioning. In 2017, a total amount of

2784 bins of scrap metal were administrated throughout on 312 unique working days, meaning almost 9 bins of scrap per day. This total covers the whole factory. However, the Stamping department, which is ignored in this study, also contributes to the total amount of scrap metal, so a minor correction downwards (in the range of a bin per day) would be fair when estimating the 'true' transport frequency for the rest of the plant. Furthermore, it is clear that Flamco does not consume as many coils of steel as empty scrap bins. However, it might be beneficial to pair trips to Voestalpine Polynorm, i.e., drop off filled bins of scrap and take a coil of steel with you on the way back. For practical reasons and to cut the number of trips, bins of scrap may first be buffered at Flamco before a trip to Voestalpine Polynorm is made.

3.7.5 Intralogistics capacity

The number of employees performing the intralogistics within Flamco is known. However, as already mentioned before, suspicions are that numerous people, besides their normal work, perform 'hidden' activities that should be counted to the intralogistics. The current intralogistics capacity, as also defined as such within Flamco, is displayed in Table 10. We call the temporary storage locations in this case Pickup and Delivery hubs (P/D-hubs), because these areas are in practice often used as hubs, i.e., temporary storing materials, cross-docking materials, et cetera. For example, the forklift driver that works in the incoming goods warehouse brings materials to a P/D-hub, where an operator picks them up and brings them to a P/D-point directly at a production line. Note that many P/D-points can exist within a P/D-hub; and, both P/D-points and P/D-hubs reflect an area (in m^2) within the production plant. So, a more intuitive name, we use from now on and captures it all, is *P/D-area*. In P/D-areas, almost any logistical activity can be executed, i.e., materials can be delivered, picked up, (temporarily) stored, stacked, retrieved, handled, turned, consumed, damaged, and left behind.

3.7.6 Baseline system performance

Only the handling workload for the finished goods, i.e., from factory to FG WH and back, could be estimated fairly accurately. Hence, only for this category we can calculate some performance metrics.

Evidently, as this is a very narrow definition of an intralogistics "system" performance, the focus of the rest of our research is aimed at providing insight in the total intralogistics workload, especially associated with all the transportation of the raw materials.

Table 10: Overview of current intralogistics capacity

Type of goods	Origin	Destination	FTE	Remark
Raw materials ❖ Carton ❖ Diaphragms ❖ Plates of steel	Incoming goods warehouse	P/D-hubs at the beginning of the production lines (BVL, MGV, OEM)		Confidential
Raw materials ❖ Carton ❖ Diaphragms ❖ Discs ❖ Clamping rings	P/D-hubs at the beginning of the production lines (BVL, MGV, OEM)	P/D-points right next to the machines		
Tactical WIP	P/D-points right next to the machines	P/D-hub within the factory		
Finished goods	End of the production lines (BVL, MGV, OEM)	Finished goods warehouse		
Totals				

3.8 Conclusion on case study

With this chapter coming to an end, we also end phase 3 of the MPSM, i.e., the analysis of the problem. Research question 1 and all related sub questions are answered. We recall the answers briefly.

Flamco Bunschoten manufactures expansion vessels. This product is built from two discs of strip steel, which are deep drawn to vessel halves. The steel vessel halves are coated to prevent corrosion and to make it an appealing product. In between the vessel halves, a non-permeable rubber diaphragm is placed to fulfil the expansion function later on. The assembly is clamped together using a shiny clamping ring. The product is now almost finished, i.e., a customer specific pre-pressure can be applied and the expansion vessel can run its last (leaking) tests, after which it is packed, palletized and sent away to the customer.

The layout of Flamco Bunschoten consists of a large finished goods warehouse, three large production lines (OEM, MGV and BVL) and a large temporary storage area. Next to that, there are two smaller production departments, i.e., the Air+Dirt department and the Stamping department. The latter is out of our research scope, because it will be moved to a subsidiary company in Germany. Lastly, there is an incoming goods warehouse connected to the facility, where a lot of raw materials are stored.

On the production lines various expansion vessels are produced, which can be clustered in product groups. Each final product (article) has its own raw materials, but within product groups, articles often share some raw materials. In terms of demand, high season is expected to start in September and end in February. The summer is utilised to build up seasonal inventory. During high season, on average, smaller batch sizes of each product are produced to keep every customer happy. This obviously means more changeovers in production, sometimes working in overtime and a continuously changing production planning.

Then, in all the hustle and bustle, it would be helpful if one could fall back in standardised procedures. At Flamco, the production processes are automated to a certain extent, but standardisation in the intralogistics is limited. Yet, when analysing the available and gathered data, it says that a forklift driver takes on average x minutes to drive a full pallet with expansion vessels to the finished goods warehouse – an outcome that seems to be feasible, i.e., at least not completely wrong when one takes into account the average driving speed and distance.

But yet of course, operators and handling personnel drive with a lot more than only pallets of finished goods. Raw materials, work in progress and return flows are also part of the job. As Flamco misses the data and insights on this, our remaining research has a strong focus here.

Apart from the chapter, more detailed information can be found in the appendices A, B, C, and D.

4 Literature study

Now that the case study at hand is described in detail, we discuss in this section the relevant (scientific) literature.

4.1 The context of material handling and intralogistics

In this section, we explain the context of material handling and intralogistics in a manufacturing environment. We explore the area of facilities planning, discuss various related problems, list questions that should be answered and present solution approaches tried by others in similar situations.

Facilities are the entities that provide the necessary physical infrastructure to produce any product or service for the purpose of meeting customer demand. Facilities planning is the part of supply chain and operations management that develops plans for the creation of facilities. Tompkins et al. (2010) stated that historically facilities planning was viewed primarily as a science, but nowadays it has become a vital part of a company's supply chain strategy. As the context of our case study is a manufacturing environment, we focus our discussion on facilities planning in a manufacturing environment.

As shown in Figure 22, the planning process can be split up in two parts: a location related part and a design related part. Determining a facilities location roughly corresponds with answering the question of where to place a facility such that, e.g., the total transport costs or distance required to deliver all customers are minimised. Facility location problems are not in the scope of this research and will therefore be further ignored.

The design component of facilities planning can be further split into three subcomponents: facilities systems design, layout design and material handling system design. Facilities system design covers the development of all structural systems, i.e., the building and all related installations covering building safety, HVAC, lightning and electrical, and sanitation systems. As this is a rather specialised design area with a potentially limited connection to the production processes, it also falls beyond the scope of this research.

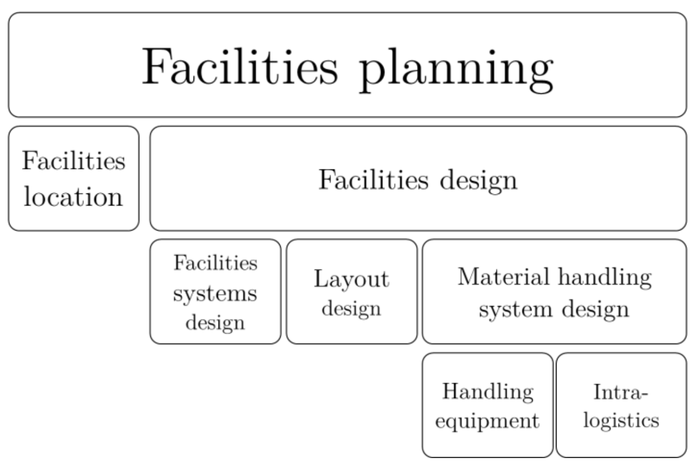

Figure 22: Decomposition of the field of facilities planning

The other two design elements are very closely related: layout and material handling system design. To illustrate, the Facility Layout Problem (FLP), as defined in for example Koopmans & Beckmann (1957) and Y. H. Lee & Lee (2002), has minimizing the total material handling costs as its objective. In general, a facility layout describes the arrangement of everything required to manufacture products or services (Drira, Pierreval, & Hajri-Gabouj, 2007). In addition, a material handling system is the set of mechanisms satisfying all required interactions within a facility (Tompkins et al., 2010). As the arrangement of departments, machines, equipment, etc. determines to a large extent the interactions within a plant, i.e., the material flows and distances travelled, a specific layout often induces a way of handling materials. The fact that material handling is important in the manufacturing business, is illustrated by Frazelle (1986), who states that material handling in a typical industrial facility occupies 87% of the total production time, 25% of all personnel, and 55% of all space in the plant. It is estimated that material handling costs may contribute for 15% to 70% to the total manufacturing cost of a product. A common method to analyse and quantify the material handling in a factory is the Systematic Handling Analysis, first described in Apple (1972) and also explained in Tompkins et al. (2010).

A framework to assist in the development of alternative material handling designs is the material handling system equation, as presented in Tompkins et al. (2010). This framework helps identifying solutions by posing all necessary questions, in a logical and structured way, to eventually end up with a recommended system design that includes the materials to be moved and the means and methods to do this.

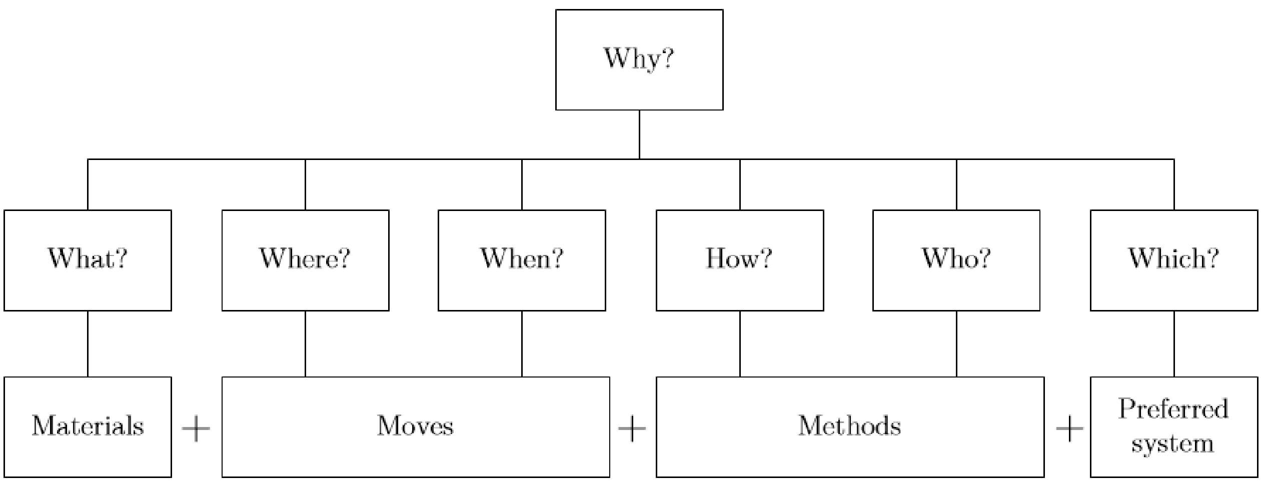

Figure 23: Material handling system equation (Tompkins et al., 2010)

First, one should ask the question why we should handle some material in the first place. In line with the *Lean* philosophy, first applied in the Toyota Production System (Ohno, 1988), material handling could be considered as double waste. Transporting material in itself does not add value, and if one does it inefficiently, it is even worse. Nevertheless, if handling is in a certain situation inevitable, one should address a list of questions that are fully covering and complying with the nine "rights" as pointed out in Section 1.3.

The design process can then be set up in different ways. Rembold & Tanchoco (1994) state that a designer of a material flow system - or similarly, a material handling system - should have one central design workbench on which all supporting (computer-aided) tools are brought together, and hence, can be used synchronously. Talavage & Hannam (1988) and Sharp & Liu (1990) studied the design of a flexible manufacturing system, of which a large part is taken up by the design of a material flow system. In contrast to Rembold & Tanchoco (1994), they proposed a sequential approach, in which the designer starts with a rather abstract model of the system, gradually adding more details based on the increasing (data) requirements of more sophisticated modelling software and tools. This way one advances - step-by-step – from, e.g., a rough cut model to, e.g., a queueing system to, e.g., a detailed simulation model.

4.2 Smart industry

In this section, we explain the concepts of Smart Industry and relate them to the business context of Flamco.

Smart Industry is the international name for what was first called *Industrie 4.0* during its introduction in 2011 in Germany, at the famous Hannover Messe. It comprises a multitude of concepts and corresponding means to achieve a truly Smart and Digital Factory. The infographic in Figure 24 shows in which directions one could seek for improvements. Rüßmann et al. (2015) distinguish nine main groups of technologies and methods.

1. Big data and analytics
2. Simulation
3. Internet of Things (IoT)
4. Cyber-physical systems (CPS)
5. Virtual reality (VR)
6. Cloud computing
7. Cyber security
8. Machine-to-machine communication
9. Collaborative robots

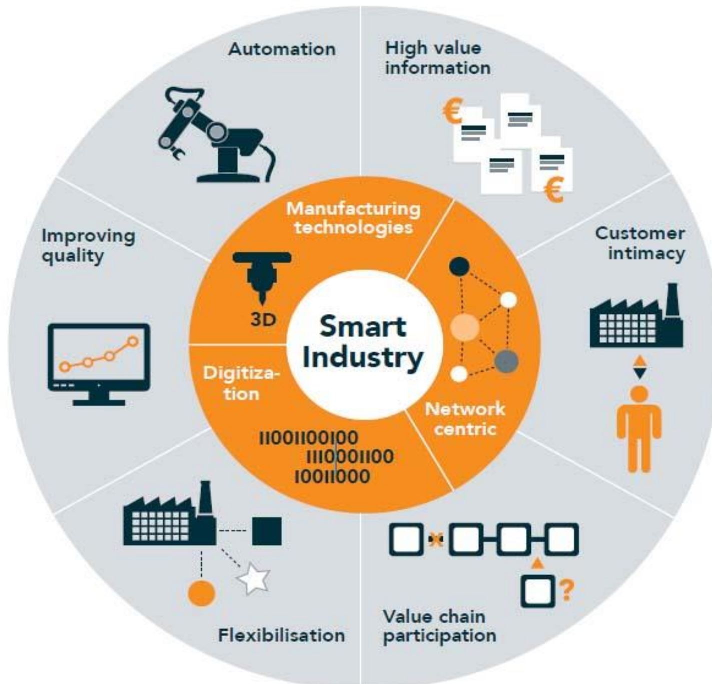

Figure 24: Infographic Smart Industry (TNO, 2018)

Big data and analytics. Business Intelligence (BI) tools and Data Mining (DM) techniques in combination with continuously growing computational power enable us to exploit large amounts of (production) data, which, until recently, has always been a challenge (Babiceanu & Seker, 2016).

Simulation. Modelling (a part of) a production system and thereafter simulating future (what-if) scenarios yields the possibility to anticipate on what will probably happen in the actual physical production system. Two main approaches are identified: scheduling optimisation through simulation and scenario-based simulation (Moeuf, Pellerin, Lamouri, Tamayo-Giraldo, & Barbaray, 2017). In the first approach, simulation is used to generate production schedules online. The second approach uses a simulation model to analyse the impact of different interventions on the production system. Obviously with the aim to improve the system.

Internet of Things (IoT). "A world where basically all (physical) things can turn into 'smart things' by featuring small computers that are connected to the internet." (Fleisch, 2010). A common example of the IoT are the RFID tags that gather useful product data in real time (e.g., for track-and-trace). Another example are temperature sensors in trucks that are used to ensure product quality during refrigerated transport.

Cyber-physical systems (CPSs). CPSs are defined as "The integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.'' (E. A. Lee, 2008). A CPS in a manufacturing environment tries to synchronise and integrate the information of the physical production floor with the information of the digital counterpart, a virtual factory that might go as far as being a digital twin. This allows for automatic real-time surveillance and control of the production process, which potentially increases transparency and efficiency, because of the fact that a CPS can now make smarter decisions based on more and the latest information. The structure of a CPS is defined as "Two parallel networks to control, namely a physical network of interconnected components of the infrastructure and a cyber network comprised of intelligent controllers and the communication links among them." (Parvin, Hussain, Hussain, Thein, & Park, 2013). This simply means that, e.g., machines encapsulate some sort of computational entity (e.g., a sensor, a PLC, a communication device, or otherwise) that is connected to the Internet, making it possible to gather, access and process data (in real-time) of the on-going physical production processes, and act upon it.

Virtual reality (VR). A lifelike scenery generated by a computer, in which an experience that comes close to reality can be simulated. In a manufacturing context, VR can facilitate the visualisation of, e.g., a future factory. Using VR, a new plant layout could be inspected before it is even built, verifying, e.g., the feasibility of robot arm movements, product routings, or storage and manoeuvre space for forklifts and AGVs.

Cloud computing. A paradigm enabling ubiquitous access to shared computing systems and resources, often through the Internet. Working in the cloud allows for, amongst other things, sharing documents, collaboration, distributed production and optimisation of resources.

Cyber security. When linking things to the Internet, to let them communicate and interact with each other, there always is a safety issue. As computers can be hacked, so can smart things, cyber-physical systems and the cloud.

Machine-to-machine communication and collaborative robots. As communication creates the soil for collaboration, they cannot be viewed separate from each other. If one wants to collaborate, some sort of communication will always be needed. In a hierarchal context, communication can be top-down or bottom-up. Top-down communication and collaboration in a manufacturing environment could for example be working according to a centralised production- and or transport planning. However, looking at what Smart Industry offers, one could also organise a factory in a decentralised manner, using bottom-up communication and decentralised decision making. Such decentralised production systems - consisting of many 'smart things' - are often modelled as a Multi Agent System (MAS), see for example (Adeyeri, Mpofu, & Adenuga Olukorede, 2015). In a MAS, one could view every (group of) actor(s) in the system (i.e., a machine, an AGV, whatsoever) as an individual agent that has its own resources, goals and responsibilities. Through communication and negotiation, agents are able to cooperate and achieve goals - both personally and collectively.

In the context of Flamco, still counted as being a Small and Medium Enterprise (SME), Moeuf et al. (2017) showed that cloud computing and the Internet of Things are most often used when initiating a Smart Industry project. These initiatives are often small and stand-alone, i.e., one can rather easily add a smart sensor to a product or a machine (IoT). However, to make Smart Industry tangible, one needs to connect a whole production system thereby turning it into a CPS. This naturally induces, amongst other things, a complex web of interrelations, many (new) links of communication and lots of resulting data - in all kind of different formats. Hence, within a Smart Industry context, one technology cannot go without the other. It is therefore also not surprising that a lack of knowledge and competences within SMEs on (all) these topics is a major obstacle in the adaptation and implementation of Smart Industry initiatives (Evangelista, McKinnon, & Sweeney, 2013). Erol, Jäger, Hold, Ott, & Sihn (2016) also argue that the perceived abstractness and complexity of Smart Industry forms a barrier to put it into practice.

Many technologies and methods are also related to our research: (big) data analytics, simulation, the Internet of Things, cyber-physical systems, machine-to-machine communication and collaborative robots seem to be the most promising technologies and methods. Virtual reality could also enrich the research, provided that one also has the experience and resources to incorporate it successfully in the project. In the context of this research, one would need (experience with) 3D scanning equipment, which is not the case. The topics of cloud computing and cyber security clearly fall beyond the scope of this research.

4.3 Simulation

In this section, we discuss simulation as one of the main technologies used in the context of Smart Industry. With the context of our research in mind, we define simulation, explain the different types of simulation, and elaborate on other relevant elements of simulation such as model design and experimental setup.

Starting from the desire to understand a (production) system and its performance, there are various techniques to do so. Simulation is one, analytical models or experimenting in reality are others. However, simulation is a broad concept, as today nearly anything can be simulated. In the context of our research, various types of simulation come to mind, such as Discrete Event Simulation (DES), System Dynamics, Agent-based simulation, and Monte Carlo simulation. However, instead of immediately jumping to a suitable method, it is valuable to provide some background on simulation. A logical starting point is of course a definition. In the context of this research a commonly used definition of simulation is that of Shannon (1975), which defines simulation as follows.

Simulation *"The process of designing a model of a system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system."* (Shannon, 1975)

Important components of this definition are model design, the fact that experiments are conducted, and the eventual goal, i.e., to provide insight in the system or to improve the system by applying smart strategies.

Model design. Talking about the first important component of Shannon's definition, i.e., model design, one should first determine which kind of simulation is appropriate, i.e., tailored to the system properties and goals of the simulation study. In this context, it is important to know that a system is usually described by so-called states. A state is generally defined as *"A collection of variables necessary to describe a system at a particular time."* (Mes, 2017a). Having said this, Law (2014) distinguishes different types of simulation models on the basis of three opposites.

- Static versus dynamic: Static models show a system state at certain point in time, whereas dynamic models show a system that changes its states over time.
- Deterministic versus stochastic: Deterministic models do not contain any randomness / stochasticity, whereas in stochastic models the system can be viewed as a random variable that in turn consists of a set of random variables each having their own random input.
- Discrete versus continuous: In continuous models, the system state changes continuously, whereas in discrete models this only happens at discrete points in time.

In the context of our research, Dynamic Stochastic Discrete Event Simulation (DSDES) seems to be the logical choice in terms of simulation type, as we consider the intralogistics in a production system, which is in essence a complex queueing system, both dynamic and full of stochastic elements. Robinson (2014) supports this claim saying that *"Discrete-event simulation is used for modelling queueing systems"*. Furthermore, many researchers have been using DES in a manufacturing and supply chain context (Hao & Shen, 2008; Negahban & Smith, 2014; Terzi & Cavalieri, 2004).

DES works with discrete events, i.e., state changes at discrete points in time. In between events, the time can be skipped, as 'nothing' happens. In our context, examples of events are an expansion vessel leaving a production line or a machine failure in the production line. Note that state changes (events) can be state dependent or state independent. For example, a product might be added to the production planning regardless of the current status of the production, and hence, is state independent. On the contrary, a state dependent event is, e.g., an expansion vessel coming off a production line, as this obviously depends on the performance of that same production line and all related supporting activities. Stochasticity in the system expresses itself for example when it comes to failure behaviour of production lines, as this generally has a random character.

Conducting experiments. The second part of Shannon's definition of simulation points out that conducting experiments is the means to understand a system and evaluate strategies to improve the system's performance. Conducting experiments may sound straightforward, yet it can be done in many ways, which is also illustrated by the fact that experimental design in itself is a research area, i.e., Design of Experiments (DOE). As a decent experimental design is situation dependent, we discuss this in section 5.3. Nevertheless, there are some common experimental design, which we discuss here. In addition, an experiment in simulation is in essence a statistical experiment, meaning that the output should treated as a random variable. Hence, we also express the value of a certain output factor using a confidence interval. But, a wide confidence interval may not learn us too much. So, we need a method that makes sure we end up with simulation results that are useful and tell us something. This, we also discuss underneath.

First, back to the methods to create an experimental design. Suppose we have 3 factors we want to experiment with. Each factor has a range of levels, respectively range1, range2, and range3. A logical next step would be to choose and simulate everything. This is called a *Full Factorial Design* yielding a total number of experiments equal to NrExperiments = range1 * range2 * range3. In addition, one gets all interaction effects between the factors, i.e., the value of factor1 might have an influence on the value of factor2.

To cut the number of experiments and save computation time, one could execute a *Fractional Factorial Design* of which a *2k-factorial design* is most common. In a 2k-factorial design, one only simulates the highest and lowest level for each factor. This yields 2^n experiments, which is already significantly less, still holding onto the most important interaction effects. Note and be careful about the fact that the main effects of a 2k-factorial design are based on linear relations, which might lead to disastrous conclusions. E.g., when a system's utilisation goes to 1, the waiting time explodes (Little), which is definitely nonlinear. To decrease the chances of falsely assuming a linear relation between the highest and lowest factor level, one should take those values not too far apart. If a 2k-factorial design suggests the optimum to be somewhere in the middle, one can use, e.g., a genetic algorithm / simulation optimisation to search and quickly go in the direction of the system optimum.

Another obvious way of experimenting is using the *one-factor-at-a-time* (OFAT) method. That is, one uses a default - maybe smartly chosen - start scenario, vary factors one-by-one and choose per factor the best level from a range of values. This way, one has a number of experiments equal to NrExperiments = range1 + range2 + range3 – 2. However, one does not get a hand on the interaction effects, while factors may still depend on others. To give an example in the context of our research, a fixed SupplyInAdvanceTime of, e.g., 24 hours might induce a (minimal) vehicle fleet size, whereas there could be a better combination of the two possible.

Now, talking about simulation output being a random variable. In a non-terminating simulation, the simulation run length and the number of replications are correlated. As stated by (Mes, 2017b), the simulation output, i.e., a set of predefined Key Performance Indicators (KPIs), is a complex function of the simulation input. As there normally is uncertainty in the input of the model, reflected by random input variables, the simulation output has a random character as well. This means that the KPIs can be viewed as random variables. As a result, each simulation run / replication provides a point estimate for each KPI. A confidence interval (CI) then gives an idea of the bandwidth in between which the KPI point estimates will lie with a certain probability. E.g., a 95%-confidence interval (95%-CI), obtained by executing multiple replications, then reflects the bandwidth in between which a new KPI point estimate will lie with a probability of 95%. The general formula for a CI in which the variance of the KPI is unknown, is as follows:

$$\left[\bar{X} - t_{n-1,1-\frac{\alpha}{2}}\frac{s}{\sqrt{n}}\,,\bar{X} + t_{n-1,1-\frac{\alpha}{2}}\frac{s}{\sqrt{n}}\right]$$

In which

$$\bar{X} = sample\ mean$$

$$t_{n-1,1-\frac{\alpha}{2}} = t\ value\ from\ the\ Student's\ t\ distribution\ with$$

$$n-1\ degrees\ of\ freedom;\ n = number\ of\ replications$$

$$1-\frac{\alpha}{2}\ significance\ level\ one\ tail;\ \alpha = significance\ level\ of\ the\ CI$$

$$s = sample\ variance$$

Hence, there are two ways one could narrow the confidence interval: 1) extend run length such that the sample variance (s) decreases and as a result the sample mean ($\bar{X}$) flattens out, and 2) increase the number of replications (n).

However, there is more than only the width of the confidence interval, as the acceptability of this width also depends on the size of the sample mean. Suppose a CI-width of 100. In case the sample mean is 100, this means a CI of [50, 50], whereas when the sample mean is 1000, we end with a CI which is equal to [950, 1050]. The latter is obviously much better. For this, we have the so-called relative error (γ). In simulation, we aim for a CI that is, relatively to the average, sufficiently small. That is,

$$\frac{t_{n-1,1-\frac{\alpha}{2}}\frac{s}{\sqrt{n}}}{\bar{X}} < \gamma'$$

where $\gamma' = \gamma/(1+\gamma)$.

However, Law (2014) states that one should perform at least five replications; and if one performs less than five replications, one should either decrease the run length or show that, regardless of the number of replications, the relative error stays below the threshold. This is because one could be ‘lucky’ having two subsequent replications showing similar results, and hence, yielding a low relative error suggesting that one could stop. Yet, the third replication might show different results, which could potentially increase the relative error to an unacceptable level. To tackle this issue, one should plot how the relative errors of the KPIs behave over the replications, and draw conclusions on the number of required replications accordingly.

Scenarios, interventions and strategies. The third and last part of Shannon's definition of simulation is about evaluating scenarios and strategies, i.e., coming up with smart plans and rules to intervene in the simulation with the aim to improve the system's performance. Sabuncuoglu (1998) confirm that improvements in manufacturing productivity are not only due to technical innovations, but also the effective and efficient usage of advanced systems through control algorithms plays a role. Doing things the smart way is of course a broad statement; and, smart strategies can be applied in various areas of the simulation. Still, we distinguish between two categories, i.e., scenario-based simulation and improvement strategies.

Firstly, there is scenario-based simulation, which is more or less self-explaining. Interesting examples can be found in, e.g., the construction business (Zeng, Dichtl, & König, 2017). However, also more in our field of study, layout planning, scenario-bases simulation is used (Dombrowski & Ernst, 2013).

Secondly, there are the countless number of improvement strategies. Within simulation, researchers try to optimise (or at least improve) their chosen KPIs in many ways.

One improvement strategy is to do nothing smart in the system itself, but simply simulate everything and pick the best. This is possible for small systems, but problem formulations tend to grow quickly, which makes that the strategies to search and find the best option become the creative and smart part of the research. Examples of techniques one could think of are, e.g., Simulated Annealing (SA), Tabu Search, and Simulation optimisation / Genetic Algorithms.

On the contrary, literature also shows tons of papers claiming to do something smart within the system / simulation. To make things concrete and related to our research, we kindly refer to an extensively studied example, e.g., dispatch rules for AGVs to enhance the intralogistics performance in, e.g., a Flexible Manufacturing System (FMS). To sketch some example background, we provide a definition.

Definition *"A Flexible Manufacturing System (FMS) is an integrated, computer controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium sized volumes of a variety of part types"* (Browne, Dubois, Rathmill, Sethi, & Stecke, 1984)

Reading the definition of a FMS, the question remains what medium size volumes are. Chances are that Flamco produces for the most part high volume articles in a line process instead of a job shop setting, which makes the intralogistics improvement solutions (i.e., priority rules and strategies) provided for FMSs less suitable for our research. Still, the rules might be useful.

Sabuncuoglu (1998) lists a number of studies that use different 'smart rules' in combination with simulation. In, e.g., Sabuncuoglu & Hommertzheim (1992a, 1992b, 1993) various of what they call AGV scheduling rules are tested in an FMS. We list a few of them:

- First Come First Served (FCFS): Transportation job that arrives first, gets assigned to an AGV;
- Longest queue size (LQS): The transportation jobs related to the station with the largest queue get assigned to an AGV first;
- Shortest travel distance (STD): The transportation job that is closest to the current position of the AGV gets assigned first to that particular AGV;
- Least work remaining (LWKR): The transportation job for a material that has the least process steps left to perform, gets assigned to an AGV first.

Note that all rules are rather basic, yet exploit different types of information. FCFS uses the time aspect, LQS uses (dynamic) queue information, STD uses layout information, and the LWKR rule uses information about the primary process that is supposed to be supported by the AGV movements.

4.4 Conclusion on literature study

With this section, we have come to the end of our literature study, thereby handling research question 2 and 3. We discussed the context of Facilities Planning, the Facility Layout Problem (FLP) as the most dominant research problem in the field, and how intralogistics - as a part of material handling – complements to it. Furthermore, we pointed out the concepts of Smart Industry, their innovative character and disruptive abilities. Knowing that Flamco wants to proceed in the direction of Smart Industry, we tried to connect the concepts to our research, finding in, e.g., simulation a suitable concept. Simulation as a research method has been explained. We started with stating the definition of Shannon (1975), which we thereafter decomposed into three stepping stones: model design, conducting experiments, and scenarios, interventions and strategies. We frankly discussed all three parts to see what could be of further use, e.g., in the model building process.

5 Solution design and model construction

In this chapter, we discuss the solution design that should eventually yield a solution, i.e., the provision of relevant advice regarding Flamco's intralogistics based on quantitative evidence resulting from a discrete-event simulation. We start with describing the model on paper, irrespective of the software implementation. This so-called conceptual model covers all relevant aspects of the system we are modelling and also addresses the fact that a model will always be a simplification of reality. In order to produce quantitative results, which are also statistically meaningful, we then discuss our experimental design. Lastly, we thoroughly reflect on the soundness of both our simulation model and experimental design - making sure we perform a valid analysis.

5.1 Conceptual model

In this section, we describe all aspects of the conceptual model. First, we give a broad model outline to introduce the reader to the simulation model. Second, we describe the level of detail of the simulation model, which is to a large extent implied by the research objectives and scope as defined in Chapter 1. Next, we address the in- and output of the simulation model as well as the accompanying assumptions and simplifications. Finally, we present some process- and logic flowcharts to help one visualising the model logic.

5.1.1 Model outline

In this section, we broadly describe the simulation model.

The simulation model, of which an impression can be seen in Figure 25, tries to mimic the daily operations of Flamco Bunschoten, especially the internal logistics processes.

In short, the model displays the production floor with production lines that produce full pallets expansion vessels. Obviously, pallets with raw materials are needed during the manufacturing process. All transportation related to these pallets going from and to the production lines is done by vehicles (depending on the scenario considered, either forklifts or AGVs). Vehicles can move throughout the factory by means of tracks. The transfer of a pallet from a vehicle to a production line (or vice versa) is done through a temporary storage location, a P/D-point.

Recall that this research focuses on the transportation part rather than the production part. However, one cannot go without the other. As a result, the model consists of a production system, an intralogistics system and the interactions present between the two systems.

Confidential

Figure 25: Screenshot of the simulation model

The production system contains the three main production lines, i.e., BVL, MGV, and OEM. To keep things as simple and intuitive as possible, each production line is modelled as a line process. At different points along the line, raw materials need to be supplied in order to manufacture the final product, i.e., an expansion vessel. Only the most important raw materials are considered. I.e., those materials that account for the majority of intralogistics workload, e.g., discs, clamping rings, diaphragms, carton.

When the production system produces, it creates work for the intralogistics system, i.e., transportation jobs for, e.g., raw materials that need to be retrieved from the incoming goods warehouse and thereafter supplied to the right point at the right production line. The intralogistics system itself consists of a bunch of vehicles performing the transportation tasks within the factory. Each vehicle has specific working days, shift hours, default return location, possibly a dedication to a single production line, and a priority rule with which it chooses its next task to execute. If a vehicle is off-duty or there are no tasks to perform, it returns to its default location and waits.

The interface between the production and intralogistics system is a set of P/D-points that are connected with each other through tracks. This way, vehicles can drive through the factory and pickup and drop-off materials at the various P/D-points.

Statistics are gathered for both the production system and the intralogistics system. In case of the production system, statistics are mainly used to validate the model. Experiments are run in a search to improve the intralogistics performance. A predefined set of experiments investigates different scenarios (e.g., factory layout) and interventions (e.g., vehicle fleet size).

5.1.2 Level of detail

In this section, we discuss the level of detail of our simulation model.

In Section 1.4, we already deliberately narrowed down our project scope. This implicates that also our simulation model will not cover every system aspect in detail. The level of detail of this simulation study is such that all research questions can be answered adequately, yet not more extensive than that.

Important to mention is that we, from this point onwards, exclude the *Rondellensnijlijn* (RSL), *Klemringenwals* (KW), and Air+Dirt department from our analysis. Reasons are, amongst others, that the RSL and KW operate separate from the production lines (i.e., BVL, MGV, and OEM). As such, the RSL and KW are working to supply all production lines with discs and clamping rings using their own production planning, which is decoupled from the production lines' production. Incorporating the dynamics of the RSL and KW would add a lot of complexity, whereas capacity is normally not a hot issue and from Figure 21 we already can conclude that in terms of minimising intralogistics it is beneficial to place the machines right next to the points of major usage (which is by the way also done in the current situation). We exclude the Air+Dirt department, because of the following reasons. First, the intralogistics workload, e.g., daily number of pallets to be transported, is estimated to be rather small compared to the other production lines. Second, in contrast to all other products, Air+Dirt products are not produced in a line process; the department is organised like a job shop. Third, the way the Air+Dirt department is supplied with raw materials is to a large extent different from the other three production lines, i.e., a Kanban replenishment system is used to control the inventory of raw materials and subassemblies.

The production system we model consists of the *Bandvatenlijn* (BVL), the *Middelgrote vaten lijn* (MGV), and the *OEM lijn* (OEM). The different production lines are not modelled in great detail. The emphasis is on when a line produces output and when it does not, i.e., including setups and failures, as this has a strong influence on the timing of materials required – and thereby on the intralogistics. For the BVL, MGV and OEM, we only include the key (raw) materials, which together account for the majority of goods (in terms of pallets) that flow through the factory every day. Examples of excluded materials are the coils of strip steel, as these are input for the excluded RSL and KW. Next to that, the water nipples and air valves are not considered, because many expansion vessels share the same water nipple and air valve, and more importantly, due to the fact that one pallet equals several thousand pieces, the intralogistics associated with these materials is negligible compared to the other streams of goods. Also, all materials which are incidentally brought to the line or for which it is obvious that they should be placed right next to the point of usage, are out of scope. An overview of what is in- and excluded in the model can be found in Table 11.

Table 11: Simulation model scope regarding goods and materials

Stream of goods	
In scope	**Out of scope**
Discs ❖ Discs BVL (in Dutch: *Rondellen*) ❖ Discs OEM (in Dutch: *Platines*) ❖ Plates and discs MGV (in Dutch: *Vlakke maten en rondellen*) Clamping rings Diaphragms Carton Empty pallets, cages, boxes, etc. Finished goods	Coils of strip steel ❖ for Discs ❖ for Clamping rings Vessel halves (tactical WIP) Water nipples Air valves Instruction manuals Accessories Stickers and labels Chemicals for vessel washing Powder for power coating Scrap metal Waste Chemical waste

The intralogistics system operates in and around the production system. The connections between the production system, the intralogistics system, and the inbound- and outbound warehouses are made by means of P/D-areas. Each P/D-area indicates a preserved area within the plant that is used to (temporarily) host a certain material. P/D-areas can be found at different places right next to the production lines, as well as at other storage locations.

Vehicles transport pallets from P/D-area to P/D-area (from source to sink). We model the behaviour of vehicles (e.g., forklifts, AGVs) accurately, because we need reliable data on the intralogistics workload, the assignment of transportation tasks, and the utilisation of vehicles. A vehicle has working hours, a possible dedication to a production line, a default return location in case free or off-duty, and a priority rule to choose the task seen as most urgent.

Statistics are gathered per shift. We log all transportation tasks performed by vehicles, the tracks that are travelled, and the vehicles' utilisation per shift. In addition, to get an idea of space requirements, we keep track of how much pallets have been present at some point in time in a P/D-area. Normally, one creates a model that is as simple as possible, yet complex enough to meet output data requirements. However, in our case, to properly mimic the production system and to achieve model acceptance, the model could potentially do more than we use it for.

Regarding the software implementation, an object-oriented modelling approach is taken, which also facilitates the duplication of standardised objects. This results, e.g., in P/D-areas all having the same structure and production lines sharing all the same basic logic.

In short, the simulation model consists of the following:

Product data

- For each final product, a *bill of materials* defines which (in scope) raw materials go into the product.
- For each final product and raw material, the *amount on pallet* is used to calculate – based on the production planning - how much pallets need to be supplied to the production.

Layout and P/D-areas

- *Distances between P/D-points* can be adjusted interactively (by the user, i.e., drag-and-drop).
- Various *distance metrics* can be used to calculate the distance between different factory locations, i.e., the Euclidean and Manhattan distance metrics.
- *Size of the buffer* is registered over time to get an idea of space requirements.

Production lines

- Working hours can be adjusted, i.e., *public holidays, number of shifts, shift hours, pauses, and scheduled maintenance*.
- *Production speeds* are changed according to the products produced in the line.
- Raw materials are created and supplied based on an adjustable *SupplyInAdvanceTime*. This means that the model starts making transportation requests for materials expected to be used the *SupplyInAdvanceTime* from now.
- The frequency with which the model checks if new raw materials need to be created, is adjustable.
- When creating raw materials, the model checks if the raw material in question is already present at the line and if there are residual portions that can be used.
- Leftovers of raw materials, which are not used anymore by the production orders currently in sight, are assumed to be empty pallets and returned to their origin location.
- Apart from leftovers, empty raw material pallets are returned to their origin location.
- Failure behaviour, modelled using an exponential distribution with the MTBF and MTTR based on a year of real-life historical data.
- Setups, modelled using an average setup time that is calculated based on historical data.

Vehicles

- Working hours can be adjusted, i.e., *public holidays, number of shifts, shift hours, pauses, scheduled maintenance*.
- Fleet size, i.e., the *number of vehicles (depending on the scenario considered, either forklifts or AGVs)*.
- *Dedication of a vehicle*, i.e., performing transportation for a) a specific line, or b) all.
- *Default parking*, i.e., return location when a vehicle has nothing to do or is off duty.
- *Priority rule*, i.e., procedure for prioritising candidate transportation jobs.
- *Vehicle speed*, i.e., constant driving speed in m/s.
- *Vehicle loading capacity*, i.e., amount of pallets the vehicle can transport at once.
- *Vehicle handling time*, i.e., fixed time that a vehicle needs at each pickup or delivery of goods.

5.1.3 Input

The section contains a longlist of input factors accompanied with explanation of, e.g., the way input data is obtained. The longlist is split in categories to enhance readability. Note that the assumptions and simplifications lying underneath some of the input factors are discussed in a later section.

Product data

Bill of Materials. A database lists all final products with the raw materials. Corresponding with the predefined scope of Table 11, only the relevant raw materials are mentioned.

Amounts on pallet. For all final products and raw materials, separate tables are made to store the amounts of material that go on a pallet. In this context, a pallet might be a (Euro) pallet, a cage, a box, or else. The (estimated) data comes for 90% out of trustworthy data sources. The remaining 10% is an estimation based on similar articles.

Layout and P/D-areas

Layout. The factory layout, which is one of the basic components of the model, is defined by a scaled version of a 2D CAD drawing containing the layout plan in its true dimensions.

Distance metric. Distances from P/D-area to P/D-area are calculated using the Manhattan metric. This is because within the factory one drives only in straight lines perpendicular to either the X- or Y-axes. In reality, in some cases, the distance calculation might be more complex, as there are only a number of vertical and horizontal lanes where vehicles can drive. That is, one cannot go right through a machine when driving to a certain destination. The phenomenon is comparable with a warehouse that has no cross isles; in such cases one also needs to drive to the end of the lane first and then enter another lane.

Distance calculation. Distances between P/D-areas are calculated using the midpoints of the P/D-areas. One could imagine that in reality, goods can be picked up and delivered from, e.g., the edges of a P/D-area and/or pallets might be stacked or put away in predefined storage lanes.

Production lines

Working hours. Flamco Bunschoten is like a church, always open. The working hours of the production lines are as defined in Section 3.1. Scheduled maintenance is every Wednesday morning from 9:00 until 12:00, which means that every line temporarily stops producing. The plant is shut down on the predefined public holidays, the so-called *Collectieve ADV dagen*, and during the obligatory summer break in calendar week 31 or 32.

Line speeds, processing times and line capacities. At Flamco, every production line is controlled and planned based on so-called 'planning norms', which reflects, per article, the expected production output per hour (in number of vessels). This is a number resulting from experience, taking into account the (average) effects of scheduled maintenance, failures, and setups, and is only available for the production planning staff.

Besides this 'planning norm', there are two other norms: the so-called 'OEE production norm' and 'financial production norm'. The latter is used for accounting purposes and reflects the production output that is needed to have financially a break-even situation for the factory as a legal entity (private business).

The OEE production norm reflects the maximum possible output of a production line, i.e., in a perfect situation with no downtime and a pace equal to the maximum machine speed of the bottleneck machine. If one would correct this OEE production norm with the average failures and setups, the resulting net production should be similar to that predicted by the 'planning norm'.

After six months of research, we need to conclude that, to the best of our knowledge, the only data that Flamco has available is either coming from the OEE software, or is about the production norms mentioned above, i.e., OEE norm, planning norm, and financial norm. Hence, we know per article / expansion vessel what the norm production is and how the production lines behaved during 2017, i.e., in terms of production, failures, and setups. Flamco does not have data on processing times of the different stations in a production line (e.g., DTL, RNL, AWL, etc.). This obviously complicates modelling the production system to a large extent.

As our research focuses on intralogistics more than on process improvements in the different production lines, the timing of material deliveries is the most important; what actually happens in the production system is of minor importance. Hence, to keep things simple and intuitive, we have chosen to model the production lines as a line process with a given length and speed instead of a set of stations having their own processing times.

The best shot we have is using the OEE production norm in combination with the failures and setups as an input for our simulation model. Following Little's Law, the processing time of an article on a line, i.e., the cycle time (CT), can be determined by the division of the number of products in the line, i.e., the work in progress (WIP), and the speed of the line, i.e., the throughput (TH). As only the TH is known per article, i.e., the OEE production norm, it is hard to determine accurate processing times. Especially if one considers that, at an arbitrary moment in time, more than one article can flow at different positions on the line. As a result, the actual TH might deviate. Nevertheless, by estimating the WIP on the production line (i.e., simply counting by hand), we could calculate estimations of the actual processing times (CT) of a production line. Figure 26 gives a diagrammatic representation of the method explained above.

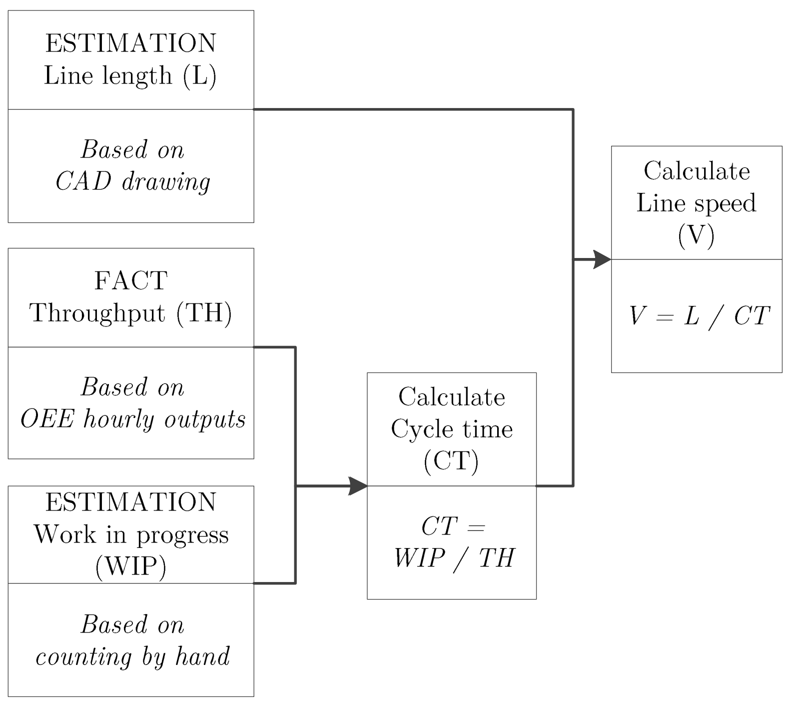

Figure 26: Method to calculate line speeds

We use the method for the MGV respectively OEM line. We measure the length of the line using a 2D CAD drawing of the factory, use the hourly OEE throughputs of a commonly produced vessel, and estimate the work in progress on the line through counting by hand and common sense. The line speed is calculated accordingly. This baseline line speed is then used to calculate the line speeds of all other articles, i.e., we scale the baseline line speed using the hourly OEE production norms (assuming a linear relation between the production norms, which might not always be true).

An exception is made for the BVL, because for the BVL, the chain conveyor speed is known for each article. We use these (more precise) speeds instead of calculating our own speeds based on the method displayed in Figure 26.

As a line process needs to be always balanced, the model makes sure the line speed is equal across the whole production line at any point in time. In case more than one article flows in the line, the line speed is such that it complies with the minimum TH or the minimum chain conveyor speed associated with the articles in the line. Hence, the cycle time of a vessel results from 1) the length of the production line, 2) the hourly OEE TH or chain conveyor speed, 3) the setups (and hence, possible changes in chain conveyor speed) that have happened during the entire production process, and 4) the downtime of the line incurred during the entire production process. The maximum number of vessels in the line is restricted such that it does not exceed the WIP estimations, we made earlier. All in all, this rather simple way of modelling should yield (average) hourly output figures that roughly correspond with the 'planning norms' mentioned earlier.

However, deliberately ignoring some of the complexity that comes with the production system also means that we are not always spot on with our production output figures. Causes that are not captured in detail in the model, yet influence what happens on a production line and with the resulting output, are, e.g.,

* inconsistencies in line length, e.g., due to backtracking in production or (selective) use of new robots
* speed losses at different machines under different circumstances;
* deviations in WIP, as vessels can have different sizes;
* deviations in distance between subsequent vessels at different points in the line, e.g., the distance between vessel halves on the chain conveyer is much larger than the distance between vessel halves in a buffer waiting to be assembled;
* differences in the production process, i.e., additional welding, coating and/or testing;
* interaction between different production lines, e.g., Air+Dirt products are coated at the MGV
* varying capabilities of operators and temporary labour staff;
* and, throughout the year the occurrence of working in overtime, (temporarily) adding an extra shift, and outsourcing a part of production.

Emphasising the facts that 1) the range of influence of the things mentioned above can hardly be estimated, and 2) especially the method explained in Figure 26 is relying on estimations, we see no other option than to slightly tweak line speeds such that the yearly production numbers are approximately conform reality, i.e., correcting for all factors mentioned above. As we do capture major influences like failures and setups in the model (using real historical data), we believe that we create a stochasticity in the model that in the end reflects the average situation in terms of spread in output. More on this can be found in 5.4.

Setups. To incorporate setups in the model, we use the system Flamco uses to measure the Overall Equipment Effectiveness (OEE). As one can measure the OEE of a line process at only one place along the line, Flamco defined a bottleneck machine for each production line. These machines are usually the bottleneck of the process, but not always due to, e.g., different products or speed losses at other machines. Nevertheless, in this system, machines and operators together register what happens in production. The resulting timeline contains data in four categories: Production (in Dutch: *Productie*), Setups (in Dutch: *Inrichten*), Downtime (in Dutch: *Stilstand*), and Failures (in Dutch: *Storing*).

Currently, Flamco seems to do not much of a structural analysis on the OEE data. As a result, there is a strong focus on speeding up (what is viewed as) the bottleneck machine, both during production as well as during setups. The facts that a) the bottleneck machines of the BVL and OEM are at the end of the process, and b) setups often happen in stages (e.g., within the BVL, first the DTL is set up, somewhat later the chain conveyor speed is adjusted, et cetera) make that the net setup time is often reduced from the longest machine setup time to the bottleneck machine setup time. As also mentioned in Appendix B, setup activities at single machines (e.g., DTL) might be longer, but due to all kind of smart 'tricks' in production, such as setting up machines parallel to production and adding WIP from outside the line (i.e., vessel halves) manually to the chain conveyor, this does not affect the net setup time.

When talking to operators, they put emphasise on the fact that setup times are dependent on multiple factors, e.g., the type of products that are in the line, the amount staff and their skills, et cetera.

Nevertheless, our aim is to keep things simple, especially when it comes to the production system. Therefore, we have chosen to work with a mean setup time based on the OEE data; see Appendix B for more details. When a new batch (i.e., a new article) is about to enter the line, we let the upcoming vessel wait for the average setup time before it enters the line. The result is a gap in the production line, similar to real life. As we know from practice that almost every change in article yields a standstill (i.e., to change the test cabins, carton, labelling, accessories, palletizing, et cetera), the average setup time should at least account for these setup activities. As the number of OEE lines in 2017 differs from the number of planning lines in 2017, we need to scale the mean setup time coming from the OEE. Hence, in the simulation model, we work with an average setup time that is calculated as follows.

$$Average\ setup\ time\ in\ Plant\ Simulation =$$
$$= \frac{Nr\ of\ OEE\ lines\ in\ 2017}{Nr\ of\ planning\ lines\ in\ 2017} * mean\ setup\ time\ (i.e., over\ the\ OEE\ lines\ of\ 2017)$$

Failures. We have chosen to aggregate all failures occurring on a certain production line. This means that for each line there exist a single aggregated failure behaviour, which determines whether or not vessels are coming off the line. A failure in our case brings the whole line to a standstill, whereas in practice a failure occurs at a single machine somewhere on the line, which does not necessarily mean that the other machines stop as well (at least not immediately). In practice, it might be beneficial to buffer some WIP in- or outside the line to prevent blocking and starvation. However, in our model, a failed line means a full standstill and no output.

Regarding the aggregated failures, we analysed for each production line a year of historical data (2017) coming from the OEE monitoring software; see Appendix H. From this data, we collected all line failures (i.e., *Stilstand*

and *Storing*) and made a histogram of the Time Between Failures (TBFs) and Time To Repairs (TTRs). In all cases, a negative exponential distribution was suspected to be the best-fitting theoretical probability distribution. However, also in all cases, a chi-squared test rejects, on a 95% significance level, the hypothesis that the exponential distribution fits the data properly. Nevertheless, we assume a constant failure rate, as for complex systems this is a commonly used assumption of failure behaviour under normal operating conditions (Kelly & Harris, 1978).

Thus, we use a negative exponential distribution with parameter Mean Time Between Failures (MTBF) to generate a realisation of the distribution, i.e., the time until the next failure of the line. Note that any exponential distribution is memoryless, and hence, the probability that the line will fail in the next hour given that it already runs smoothly for two days is equal to the probability that the line will fail in the next hour given that it is just repaired.

With respect to the line repairs, we follow a similar reasoning as with the failure occurrences. We assume a constant repair rate, as a failure may be different every time, regardless of the point of occurrence on the production line. Hence, we again use a negative exponential distribution with parameter Mean Time To Repair (MTTR) to generate a realisation of the distribution, i.e., the time until the line is repaired. Note that due to the memoryless property of the exponential distribution, we have a situation where for the remaining repair time it does not matter how long an engineer of the maintenance department is already busy repairing.

Production planning. To feed the model with a realistic production planning, we use historical planning data to sample from, thereby creating a new planning for each production line in each replication. Sampling means that we randomly exchange, cut and paste together parts of the planning, yet still taking into account the original ideas behind the batch sequencing. Sampling is done offline with help of a VBA script in MS Excel; see Appendix H for details. We use the original planning to validate the model. We discuss model verification and validation in Section 5.4.

Vehicles

Working hours. The working hours of vehicles can be different per vehicle. Vehicles dedicated to a line work as long as the line produces. Vehicles that are not specifically dedicated can work in theory any hour of the day. Note that in the current situation, there is one forklift driver working during the dayshift, i.e., driving materials from the incoming goods warehouse to the production floor. Scheduled maintenance is every Wednesday morning from 9:00 until 12:00, which means that every line is paused; and vehicles are paused as well.

Destinations. Vehicles determine their destination using a table. At the moment, each origin P/D-area is associated with only one destination P/D-area. The pairs (origin → destination) have a certain FlowType (i.e., InFlow, OutFlow, and ReturnFlow). This FlowType may be used in the priority of transportation tasks.

Vehicle speed. The speed of the vehicle is assumed to be a constant. Opinions differ on how fast vehicles drive within the production halls of Flamco Bunschoten. The current estimation of the plant manager is between 6 and 10 km/h. Stichting van de Arbeid (2018) prescribes 6 km/h. We will use 6 km/h as input value.

Vehicle loading capacity. The loading capacity of a vehicle is equal to one unit load, i.e., one (euro) pallet or box or cage or else.

Vehicle handling time. The vehicle handling time, which is accounted for at each physical pickup or delivery is assumed to be a constant 30 seconds.

Fleet size. The amount of vehicles driving around can be used as an input or an experimental factor. For each vehicle type (i.e., due to differences in, e.g., dedication, default parking, priority rule, etc.), a number of vehicles can be created. For the current situation, four vehicles are used, i.e., three dedicated to a production line and one extra that assists all lines.

Vehicle dedication. The vehicle dedication is used to model situations where vehicles are only responsible for a subset of the intralogistics workload, e.g., transportation jobs of only one production line.

Default parking. The default parking is used by vehicles as a return location when there are no transportation tasks available to execute or when a vehicles is off duty. It might be beneficial to make a tactical choice for a default parking location, i.e., there where transportation jobs are likely to occur.

Priority rule to select next transportation job. Vehicles have a dynamic list of candidate transportation tasks based on, e.g., their dedication. From this list, the most urgent job (in the eyes of the stakeholder) should be chosen. This is done by means of a priority rule, which can be an input or an experimental factor.

Priority rules. The model offers four priority rules, which are listed below. The rules are not rocket-science, yet the current way of working is also not much more than pragmatic. As to date, communication between transporting vehicles is limited, introducing communication could already have a large impact, regardless of the priority rule used. Note that priority rule 1 and 2 were also proposed in (I. Sabuncuoglu, 1998).

1. First Come First Served (FCFS): Choose the 'oldest' task.
2. Nearest: Choose the task for which the pickup location is the closest to the current location of the chosen vehicle.
3. FlowType: Choose a task based on FlowType, i.e., InFlow (raw materials) have priority over OutFlow (finished goods) have priority over ReturnFlow (empty and leftover pallets). If there is a draw on FlowType, apply FCFS.
4. Consolidate: Extension of the FlowType priority rule. I.e., InFlow pallets are clustered per P/D-area and sorted in the same order as the production process, which means, e.g., *Rondellen* have priority over, e.g., *Diaphragms*. Consolidation lies in the fact that first all pallets with *Rondellen* are brought to the production line making sure the first machine does not starve; we thereby assume that production itself buys us enough time to supply the succeeding machines in time.

5.1.4 Output

This section discusses the output produced by the simulation model. We elaborate on which statistics are gathered to be able to provide an answer on the research question posed in the first chapter.

Recall that the research questions posed in Section 1.5 cover almost the full knowledge gap related to Flamco's intralogistics. From important to relatively unimportant, we want to know what the intralogistics' workload is, where traffic is mainly concentrated within the factory, what space requirements are for (raw) materials on the production floor, how we can fight driving empty, and if theoretically there is a situation of over- or under capacity.

To this end, within the simulation, we installed the following ten tables in the frame *Performance* to store statistics: StatListAGV, AGVutilisation, TracksTravelled, TracksTravelledEmpty, TotalDistTravelled, PDpointBufferSize, ProductionHistory, ProductionPlanningHistoryBVL, ProductionPlanningHistoryMGV, and ProductionPlanningHistoryOEM. Table 12 presents an overview, after which they are further elaborated on. In addition to the ten statistics tables, we have three additional performance indicators, which one obviously wants to minimise, i.e., TotalDistanceTravelled, TotalDistanceTravelledEmpty, and AvgResponseTimeDelivery.

Table 12: Overview statistics tables

Output table	Description	Level of aggregation	Data gathering frequency
StatListAGV	Overview of all transportation tasks	Shift	Every task
AGVutilisation	Overview of the utilisation of vehicle(s)	Shift	Every shift
TracksTravelled	Overview of tracks (from/to) travelled	Replication	Every track travel
TracksTravelledEmpty	Overview of tracks travelled empty	Replication	Every track travel
TotalDistTravelled	Overview of distance travelled	Shift	Every shift
PDpointBufferSize	Summary of the nr of pallets per PDpoint	Shift	Every change
ProductionHistory	Overview of historical production output	Shift	Every shift
ProductionPlanning-History	Summary of the production history; a table per production line	Shift	Every batch end

StatListAGV. StatListAGV stores every transportation task thereby registering the week, day, and shift, in which the task was created. Also, the origin and destination of the task are logged. Apart from these facts related to the transportation task itself, the model keeps track of the vehicle that gets the transportation task assigned and how long it then takes to pick up and deliver the associated load.

Interesting information that can be unravelled from the table StatListAGV on a week, day or shift level:

- ❖ How many transports per week, day or shift;
- ❖ How many transports are executed and by which vehicle type (i.e., with a certain dedication and priority rule);
- ❖ Indirectly and in extension to the transport frequency, the travel distance and time.
- ❖ ResponseTimePickup (i.e., time from request to pick up) and ResponseTimeDelivery (i.e., time from request to delivery);
- ❖ Possible relation between production planning and intralogistics workload;
- ❖ Possible relation between intralogistics workload and response time;
- ❖ Possible relation between dedication or priority rule and response time;
- ❖ Insight in the share of a certain raw material in the total intralogistics workload.

The variable AvgResponseTimeDelivery calculates the average ResponseTimeDelivery over all delivered tasks in a shift. Note that response time is not corrected for the time a vehicle is off-duty, which might give a distorted view. Nevertheless, the goal of minimising the AvgResponseTimeDelivery does not change.

AGVutilisation. AGVutilisation stores the utilisation of vehicles by making use of the attribute *Transporter.statTransportTimePortion* in Siemens Plant Simulation. This statistic keeps track of the time per shift that a pallet was located on the vehicle, i.e., the time that actual value is created through transportation of pallets.

TracksTravelled and TracksTravelledEmpty. The TracksTravelled tables register which tracks are travelled during the simulation, either by a loaded vehicle or an empty vehicle or both. This 'frequency' table normally forms the main input for a Facility Layout Problem (FLP), which already demonstrates its usefulness. From this tables one can read where busy traffic is likely to occur, even though a translation to the actual factory paths might still be necessary. In addition, the TracksTravelledEmpty table could highlight between which points in the factory a lot of empty drives occur; this could then suggest improvement directions.

TotalDistTravelled. This table stores the total distance that is travelled by all vehicles during a replication.

PDpointBufferSize. PDpointBufferSize registers the minimum, average, and maximum amount of pallets that have been in a certain P/D-area during a shift. Also, the number of mutations are logged, which means that one can see how much changes there have been in the number of pallets in a certain P/D-area.

Interesting information that can be distilled from the table PDpointBufferSize:

- ❖ Average space requirements over the year, expressed in number of (full) pallets;
- ❖ Maximum number of pallets that can be expected in a P/D-area;
- ❖ Possible relation between production planning and peaks in the number of pallets in a P/D-area.

ProductionHistory. ProductionHistory saves for every production line the production output per shift. By zooming in on the shift, one can see the article number(s) / product group(s) that were produced that shift.

ProductionPlanningHistoryBVL MGV and OEM. ProductionPlanningHistory looks at what has happened in production from a different angle than the table ProductionHistory. Here, all production orders are registered together with details on the timing of material availability, (estimated) start of production, and (estimated) end of production.

5.1.5 Assumptions and simplifications

In the previous sections we explained already a lot of what is behind the simulation model. In order to keep the main report concise and to avoid much repetition, we briefly explain the assumptions and simplifications that were not explicitly mentioned earlier.

Product data

Amounts on pallet. For some articles, either final product or raw material, the amounts on a pallet have been estimated based on interviews, observations or similar articles. E.g., for steel products, every pallet contains a different load in terms of weight and pallet amounts. This is the nature of the industry.

Layout and P/D-areas

Distance metric. The simulation model uses the Manhattan metric as its distance metric. A deviation between model and real-life is expected, especially in situations when one is expected to drive straight through the factory.

Distance calculation. Distances between P/D-areas are calculated using the midpoints of the P/D-areas. One could imagine that in reality, goods can be picked up and delivered from, e.g., the edges of a P/D-area. Furthermore, in reality, pallets might be stacked or put away in predefined storage lanes. We do not take this into account. The pixel distance in the model is determined and multiplied with a scaling factor which translates pixels into meters.

Symmetrical distances. Distances between P/D-areas are assumed to be symmetrical, which means that the distance from A to B is the same as the distance from B to A.

Production lines

Working hours, Shifts, Days and Weeks. The production shifts are leading when counting days and weeks. We assume a week starts on Monday. However, in practice, the first shift starts Sunday night at 23:00. Yet, we call this shift the *Night* shift belonging to the Monday, as the majority of the shift falls within Monday. Each day contains 3 shifts of 8 hours. Hence, day 1 start Sunday at 23:00 and ends at Monday 23:00. The rest of the shift numbering can be found in Table 13.

We assume all production lines use the same shift hours; also when a line works in only 2 shifts. In practice, it might be that a production line - working in two shifts - starts at 6:00 in the morning and ends at 22:00 in the evening. We do not take this into account.

Last but not at least, we assume the whole plant is shut down on the predefined public holidays, the so-called *Collectieve ADV dagen*, and during the obligatory summer break of production in calendar week 31 or 32. We add the *Suikerfeest* to this, as the majority of operators is Muslim and most probably will take the day off.

Table 13: Shift numbering

Shift	Day	1	2	3	4	5	6	7
Shifts	**Timing**	Monday	Tuesday	Wednes-day	Thursday	Friday	Saturday	Sunday
Night	*23:00* - 07:00	1	4	7	10	13	16	19
Day	07:00 - 15:00	2	5	8	11	14	17	20
Evening	15:00 - 23:00	3	6	9	12	15	18	21

Overtime, number of shifts and production pace. We assume no production line works in overtime. In reality, working in overtime is avoided as much as possible; only in high season, there might be exceptions. In addition, we assume that the number of shifts stay the same over time. This is normally true, as Flamco does not want to pay too much additional fees, i.e., *Ploegentoeslag*. Lastly, we assume that the production pace is always the same; equal to the current production speed. However, during, e.g., *Ramadan*, it might be that a significant part of the factory works at a slower pace to persevere.

Supply availability raw materials. We assume that all raw materials are always available when they are needed in production. Hence, we exclude external factors, e.g., supplier delivery problems et cetera.

Raw material pallets. To increase the simulation speed, we try to restrict the number of movable units in the simulation. This is reflected in the pallets containing raw materials. In the computer model, we create those pallets (i.e., moveable units) in the fictitious incoming goods warehouse (i.e., a P/D-area), which means they seem to appear out of nowhere. After creation, they are subsequently, put on the to-do-list of the vehicles, shipped to their point of usage, used, put on to-do-list of the vehicles again (this time as an empty pallet, i.e., a return flow), and last but not least, corrected for when new yet similar raw material pallets are created. In case there a leftover pallets that are not used up fully, a return flow is created, after which we assume they are empty and treat them likewise. We see a pallet as a leftover pallet the moment there are no production orders currently in sight, where 'in sight' is defined by the predefined *SupplyInAdvanceTime*. Note that we explain the whole transportation process and control of vehicles in 5.1.6.

Exact number production. We assume that production always produces the exact number of products, as prescribed by the production planning. In real-life, due to small raw material leftovers resulting from, e.g., varying weights of coils of strip steel, production sometimes chooses to finish up a pallet of raw materials (e.g., *rondellen*), as it is not an economical decision to perform all the handling if it takes only minutes to finish up the raw materials. In practice, given the fact that all vessels are eventually sold, this is not a problem.

Net production time. Within production, there might be countless reasons why the actual production time deviates from the anticipated production time. Production normally tries to keep producing during breaks, but due to (permanent) understaffing, this is generally not happening. Hence, we assume lines to pause fully when operators have their coffee or lunchbreak(s).

Friday night at 23:00, production generally starts its weekend. A part of the line (washing street) is run empty to avoid vessels corroding during the weekend. As this 'hole' in the chain conveyor is estimated to be only 100 vessels, we ignore this and simply pause the line when Friday's evening shift ends.

No learning curve. The production speed is assumed to be equal across the whole batch of an article that is produced. A learning curve does not exist. In practice however, one could imagine that starting a new batch results not only in some setup activities, but also in a need for fine-tuning of machine settings, et cetera.

Balanced line with a variable production speed. The production speed is assumed to be equal across the whole production line, this implicates that the line is fully balanced, regardless of the production speed. In case at different points in the line different vessels are produced, which can happen of course due to staged changeovers, the minimum production speed associated with the vessels in the line is leading for the entire production line. In addition, we assume that, on average, the distance between subsequent vessels on the line is equal.

Setups. Before a new article can be produced on a production line, a setup is needed. To this end, we determine and wait an average setup time before a new batch is started. We ignore the fact that setups are staged, i.e., at different points in time, different setups of different time lengths are executed to changeover the line. We also ignore other factors of impact such as staffing and product type.

Failures. Recall, we have chosen to aggregate all failures occurring in a certain production line. This means that for each line there exist a single aggregated failure behaviour, which determines whether or not vessels are coming off the line. A failure in our case brings the whole line to a standstill, whereas in practice a failure occurs at a single machine somewhere in the line, which does not necessarily mean that the other machines stop as well (at least not immediately). In practice, it might be beneficial to buffer some WIP in- or outside the line to prevent blocking and starvation. However, in our model, a failed line means a full standstill and no output.

Supply in advance time. Recall that the triggering to start delivering raw materials for a certain production order / batch is based on a discrete variable called *SupplyInAdvanceTime*. The idea is that all raw materials for a certain production batch should be available at the production floor a *SupplyInAdvanceTime* in advance, i.e., compared to the expected starting time of the batch. Hence, the variable denotes how much safety is built in the intralogistics process. The larger the *SupplyInAdvanceTime*, the more production batches are expected to start within the time window [now, now + SupplyInAdvanceTime], the more raw materials are brought into the factory, the more flexible production is as raw materials are expected to be always available. Nevertheless, for this triggering system to work, one should be able to (fairly) accurately estimate the expected duration of a production batch (given intermediate setups, failures, pauses, etc.). This is where we need to make assumptions. We calculate the "expected production time left for which the materials are (expected to be) brought in to the factory" by adding the expected durations of all (partial) production batches currently in sight and compare it with the predefined *SupplyInAdvanceTime*. Once the sum of expected durations falls below the *SupplyInAdvanceTime*, new production batches are added until the sum of expected duration exceeds the *SupplyInAdvanceTime* again. For all new production batches added, triggers are initiated to start delivering the needed raw materials to production. The main assumption in this whole process is of course the calculation of the expected duration of a production batch. The expected duration of production batch i on production line j is calculated as follows:

$$Expected\ duration\ of\ production\ batch\ \boldsymbol{i}\ on\ production\ line\ \boldsymbol{j} = \frac{A_i}{(B_j * C_i)}$$

$$A_i = Amount\ of\ products\ to\ be\ produced\ in\ production\ batch\ \boldsymbol{i}, i = 1,2,3, \ldots$$

$$B_j = 1 - \frac{Stilstand_j + Storing_j}{Stilstand_j + Storing_j + Inrichten_j + Productie_j}\ with\ j \in \{BVL, MGV, OEM\}$$

$$C_i = Planning\ norm\ for\ the\ production\ output\ of\ the\ article\ of\ production\ batch\ \boldsymbol{i}, i = 1,2,3, \ldots$$

Data to fill in the formula and comes from the OEE system (B_j; determined using a data set of 2017) and the production planner (C_i; directly from the production planning files).

Quality issues and additional (re)work. We ignore issues related to product quality, as it is generally a minor issue within Flamco. However, to give an example, in practice it might happen that vessel halves fall from the chain conveyor and are thrown away, thereby reducing the actual production output. Also, incidentally, it might be that the production planning is slightly adjusted to fit in rework or a pilot run of new expansion vessels. The incidental and unpredictable nature of such small and often last-minute planning adjustments makes that we chose to ignore them.

Every vessel produced on a production line undergoes the same production process. We ignore the exceptional situations where the production process for a certain vessel deviates slightly from the standard. Hence, per production line, we assume that all vessels have a similar production process. E.g., for the OEM, we leave out the fact that certain vessels are washed before sent to the customer.

Vehicles

Forklifts and AGVs. As the model tries to capture both the current situation and future scenarios, we need to compromise when it comes to modelling forklifts operated by humans and Automatic Guided Vehicles. The assumption is that both operate in a similar way. It can however be the case that driving speed and handling time are adjusted according to the vehicle type, i.e., AGVs might drive slower as they are generally less flexible when it comes to sudden interactions with humans.

All destinations can be reached. We assume that from any point in the factory, any destination can be reached. Hence, there are no one-way traffic situations, whatsoever.

All pallet types can be handled. We assume that any vehicle can handle and transport any type of pallet, i.e., a (Euro) pallet, a cage, a box, or else.

Vehicle loading capacity, driving speed and handling time at P/D-areas. The loading capacity of the vehicle is assumed to be always one pallet, regardless of the pallet type. The speed of the vehicles is assumed to be constant, regardless of the fact that a vehicle can drive full or empty. The handling time at P/D-areas is also assumed to be constant, regardless of the load and room to manoeuvre at the P/D-area.

Vehicles accepting a new job while driving on a track. Vehicles cannot accept a task while driving empty on a track (i.e., towards its default location). Once it has arrived at its default location, it can immediately accept a new job. This simplification saves us programming a lot of complex logic, and because distances within the factory are rather short, we assume this has no major impact.

5.1.6 Process and logic flowcharts

In this section, we explain the most important process flows that exist in the model. We discuss the transportation process and related vehicle control. In addition, we explain the process of generating raw materials, letting them be consumed in the production system, and returning (empty) pallets which are left over after production is finished. Furthermore, we comment on some other important triggers that exist in the model and always cause a series of actions.

Transportation process and vehicle control. The transportation process is about how materials are handled and transported within the factory. For the system to work, one needs three things, i.e., a unit to transport, a transporting vehicle, and the communication between the two leading to the actual transportation. In our case a vehicle needs a trigger such that it starts the transportation of a certain pallet. Even though pallets normally do not speak up, it would be logical if they would trigger the process. Hence, in the simulation model, we do so; and, four different types of pallets trigger the transportation process (each communicating their own needs):

- A pallet with finished goods leaving a production line (OnProductEntry calls FillToDoListAGV);
- A pallet with "artificial raw materials" that is newly created in a P/D-area, where "artificial" means that the raw material itself does not exist as a physical object in the simulation model, however the pallet carrying the raw materials does physically exist in the model (NewBatch calls FillToDoListAGV);
- A pallet with no raw materials left (i.e., an empty pallet) is ready to be returned to the place it originally came from (CorrectPallet calls FillToDoListAGV);
- A pallet with raw materials that will not be used anymore in the foreseeable future (i.e., a leftover pallet) is ready to be returned to the place it originally came from (Leftovers calls FillToDoListAGV).

After a pallet triggers the process, the following steps are pursued (see also Figure 27 red.):

1. The pallet is added to a to-do-list which is shared among all vehicles performing transportation.
2. All relevant details regarding the transportation of the pallet (e.g., from where to where) are registered.
3. The model identifies whether there are any vehicles available to perform a new task.
4. If so, a vehicle is chosen (randomly or based on some preference) to perform a task.
5. A list of tasks that suit the vehicle (e.g., exclude tasks from the MGV and OEM line if the vehicle is dedicated only to the BVL).
6. Choose the preferred task with help of a certain priority rule.
7. Assign the task to the vehicle and start driving to the location where the pallet needs to be loaded.
8. Let the vehicle pick up the pallet and start driving to the destination location of the pallet.
9. Let the vehicle drop off the pallet and look for new tasks. If no tasks are available, let the vehicle return to its default location – waiting for a new task.

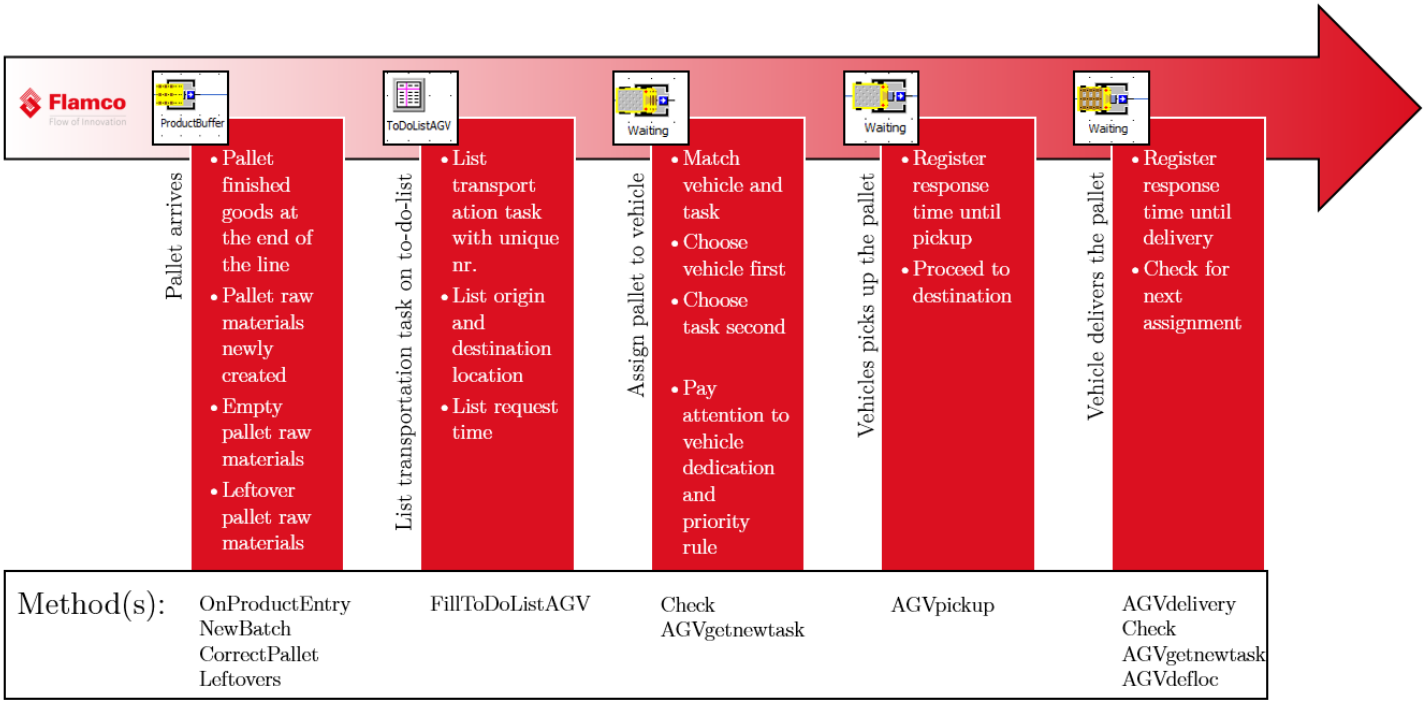

Figure 27: Process flowchart transportation process in the simulation model

Now we know how the transportation process functions within the model. For more details on the programming logic, we kindly refer to Appendix G.

Raw material generation, consumption and return. The process concerning raw materials is a multidimensional process that can be viewed from different angles. Similar to the expansion vessels, raw materials have interfaces with the P/D-areas, the production system and the intralogistics system. The process flow of raw materials through the simulation model is indicated in Figure 28 and explained underneath. In addition, in Figure 29 we zoom in on the consumption of raw materials, which is evidently an important part in the overall process.

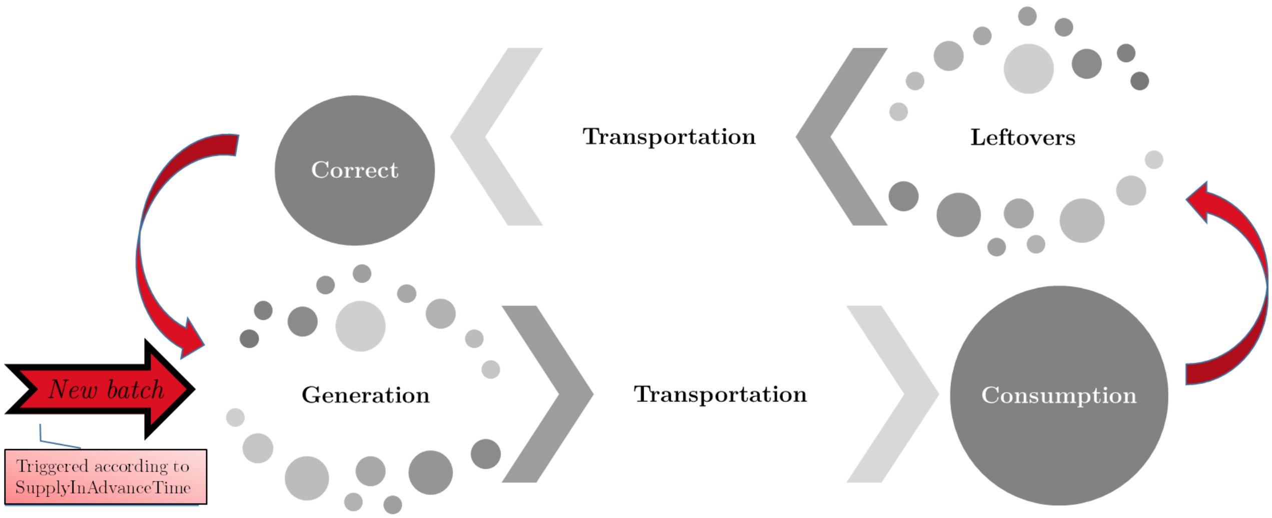

Figure 28: Process flowchart raw material generation, consumption and return

To start off, the creation of raw materials is triggered by the addition of a new production batch to the pipeline of a production line, which is done when the remaining pipeline (expressed in time) drops below the threshold, i.e., the SupplyInAdvanceTime. The frequency of which the remaining pipeline is checked, is set to 1/24 of the SupplyInAdvanceTime. Suppose the SupplyInAdvanceTime equals 24 hours, we check every hour if we need to add a new batch. The trigger of this pipeline check results from a generator called *GeneratorIfNeedBatch*.

When a new batch is added, the following sequence of events starts to happen.

1. Depending on the production line and article, the model searches for the raw materials that belong to the article
2. The current situation in terms of raw materials at the production line is charted
3. New raw materials are generated based on the production order size and current material availability at the line
4. Transportation orders are generated for all newly generated pallets with raw materials, each with their own origin and destination
5. Materials are transported to the P/D-areas at the production line
6. Raw materials are consumed when a semi-finished expansion vessel passes a sensor that is linked to the P/D-area containing a certain raw material (e.g., diaphragms). See Figure 29 for more insight.
7. Once a pallet containing a certain raw material is empty, it is marked as an empty pallet. When the articles in the pipeline no longer use a certain raw material, it is marked as a leftover.
8. Transportation orders are generated to retrieve empty and leftover pallets from the production floor.
9. Pallets, either empty or leftover, are transported from the P/D-area next to the production line to their origin P/D-area - mostly in the incoming goods warehouse. From there, all pallets are seen as empty.
10. When new raw materials are created for a new batch, empty pallets are reused. This is indicated by the step denoted with *Correct* in Figure 28.

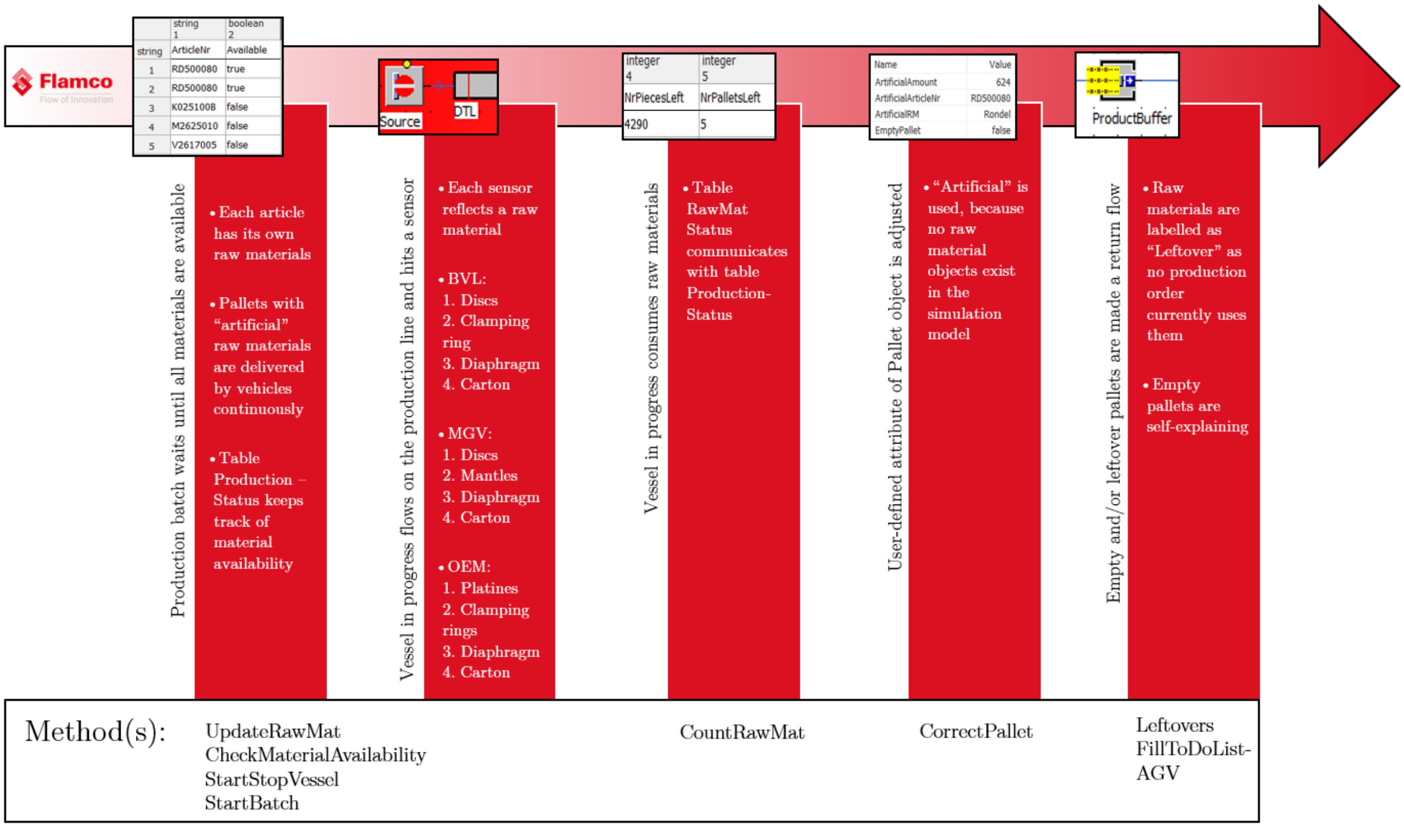

Figure 29: Process flowchart raw material consumption in the simulation model

Other important triggers. To smoothly assist in the creation and transportation of raw materials and finished goods throughout the Flamco factory, there are a number of other triggers in the model that play a role. Some are needed to smoothen, e.g., production, some are there to enhance realism in the model.

First, the most important trigger of all, the start of the simulation. In a single run, we simply hit the Start button in the EventController. When experimenting we hit the method RunExperiments. After the simulation is started, a whole lot of things start to happen. The method Init triggers a lot of other methods that are initialising the simulation, e.g., CreateNetwork, InitAGV and InitLine.

Second, Flamco divides its working days into three shifts of 8 hours. E.g., changing production crews makes it desirable to measure performance per shift. To this end, we let a generator trigger a method called EndShift to increment counting variables related to time (i.e., week, day, shift) and write statistics.

Third, we incorporate failure behaviour of production lines by scheduling begin and end times of a line failure based on a drawn random number. The begin of the first line failure is scheduled at beginning of the simulation, after which the methods *StartFailure* and *StopFailure* trigger each other to make sure future failures are carried out in a proper way.

Fourth, when a new batch is about to enter a production line, we have assumed that a setup needs to be performed. This means that we need two triggers, one that starts the setup and one that ends the setup and starts the batch. The first trigger is taken care of by the first vessel that wants to enter the production line, the second trigger is scheduled by a method that also determines the setup time.

Fifth, as a different article often means a different amount per pallet, the model needs a trigger to adjust the amount of finished products that can be put on a pallet. In addition, this trigger needs to send away the last – potentially partially filled - pallet of the previous batch and start with a new empty pallet.

5.2 Software implementation

Where the previous section explained the conceptual model, this section describes how that model on paper is translated to a computer model.

As mentioned in Chapter 2, we use Siemens Plant Simulation as a software tool to build and simulate our model. A few pages back, Figure 25 already gave an impression of how the main frame of our simulation model looks like. For the ones that are not familiar with the software, Figure 30 displays the basic look and feel.

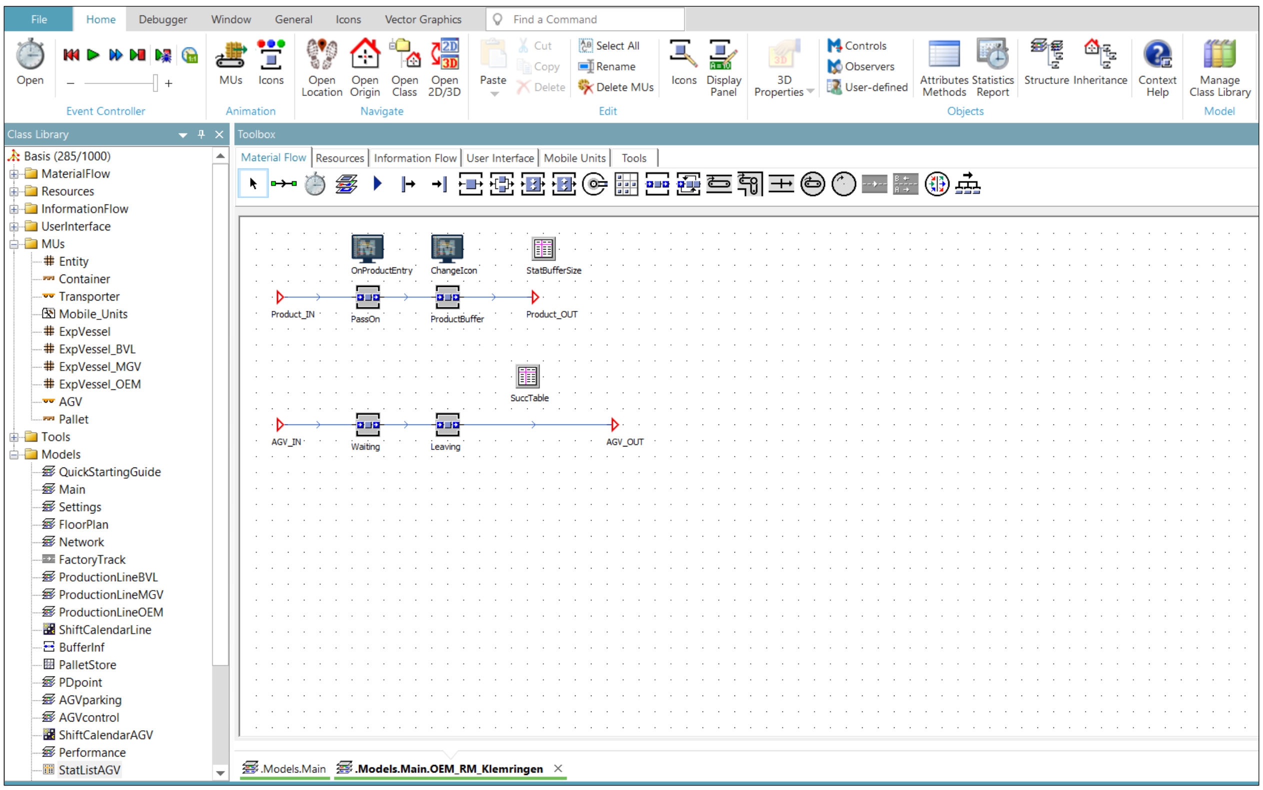

Figure 30: Screenshot of common look of Siemens Plant Simulation 13

Siemens Plant Simulation uses an object oriented way of building a simulation model. In this case, the software already contains standard pre-programmed objects, which the model builder can use to create a model. Note that these standard objects can also be customised. This allows the model builder to tailor a simulation model to a specific problem, process, and environment. Furthermore, the model builder can save a lot of time when modelling / coding by exploiting the duplication option, i.e., extending the model more customised yet identical (or rather similar) objects. In Plant Simulation, everything starts with a *Frame* object on which, e.g., *MaterialFlow* and *InformationFlow* objects can be placed. Even though we will not go into the details here, Figure 31 gives some idea of the structure of the model, i.e., which Frame objects contain which *Methods* which in turn contain the programming code that make things work in the model.

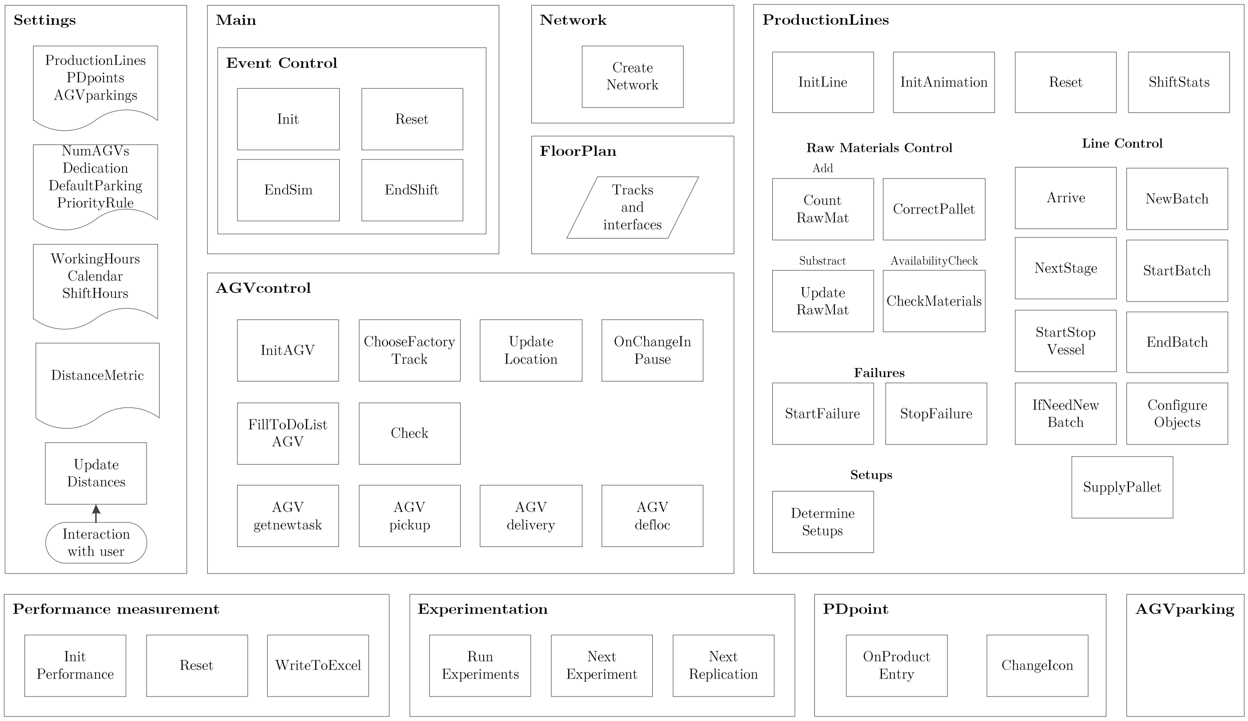

Figure 31: Overview of frames and methods in the simulation model

Now we have an idea of the software and global structure of the computer model, we start to discuss the way we translated the conceptual model into a computer simulation. We address the same points we discussed earlier in the conceptual model.

Product data

Bill of Materials. The model uses a table *ProductionLine_DATA_Products* on the frame *Settings* in which all final products are listed with their raw materials.

Amounts on pallet. For all final products and raw materials, separate tables are made to store the amounts of material that go on a pallet.

Layout and P/D-areas

Layout. In order to have the factory layout fit into the simulation software, the model uses a frame *FloorPlan* with an icon that is a downscaled version of the 2D CAD drawing having the true dimensions.

P/D-areas. P/D-areas are in the model reflected by instances of the *PDpoint* object, which is a frame object in the library.

Distance metric. The simulation model allows for two distance metrics, i.e., Euclidean and Manhattan. A distance metric can be chosen in the frame *Settings*.

Distance calculation. Distances between P/D-areas (in the model denoted by *PDpoint*) are calculated using the midpoints of the P/D-area icons. The pixel distance in the model is determined and multiplied with the scaling factor, because the *Floorplan* icon is a scaled version of the true floorplan, as it needs to fit in a computer screen. The scaling factor translates pixels into meters. Distances are calculated in the frame *Network* using the method *CreateNetwork* and the variable *ScalePixelToDist*.

Production lines

Working hours. Each production line has a *ShiftCalendar* object taking care of the calendar, shifts and maintenance hours. The data with which the *ShiftCalendar* objects are initialised can be found in tables the frame *Settings*.

Line speeds, processing times and line capacities. In our context, where the timing of delivering materials is key, it is easier to model a production line as a (series of) *Line* object(s) with a given length and speed instead of, e.g., a single *ParallelProc* station with a fixed processing time. Therefore, referring to Little's Law again, we use the TH and WIP as input for the simulation model. Yet, because the three production lines are quite different in terms of physical length, production speed and physical product dimensions, we were forced to create a tailored approach for each production line, tweaking things here and there.

The BVL production line is modelled using three *Line* objects, i.e., *Dieptreklijn* (DTL), *ChainConveyor*, and *Afwerklijn* (AWL). The chain conveyor - guiding the vessel halves through the powder coating process – is by far the longest in terms of physical length (meters). For the BVL, it happens to be that the speed of the chain conveyor is known for all articles. As a line process always needs to be balanced, we use this chain conveyor speed across all three *Line* objects. In case more than one article flows in the line, the minimum chain conveyor speed is used for the whole line. Hence, the cycle time of a vessel results from 1) the length of the production line, 2) the chain conveyor speed, 3) the setups (and possible changes in chain conveyor speed) that have happened during the entire production process, and 4) the downtime of the line incurred during the entire production process. The capacity of the line is determined using the estimation of WIP in the line (counted by hand). Within Plant Simulation, we generate MUs with an interarrival time of zero, yet allow only a limited number of MUs to enter the line by setting the capacities of the different lines using the attribute *Line.Capacity*.

For animation purposes, we set the *Line.MUDistanceType* to *MinimumGap* and *Line.MUDistance* to the *Line.Length* divided by *Line.Capacity*. This should not influence any of the simulation. On average, this method should of course result in output figures corresponding with the expected hourly output.

The OEM production line is modelled using two *Line* objects, i.e., *Dieptreklijn* (DTL) and *Afwerklijn* (AWL). As this line does not have a chain conveyor nor a powder coating process, the physical length of the line is with 32 meters much shorter than, e.g., the BVL. Line dynamics are similar to the BVL; we also set the capacity of the whole line using the estimation of WIP in the line (counted by hand). Line speeds are calculated using the method explained in 5.1.3. Again, using these calculated line speeds, WIP, and adding setups and failures, this method should on average yield output figures corresponding with the expected hourly output.

The MGV production line is modelled using three *Line* objects, i.e., *Rondnaadlas* (Lathe), *ChainConveyor*, and *Afwerklijn* (AWL). Apart from line details (e.g., length), the remaining modelling part does not differ from the OEM production line.

Proper animation of the different production lines is guaranteed by the methods *CreateNetwork* (frame *Network*) and *InitAnimation* (frame *ProductionLine*). The former makes sure animation lines are drawn on the *ProductionLine* icon, which lies on top of the *FloorPlan* icon. This way, one can see the expansion vessels flow in the frame *Main*, even though they actually flow in the frames corresponding to the different production lines. The latter takes care that the MUs flow nicely over the animation line with an equal distance between them.

Setups. Within a production line, a setup is triggered by the method *StartBatch*. The method *CalculateSetupTime* is a function that calculates the setup time. To date, calculating the setup time means returning the average setup time (fixed and discrete period of time). Exactly the setup time from now, the method *StartBatch* is called again to actually proceed with production.

Failures. Within a production line, the start and stop of a line failure is determined by two methods: *StartFailure* and *StopFailure*. To calculate a survival respectively failure time, these methods draw a random number in order to get a realisation of the (negative) exponential distribution with parameter MTBF respectively MTTR. Hence, when *StartFailure* is called, it pauses all relevant MaterialFlow objects in the production line, generates a failure time using the (negative) exponential distribution with mean MTTR, and exactly the failure time later, *StopFailure* is called to do the exact opposite thing. The first failure is initialised in the method *InitLine*.

Production planning. The production planning is listed in the table *ProductionPlanning* of the designated production line. Furthermore, the model keeps track of the current status in production in table *ProductionStatus*, i.e., which batches are currently produced on the line and for which batches is transport already initiated or fulfilled, as they are scheduled for the coming *SupplyInAdvanceTime* (e.g., 24 hours). In addition, the table *RawMatStatus* lists, on the level of a single article, which raw materials are available at the line and in which quantities. A summary of the shift production is given in the table *ThisShift*.

Vehicles

Working hours. Each vehicle type has a *ShiftCalendar* object taking care of the calendar and shifts. The data with which the *ShiftCalendar* objects are initialised can be found in tables the frame *Settings*; initialisation happens in the method *InitAGV* on the frame *AGVcontrol*.

Destinations. The method *FillToDoListAGV* searches the destination in TableFile *Destinations* on frame *AGVcontrol*. At the moment, each origin *PDpoint* is associated with only one destination *PDpoint*. The pairs (origin → destination) have a certain FlowType (i.e., InFlow, OutFlow, and ReturnFlow). This FlowType may be used in the priority of transportation tasks.

Vehicle speed. The method *InitAGV* on the frame *AGVcontrol* sets the speed of a vehicle, i.e., an *AGV* object being a MU of type Transporter, according to a variable in the frame *Settings*.

Vehicle loading capacity. The attribute *Capacity* of the *AGV* object in the Library is set to one.

Vehicle handling time. The attribute *Dwell time* in buffer *Leaving* of a *PDpoint* is set to 30 seconds.

Fleet size. The amount of a certain type of vehicle can be changed in table *AGVs* in frame *Settings*.

Vehicle dedication. The dedication of a vehicle can be changed in table *AGVs* in frame *Settings*.

Default parking. The default parking is used by vehicles as a return location when there are no transportation tasks available to execute or when a vehicles is off duty. It might be beneficial to make a tactical choice for a default parking location, i.e., there where transportation jobs are likely to occur. In the simulation model, a default parking location is always used. However, the simulation has a Boolean variable *DefaultLocationAGV* in the frame *Settings*. In case it is set to false, the first parking defined in table *AGVparkings* is used as the default return location. Otherwise, the default parking location of a vehicle can be changed in table *AGVs* in frame *Settings*. The integer number within the column *DefaultParkingAGV* corresponds with the row in table *AGVparkings* where the chosen parking object is defined.

Priority rule to select next transportation job. Vehicles have a dynamic list of candidate transportation tasks based on, e.g., their dedication. From this list, the most urgent job - in the eyes of the stakeholder - should be chosen. This is done by means of a priority rule in the method *AGVgetnewtask* in frame *AGVcontrol*. The priority rule that a vehicle uses to prioritise its list of candidate transportation tasks can be defined in table *AGVs* in frame *Settings*. An overview and short description of the different rules can be found in table *PriorityRulesAGV*.

Note that we set the start date and time for the EventController in Siemens Plant Simulation at Sunday 01/01/2017 23:00. Exactly at this time, the first shift of 2017 starts, i.e., a warmup batch is produced after which the normal production planning is followed.

5.3 Experimental design

In previous sections we discussed the simulation model and its software implementation. Now it is the time to go into detail about how to use the model in order to get meaningful output that helps our research. As we use experimentation to obtain results, we here explain our experimental design. First, we list the experimental factors and scenarios, which we are going to examine. Second, we explain how we deal with the typical prerequisites for a statistical experiment within a simulation study, e.g., warmup, cooling down, run length and replications.

5.3.1 Experimental factors and scenario generation

From the problem description, we know that the Flamco finds itself in a situation with a lot of uncertainty and plenty of room to make decisions with impact, as it will certainly build a brand new factory in the coming years. As a result, the model, we presented in the previous sections, allows for investigating a broad palette of causes related to factory layout, production system dynamics, and intralogistics strategies. In addition, scenarios, in which customer demand - and thereby production capacity - increases, can be simulated.

Recall that the main research question read as follows: *"What is the current intralogistics performance, what does a smart organisation of intralogistics related processes look like in a future business environment, and what performance can be expected from it?".* It dictates three important things to figure out. First, the current intralogistics performance. Second and third, a smart organisation of intralogistics in the expected future situation, and the corresponding expected intralogistics performance.

In retrospect, unravelling the current intralogistics performance is in essence straightforward. However, as currently there is no (quantitative) insight in the intralogistics, one is also keen to understand what happens in the system, instead of only administrating performance. This means that we do more than just performing one experiment with the settings of the current situation. We experiment with different controllable factors (e.g., factory layout, resource pooling, driving strategies, etc.), as it would be pointless to try and influence non-controllable factors such as, e.g., investment budget, climate, et cetera.

After this, we continue with the (expected) future situation and its intralogistics performance. It is presumable that the future business environment, compared to the current situation, is different in multiple ways. For example, customer demand might increase causing also a need for expansion of the production capacity. This could be achieved by working more shifts, adding a production line, et cetera. We step-by-step address the way(s) to an (expected) future business environment (reflected in different scenarios), and the way(s) Flamco can cope with this (using different interventions). Logically, the management of Flamco also has its own vision in this regard. Again, we come to a set of experiments, thereby justifying why we do, or do not, simulate certain scenarios and interventions.

This all within the bounds of what is possible with the simulation model. Note that those bounds are defined along the model building process, in an ongoing dialogue between the researcher and the stakeholder(s) in the project.

In order to define the concrete experiments, we will answer a three-stage rocket of questions:

1. Which factors to vary?
2. Which levels (i.e., value ranges) to choose for each factor?
3. Which combinations of factor levels to simulate?

There are obviously many ways in which these three questions can be answered; enough to make it a research area. In Chapter 4, we briefly discussed the basics.

Yet, simulating one year of Flamco's current factory operations costs our model approximately 1 hour and 20 minutes. Simulating one year of Flamco's future factory operations is even worse, taking around 3 hours. As computational time is limited, we cannot afford the use of a structured method leading to an extensive experimental design. It would simply be too time-consuming. Still, there are a lot of research questions to be answered, and hence, we need to be creative and simulate the "right" things. In literature, this is called *factor screening*, i.e., determining which factors have the greatest effect on a response with the least amount of simulation effort. This might suggest a search for some kind of optimum. However, as can be deduced from our research questions posed in section 1.5, our research is mainly about exploring different (future) scenarios and providing insight into the system performance. As a result, our experimentation phase is about trying to come up with a significant amount of valuable information about the system, given the limitations in terms of computational time. To do so, we systematically cherry pick from the huge set of experiments one could come up with. The way we come to our final set of experiments is explained below. Note that we distinguish between scenarios and interventions, in which a scenario is not to be influenced by the researcher and interventions are. A scenario could relate for example to increased customer demand (and thereby increased production capacity). Interventions refer to more subtle changes in the system, e.g., prioritisation of tasks. In addition, we do some sensitivity analysis to check if the model is heavily influenced by factors that could hardly be estimated.

Basically, there are two interesting cases to consider, i.e., the current factory and the future factory. For the current factory, we know what the layout, production capacity and way of operating is. For the future factory, this is all still open, even though there are some new born plans for the layout and X. As there will be a new facility build in greenfield, it is important that the new factory can cope with today, but also tomorrow. Hence, it should be able to deal with the 'maximum' situation in which four production lines (BVL, MGV, OEM, and X) work 24/7. Note that we then still leave out things like the Air+Dirt department. For details on the two cases, see Appendix I.

In terms of interventions, our focus will be on the intralogistics strategies and capacity, as this is one of the main topics of this research. We do not intervene in the production system, as it is modelled and validated on an aggregated level meaning that one cannot draw too much conclusions on what happens in production on a micro-level.

All in all, we list all relevant factors and their interesting value ranges in Table 14, which we call our experimental setup. It has been discussed to make sure it is in accordance with the needs of our stakeholders. From this setup, we generate experiments a set of experiments, which can be found in the next section.

Table 14: Experimental setup

Experimental setup	
Fixed factors	**Default value**
A. Calendar B. Distance metric C. Distance calculation D. Default location vehicles E. Prefer dedicated vehicles	A. Calendar of 2017, containing public and Flamco specific holidays. B. Manhattan. C. Average distance to incoming goods warehouse taken into account, i.e., 75m. D. A single dock in the middle of the factory, between OEM and MGV *afwerken*. E. If there are dedicated vehicles, yes.
Case	**Short description**
I. Current factory II. Future factory	I. Evaluate the current situation, i.e., three production lines (BVL, MGV, and OEM), and the current production capacity in terms of shifts. II. Evaluate a future scenario where the factory has a new layout, four production lines (BVL, MGV, OEM, and X), working 24/7.
Interventions	**Short description**
1. Supply in advance time 2. No. of vehicles 3. Pooling effect 4. Priority rules	1. Evaluate different supply in advance times (e.g., 24h, 48h, 12h, etc.) to investigate the impact on, e.g., the intralogistics workload. 2. Evaluate a presumable search area around the current vehicle capacity. 3. Evaluate, within the no. of vehicles, different mixes in vehicle type to investigate the differences of using dedicated and/or non-dedicated vehicles to supply the factory. Using only non-dedicated vehicles would suggest a pooling effect. 4. Evaluate different strategies to choose the next task. Use, e.g., the current location of a vehicle to determine a new task (Nearest).
Sensitivity analysis	**Short description**
a. Vehicle speed b. Vehicle handling time	a. 6 km/h as a default value. Sensitivity analysis using ±50% (3 and 9 km/h). b. 30 seconds as a default value. Sensitivity analysis using 10 seconds respectively 60 seconds.

5.3.2 Experiments

As mentioned previously, we discussed the experimental design with the management of Flamco. This co-creation session resulted not only in the important experimental factors being defined in the experimental setup of Table 14, but it also yielded a prioritisation of experiments, which was necessary, as the available computation time is limited. Of course, the priorities of Flamco had to be aligned with the project aspirations looking at it from a research perspective.

As companies generally are especially interested in the research results, priorities were also formulated in terms of output information. In the end, the researcher translated this information into a set of input factors that should be varied. The priorities in terms of output were set as follows (from required to nice-to-have):

1. Intralogistics workload (i.e., number of transportation tasks in the current situation and in a foreseeable future situation). Hence, we need to simulate the current and an expected future situation.
2. Traffic indications (i.e., travel frequencies from an arbitrary point A to an arbitrary point B within the current and future factory).
3. Buffer sizes (i.e., space requirements of P/D-areas in the current situation and in a foreseeable future situation).
4. Relation between the SupplyInAdvanceTime and the intralogistics workload. Especially the case where one supplies production only during the day shift. Hence, SupplyInAdvanceTime should be varied.
5. Relation between the SupplyInAdvanceTime and the buffer sizes of P/D-areas.
6. Relation between the intralogistics workload and the production planning. Production planning is already varied in replications, so different replications should be analysed.
7. Sensitivity analysis, i.e., impact of some model assumptions on the model dynamics and performance. E.g., does the model strongly depend on the vehicle driving speed or the vehicle handling time at each pickup/delivery? Hence, only vehicle driving speed or handling time should be varied in an experiment.

Following the above prioritisation and terminology of the experimental setup, we defined a number of relevant experiments in Table 16. The vehicle types that are mentioned in Table 16, are explained in Table 15.

Table 15: Vehicle types

Vehicle type	Shifts	Dedicated to	Priority rule
1	BVL	BVL	FlowType
2	MGV	MGV	FlowType
3	OEM	OEM	FlowType
4	Day shift only	All	FlowType
5	Day shift only	All	Nearest
6	Day shift only	All	FCFS
7	Day shift only	All	Consolidate
8	X	X	FlowType

Table 16: Experiment overview

Experiment	**Case**	**Interventions**			**Part of sensitivity analysis**
Number	*I or II*	*SupplyInAdvance Time*	*No. of vehicles*	*Vehicle mix: pooling effect and priority rules*	*Yes or No*
1	I	24h	4	1x Vehicle type 1, 2, 3 and 4	Yes
2	I	48h	4	1x Vehicle type 1, 2, 3 and 4	No
3	I	12h	4	1x Vehicle type 1, 2, 3 and 4	No
4	I	6h	4	1x Vehicle type 1, 2, 3 and 4	No
5	I	1h	4	1x Vehicle type 1, 2, 3 and 4	No
6	I	24h	4	1x Vehicle type 1, 2, 3 and 4 with vehicle speed -50%	Yes
7	I	24h	4	1x Vehicle type 1, 2, 3 and 4 with vehicle handling time 60 sec	Yes
8	I	24h	4	1x Vehicle type 1, 2, 3 and 4 with vehicle handling time 10 sec and vehicle speed +50%	Yes
9	I	24h	4	1x Vehicle type 1, 2, 3 and 4 with vehicle handling time 60 sec and vehicle speed -50%	Yes
10	I	24h	4	4x Vehicle type 4	No
11	I	24h	4	4x Vehicle type 5	No
12	I	24h	3	3x Vehicle type 5	No
13	I	24h	2	2x Vehicle type 5	No
14	I	24h	4	4x Vehicle type 6	No
15	II	24h	5	1x Vehicle type 1, 2, 3, 4 and 8	No
16	II	48h	5	1x Vehicle type 1, 2, 3, 4 and 8	No
17	II	12h	5	1x Vehicle type 1, 2, 3, 4 and 8	No
18	II	6h	5	1x Vehicle type 1, 2, 3, 4 and 8	No
19	II	1h	5	1x Vehicle type 1, 2, 3, 4 and 8	No
20	II	24h	5	5x Vehicle type 4	No

5.3.3 Warmup period

With regard to the warmup period, we can keep it short. We study a system in which the production lines and handling personnel work in shifts of 8 hours, yet not always 24/7. This yields a situation in which there seems to be a natural end event, being the end of the shift. However, every shift starts with the situation at the end of the last shift; the system is never emptied. Hence, we face a non-terminating simulation, in which we need a warmup period, and are in the first place interested in the steady-state behaviour of the system.

The question, which then remains, is what warmup period to use. For all production lines, we chose to randomly select one production batch in the production planning and add it as warmup to the top of the planning. Next, we start the simulation, which means that the intralogistics corresponding with the warmup batches are initiated. Once the first batch marked as warmup is finished, we assume this to be the end of the overall warmup period, which means that we start gathering statistics from this point onwards.

5.3.4 Cooling down period

Due to the fact that the simulation has a random character, not all production lines finish their production planning at exactly the same time. We say that the simulation is in its cooling down period once the first production line finishes its production planning. However, this does not affect the collection of statistics, because we prefer capturing the complete intralogistics over having a 'standard' collection period in which all production lines produce. Of course, this requires a different interpretation of the data collected during the cooling down period. A replication / run ends once all production lines have finished their production planning.

5.3.5 Run length and number of replications

We take a year as an approximate run length. This arises from the fact that we create production planning samples using the original production planning of 2017. The original planning we use for model validation. As sampling in our case means nothing more than reshuffling the original planning of 2017, the production workload should still be approximately a year. In case we simulate scenarios where capacity is expanded, we extend the production planning samples such that they approximately cover a year of production.

Next, we do some preliminary runs to determine the number of replications we need for our experiments. As described in Chapter 4, the required number of replications relates to the desired width of the confidence interval(s) of output factors. We take a significance level of 95% (i.e., $\alpha = 0.05$) and a relative error of 5% (i.e., $\gamma = 0.05$). Both are commonly used values in simulation studies.

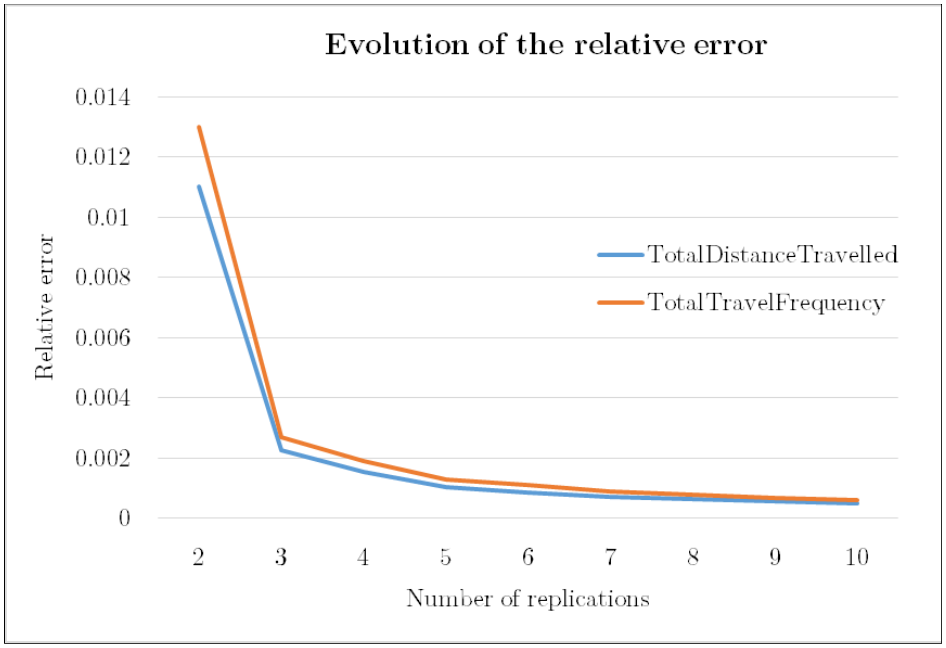

Figure 32: Evolution of the relative error over the number of replications

As we gather lots of different statistics in the model, e.g., travel frequency between two arbitrary P/D-areas, average number of pallets in a P/D-area, total travel distance, number of transportation tasks (per shift, per day, per week), and so on, it is hard to determine the number of necessary replications for all of them. Thus, we calculated the number of replications needed based on two important KPIs: TotalDistanceTravelled and TotalTravelFrequency.

The TotalTravelFrequency is simply the sum of all vehicle drives, the TotalDistance-Travelled is the multiplication of the TotalTravelFrequency and the corresponding driving distance. The determination of the number of replications can be found in Table 17.

Table 17: Number of replications

Alpha	0.05	**Est. time 1 replication current factory = 80 min** **Est. time 1 replication future factory = 180 min**			
Gamma	0.05	**Est. time 1 experiment current factory = 2 * 80 = 160 min** **Est. time 1 experiment future factory = 2 * 180 = 360 min**			
Gamma'	0.047619048				
Replication	**TotalDistance Travelled**	**Half of CI/Mean**	**TotalTravel Frequency**	**Half of CI/Mean**	**Sufficient number of replications?**
1	27,286,373	infeasible	295,759	infeasible	FALSE
2	27,333,687	0.011007	296,365	0.013004	TRUE
3	27,323,533	0.002265	295,872	0.002704	TRUE
4	27,281,091	0.001534	295,524	0.001906	TRUE
5	27,307,925	0.001037	295,971	0.001299	TRUE
6	27,328,528	0.000857	296,218	0.001085	TRUE
7	27,295,048	0.000716	295,836	0.000884	TRUE
8	27,287,180	0.000640	295,723	0.000770	TRUE
9	27,307,138	0.000551	295,892	0.000662	TRUE
10	27,296,968	0.000489	295,858	0.000582	TRUE

From Table 17, we conclude that after two replications, we are already way below the required relative error (γ'), which means we have done enough replications. Taking into account the remarks of Law (2014), which were also discussed in Chapter 4, we show in Figure 32 how the relative errors of the two KPIs behave over the replications. It shows a steadily decreasing relative error, when more replications performed. Note that already after two replications, both relative errors are significantly below the threshold, staying there regardless of the fluctuations. Hence, we perform two replications per experiment.

5.4 Towards a credible model: verification and validation

In this section, we address an important issue that comes with the usage of simulation as a solution method, i.e., the model credibility. We address this issue by stating what we have done to get our stakeholders to trust the simulation model.

5.4.1 Model credibility

A credible simulation model is a model that does what it is supposed to do, in a way that can be expected reading the conceptual model, and deliver results that are not inconceivable.

To establish credibility at our stakeholders, we verify and validate the model, following the advices of Law (2014). First, we use agile approach in the model building phase, which means that we regularly update our stakeholders about the status of the model building process, together find a compromise when it comes to the level of detail of the simulation, and discuss assumptions and simplifications that need to be made while modelling. Second, we extensively use the power of visualisation. Already in an earlier stadium of the model building process, we let vessels flow through the factory. We explicitly show that P/D-areas can be moved (using an interactive drag-and-drop procedure executed by the user) and distances change accordingly. In addition, we show the stakeholders the process of vessels triggering sensors on the line thereby consuming raw materials.

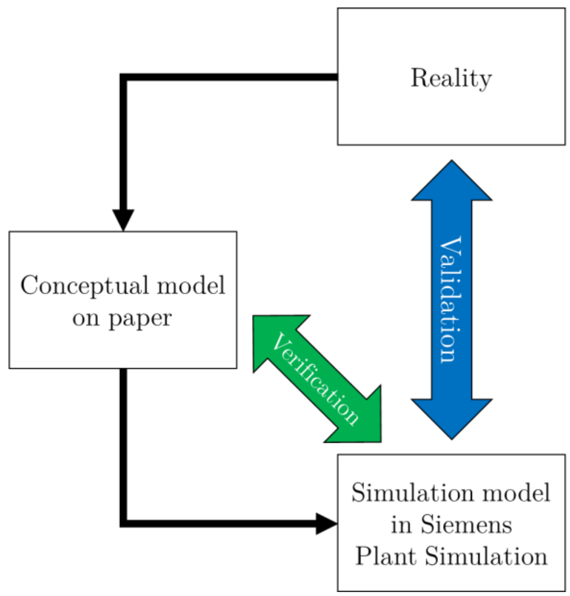

Figure 33: Model verification and validation

Even though visualisation and communication (back-and-forth) are key in establishing credibility, so are model verification and validation, see also Figure 33.

Model verification addresses whether the conceptual model on paper coincides with the software implementation in Siemens Plant Simulation. It is about the correctness of the programming. A verificated simulation model in Siemens Plant Simulation should mimic what it says on paper, i.e., the conceptual model.

Model validation addresses whether the simulation model reflects what happens (or can happen) in reality. Validating the model is obviously an important step in the model building process, as simulating some fantasy world is pointless.

5.4.2 Model verification

In order to verify the model, we perform multiple checks during the coding phase. Every method is thoroughly checked on functioning and errors by stepping through the method (line by line). Besides testing the whole simulation, we also test smaller modules. As we program in an object oriented way, we try to use – as far as possible - standardised objects and procedures to perform identical or similar tasks, regardless of the context, i.e., what triggers a certain object or procedure in a specific situation. When the individual modules do what they are supposed to do, we test the simulation as a whole, exploiting also the fact that one can see what happens (visualisation). We trace an expansion vessel throughout the model, so we can check if all events that are supposed to happen actually happen. Preliminary runs are performed to check whether the output is plausible.

5.4.3 Model validation

Once the model is verified, we perform an extensive validation run, i.e., some replications with the production planning of 2017 as input. This output is used to validate the model. The required number of replications to achieve an acceptable confidence interval for the performance indicators in future experiments is determined by another preliminary run, which uses different production planning samples.

Model validation can be split in two parts: validation of the production system and validation of the intralogistics system. The former is done by means of the planning history. For this, we simulate three times according to the historical production planning (real-life planning from 2017). Then, if the production pattern and the number of vessels produced per week in the simulation model coincide with the production history, we assume we have a valid production system. Table 18, Figure 34, Figure 35, and Figure 36, present the results of this method to validate the different production lines in the production system. We discuss the results briefly.

Table 18: Validation production system: yearly production numbers

Confidential

From Table 18, we can conclude that the yearly production output of the model meets the real yearly production output accurately enough.

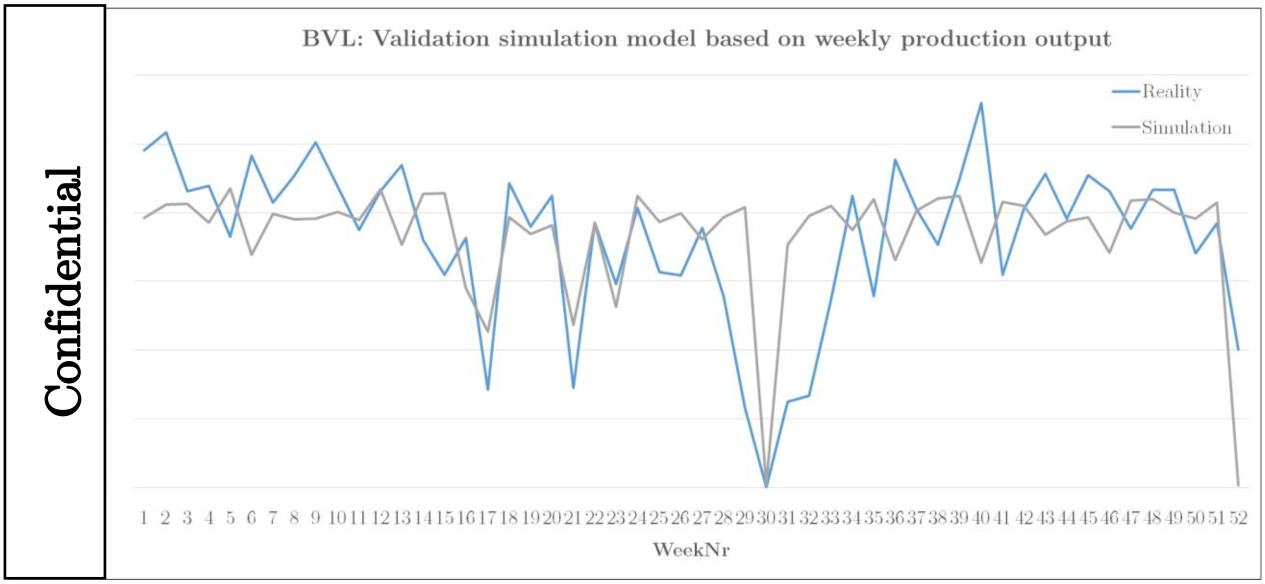

Figure 34: Validation BVL production line; by comparing production timeline in simulation and reality

For the BVL, one can see in Figure 34 that the production pattern resulting from the model is similar to what happened in reality. The general structure of highs and lows in production is roughly followed by the model. Note that the model does not use the exact failures from 2017, yet generates random failures based on the failure history of 2017. Also, the model uses an average setup time between each production batch, which deviates from reality. These naturally induces variation, which is good, as things in 2017 could also have gone differently. Around week 30, during the summer break, one can see that the model is more radical in its drop in production output. In practice, people tend to gradually reduce their working pace when holidays are coming. Furthermore, launching production after a holiday break is always a situation where failures and start-up difficulties are likely to occur. Towards the end of the year, one can see that the simulation model underestimates the production output, which is logical if one considers the fact that it is high-season then and working in overtime is not uncommon. The model does not take into account working in overtime. All in all, we presume the BVL production line to represent reality to a large extent. A discussion of the results with the stakeholders at Flamco confirmed this conclusion.

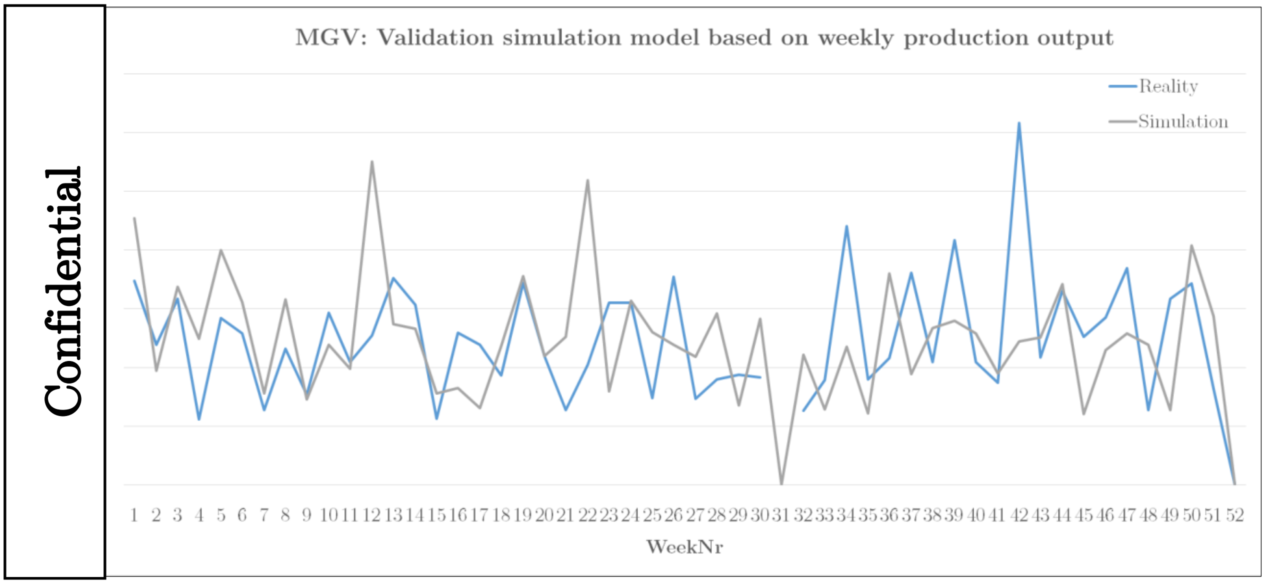

Figure 35: Validation MGV production line; by comparing production timeline in simulation and reality

Looking at Figure 35 for the MGV, the comments that were made during a discussion with the stakeholders at Flamco, were similar to those made when discussing the BVL production line. Hence, we accept and proceed with this model representation of the MGV.

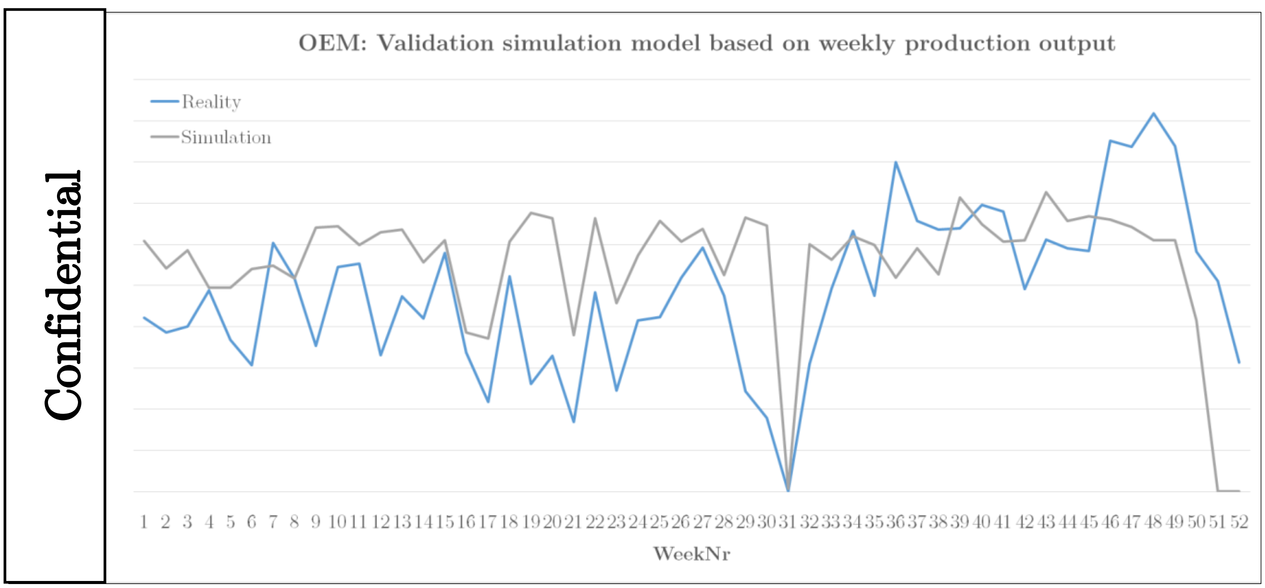

Figure 36: Validation OEM production line; by comparing production timeline in simulation and reality

Considering Figure 36 for the OEM, again, similar comments compared to the BVL and MGV can be made. However, it is remarkable that the model overestimates the production output in the first half of the year and underestimates the output in the second half a year. This can be logically explained, but the reasons have a confidential nature.

Validation of the intralogistics system is more complicated, as providing insight into the intralogistics is the topic of this research. The only thing we could validate is the amount of pallets coming from the lines. However, this does not make too much sense, as the production numbers are already checked when validating the production system. In addition, the model already uses the amount per pallet, which are known for a fact. Even though we cannot validate the intralogistics system, we perform some sensitivity analysis on what are expected to be critical factors, i.e., vehicle driving speed and vehicle handling time. See section 6.3 for this analysis.

5.5 Conclusion on solution design and model construction

This chapter has answered the question "How to construct a model that can quantify both the (expected) performance of the current intralogistics and the new Smart Intralogistics?". As the intralogistics are dependent on the production system, we modelled both. Note that the production system is already a complex queuing model by itself and the intralogistics just adds another layer of complexity. We found (discrete-event) simulation our only suitable modelling option, which is also a part of the concepts of Smart Industry.

The Flamco factory in Bunschoten has been modelled in Siemens Plant Simulation. The model consists of three production lines, modelled as line processes, of which the behaviour is mimicked using (historical) data on production norms, failures, and setups. Data on the amount of material on a pallet in combination with virtual sensors along the lines make sure there are transportation tasks created for the intralogistics system. The intralogistics system itself is added as a module on top of the production system. Vehicles can reach any P/D-area in the factory by making use of tracks that have a length equal to the driving distance, calculated using the Manhattan distance metric. By means of rules on dedication and prioritisation, vehicles are assigned to transportation tasks. An example of a transportation task could be to bring, e.g., clamping rings from the raw materials warehouse to the production line. A simulation run comprehends a year of production (using a randomly sampled version of the production planning of 2017) and the associated internal transportation.

Inputs for the model can be divided into four rather self-explaining categories, i.e., Product data, Layout and P/D-areas, Production lines, and Vehicles. For an extensive overview of the inputs, we kindly refer to section 5.1.3.

As the goal of our research, and thereby our model, is to provide broad insight into Flamco's intralogistics, the model has been made dynamic in many ways. The factors one should vary in experiments therefore depend on the type of question one wants to answer. To get an idea of what can possibly be adjusted in the model, see the list at the end of section 5.1.2. The management of Flamco puts emphasis on the travel frequencies between P/D-areas in the factory. In addition, they want to have an idea of the space requirements associated with different supply frequencies, i.e., supply, e.g., 24 hours in advance, or more, or less. This is especially important if one considers the fact that Flamco will soon build a new production facility in greenfield, replacing the facility in Bunschoten.

The output of the model consists of a broad set of data tables. One is a ledger of the executed transportation tasks. Another one registers which tracks (from/to) are travelled by the vehicles, and hence, results in a travel frequency table that can be used as an input for the Facility Layout Problem (FLP). More on model output can be found in section 5.1.4.

Note that model results only add value when the people involved believe in the validity of the model. To achieve this situation of trust, we have put a major emphasis on model verification and validation. In section 5.4, one can see that not only the model's weekly production numbers are not too far off, but also the production pattern seems to follow the pattern of real-life pretty well. Most deviations can also be easily explained, e.g., by the random components in the model as well as the fact that the model never works in overtime, whereas in reality this happens, especially during high-season. A discussion with the stakeholders established the credibility of the model.

6 Results

In this chapter, we run experiments following the experimental design as explained in the previous chapter, after which we analyse the resulting output data. This roughly means that we consider two cases, i.e., the current situation and a plausible future situation. Within these two cases, we analyse multiple things, e.g., intralogistics workload and buffer sizes. We also perform some sensitivity analysis. The chapter tries to keep monotonous data tables to a minimum and instead uses a lot of graphical representations to present the output data resulting from the model.

6.1 Intralogistics performance of the current situation

This section uses the data from experiments 1-5 and 10-14 (as defined in section 5.3.2). Recall that in the current situation, we examine Flamco's current factory in Bunschoten, i.e., the current layout with three production lines (see also Figure 25), working their common shift schedule. The default number of vehicles is equal to four, i.e., three vehicles dedicated to a production line (working also the same hours) and one vehicle dedicated to all lines, yet working only the day shift. The default supply in advance time is 24 hours.

If it is not mentioned explicitly, we show experiment results corresponding with the default settings. Evidently, we also vary factors to analyse the system, but when we compare those results with the standard case, we will refer to this explicitly.

6.1.1 Intralogistics workload

In order to show how the distribution of the intralogistics workload looks over time, we use three levels of aggregation, i.e., week, day of the week, and shift of the week. We examine one year of production for which we perform multiple replications to get an average situation. We show the results of the single replications as well as the average. The former we do to provide insight in how much the replications (can) differ from each other (due to a different production planning). As one can see in Figure 37 and Table 19, the replications do not differ much from each other, i.e., the difference stays within a bandwidth of around x pallets a week, which is around 10% of the total. On a daily or shift basis, this percentage is similar. As a result, we proceed with presenting only the average situation, as we then are at least on average 'right' – knowing that we do not know what the future production planning will look like.

Because the averages in Table 19 are calculated over the 'average replication', i.e., the average of replication 1 and 2, the average minimum, maximum, and standard deviation seem odd, but are calculated correctly. E.g., the standard deviation of the 'average' replication is lower than replication 1 or 2, because, e.g., a high workload in week 1 in replication 1 cancels out a low workload in week 1 in replication 2. The same holds for the average minimum and maximum.

On a weekly basis, in the current situation, Flamco transports around x pallets. According to Table 19 and Figure 38, the minimum amount of pallets transported during a week lies around x pallets. The timing of this minimum falls in the holiday period, which is presumable. However, those holiday weeks do have an influence on the average workload over the weeks, which makes it necessary to emphasise that in a considerable number of weeks, a number of transports close to x pallets is realised.

Table 19: Statistics on average weekly intralogistics workload

Replication	Minimum	Average	Maximum	Standard deviation
1	Confidential			
2				
Average				

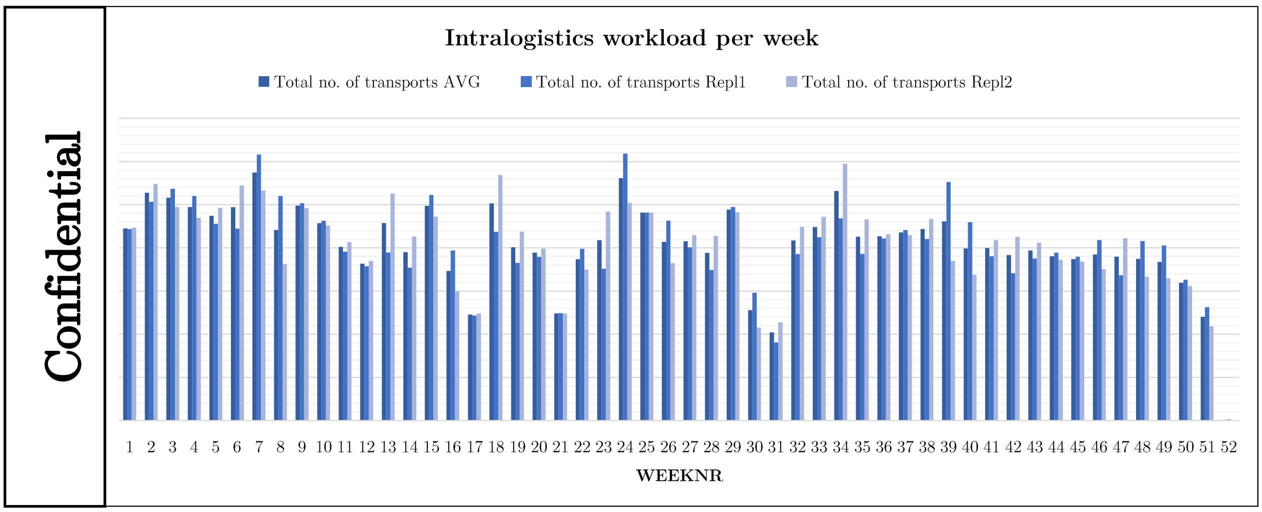

Figure 37: Intralogistics workload per week

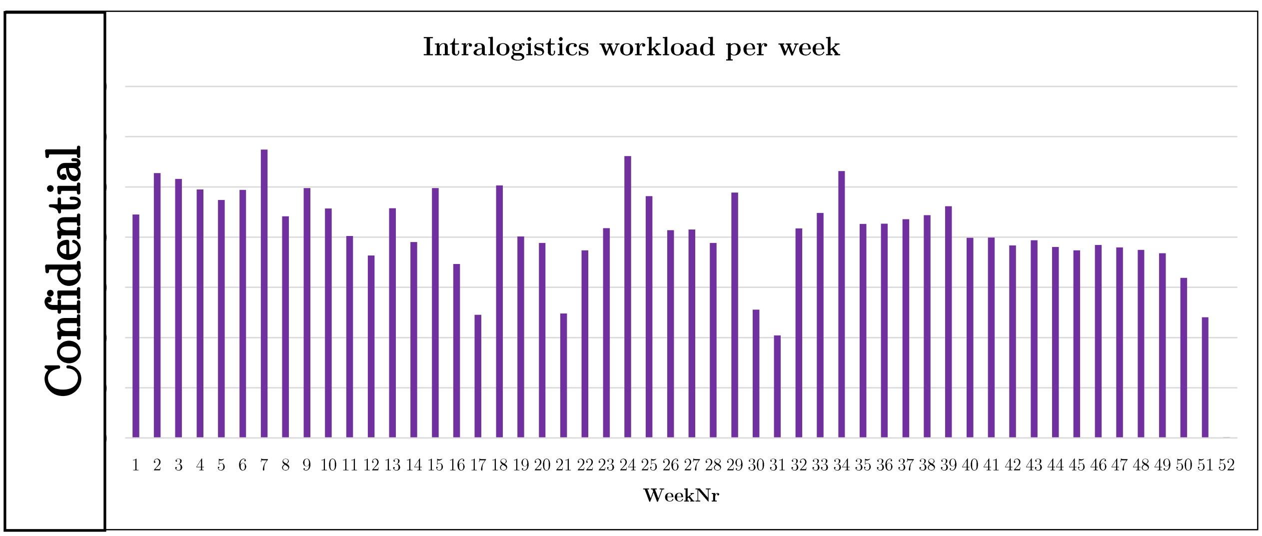

Figure 38: Average intralogistics workload per week

When dividing the total intralogistics workload over the vehicles that did the work, see Figure 39, one can see that the percentage share of different vehicles in the weekly total number of transports varies quite a bit, especially for the MGV. Comparing these percentage shares to the actual workload, as can be seen in Figure 40, the general pattern seems to be rather similar, meaning that the fleet size is sufficient and Figure 39 mainly indicates how busy a certain vehicle was in a particular week. Still, the fluctuations in workload for the MGV are remarkable.

What is also nice to see, is that the fourth vehicle - working for everybody, but only during the day – helps levelling the workload of the busiest line. Even though the vehicle only works during the dayshift, it still takes up 1/5 of the total workload, which is significant if one considers the facts that a) dedicated vehicles work the same hours as the production lines, so also during evening and night shifts, and b) the model prefers dedicated vehicles when available. Nevertheless, this levelling function proves itself to be handy when a need for a new batch (and thereby new materials) is dispatched to the production at once. The fact that the transportation tasks corresponding to a new batch are released all at once makes that the levelling function of the all-round vehicle is not sensitive to the supply in advance time.

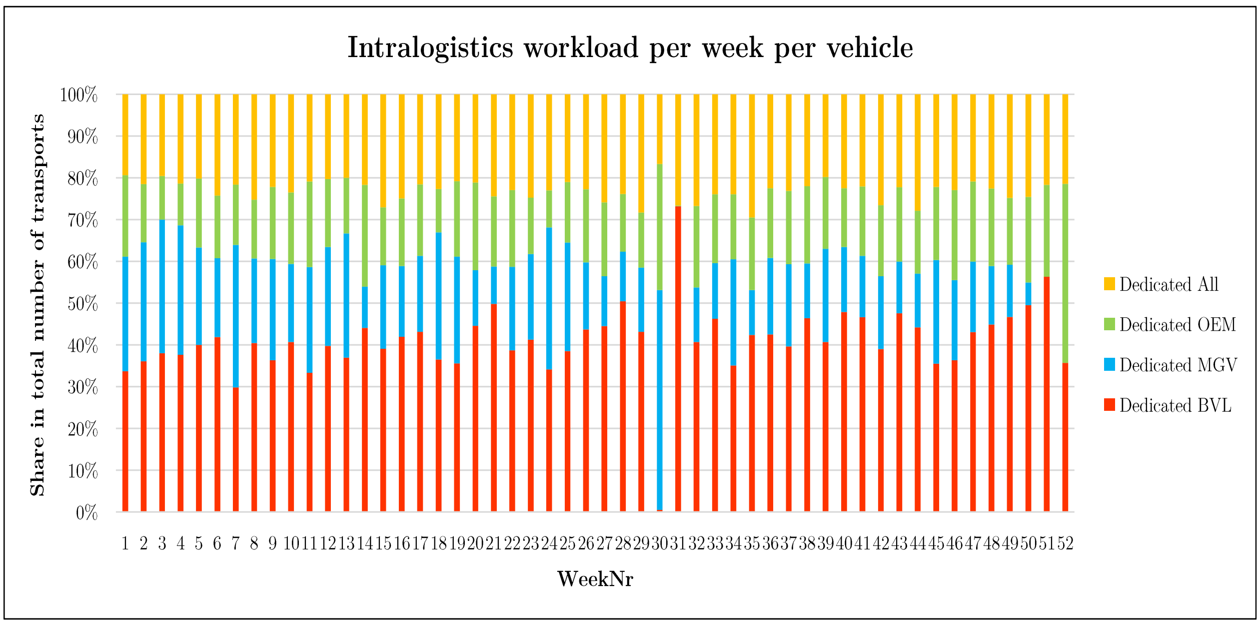

Figure 39: Average weekly intralogistics workload divided over the vehicles (in percentage)

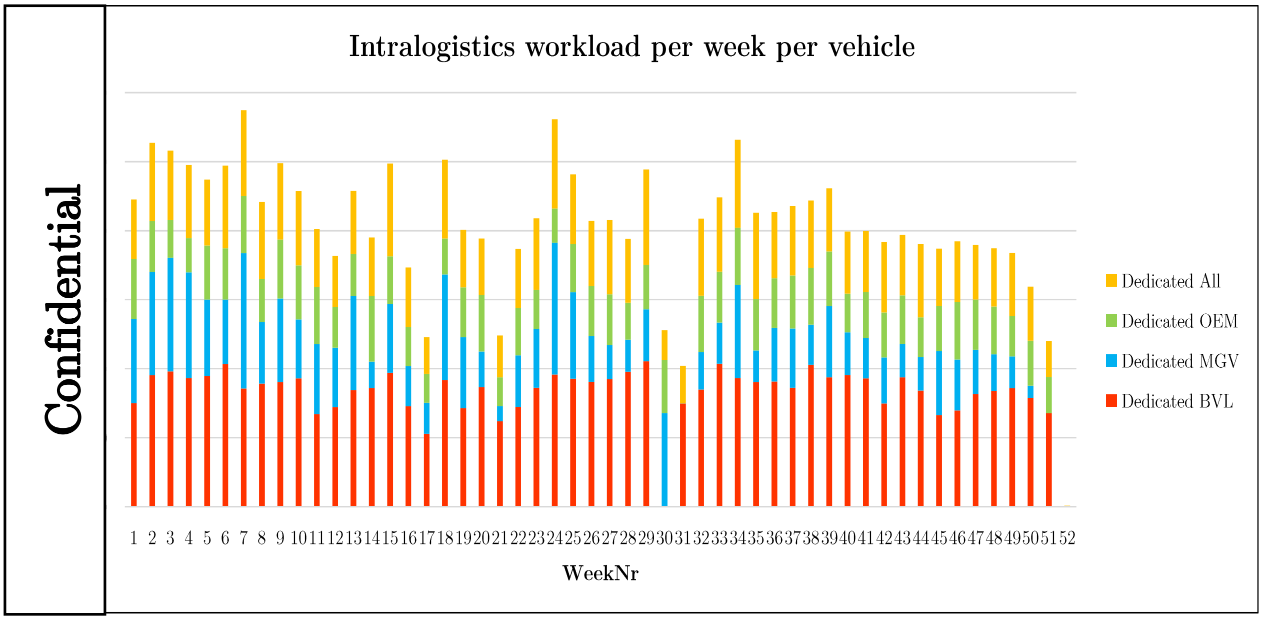

Figure 40: Average weekly intralogistics workload divided over the vehicles (in number of transports)

In addition to dividing the workload over the different vehicles, we can also split and assign the workload to the different flow types, i.e., finished goods (FinGoods), raw materials (RawMat), and return flows (Returns). What we then see in Figure 41 and Figure 42, is that the finished goods strongly dominate the intralogistics workload. When comparing Figure 41 and Figure 42, it is remarkable that the workload fluctuates while the imaginary line that indicates the share of finished goods in the total number of transports over the weeks stays flat, as it lies structurally between the x1-x2%. Hence, the fluctuation in intralogistics workload depends for ±x% on finished goods; and, when this transportation volume increases, the volume in raw materials and returns increases with it – almost at the same pace.

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Figure 41: Average weekly intralogistics workload divided over the flow types (in percentage)

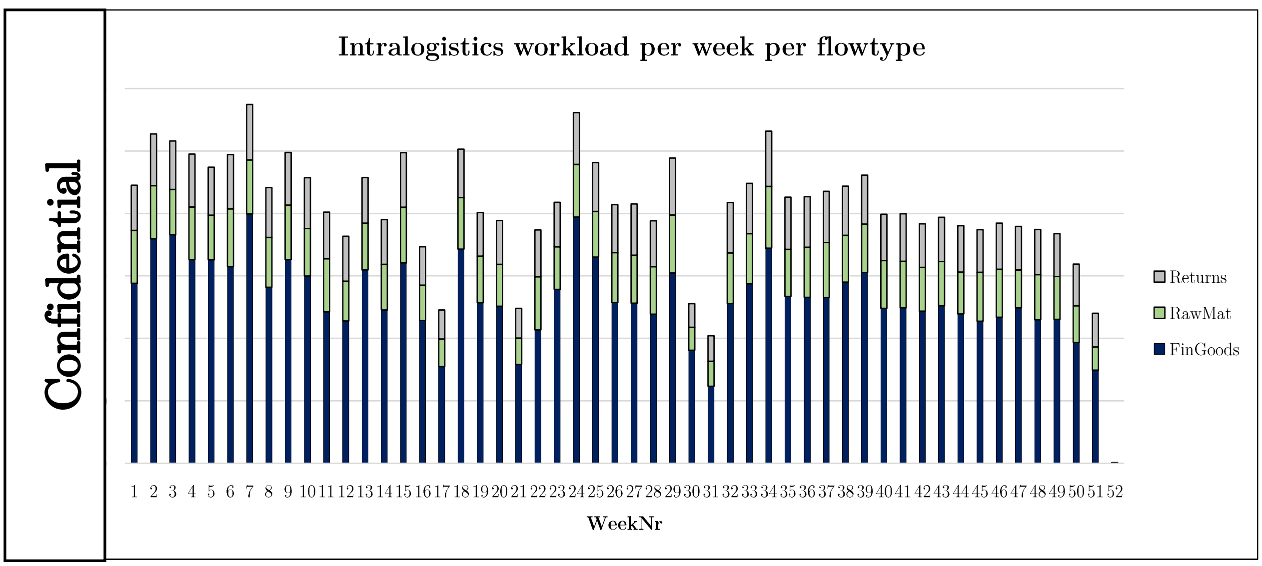

Figure 42: Average weekly intralogistics workload divided over the flow types (in number of transports)

Having said this, it is interesting to look and see if we can connect the intralogistics workload to that what has happened in production. I.e., what vessels were together responsible for a large workload. Suppose we take week 7 as an example and look for the two replications which articles/vessels were produced in that week. Table 20 displays the results. As one can see, the production history of the different replications is quite different, yet there are some remarkable things to comment on. First, in both replications, the MGV line produces vessel belonging to the product group “790”. Hence, producing “790 vessels” could be an indication for an increased intralogistics workload. This would not be surprising as “790 vessels” are large in terms of size. As a result, they consume, besides, e.g., a lot of steel and carton, one pallet per finished product, which significantly increases the outgoing flow of finished goods. Nevertheless, more analysis needs to be done to be able to prove a certain relation between the production of a certain product group and the intralogistics workload.

Table 20: Data sample for possible relation between the intralogistics workload and the production history

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Then, shifting from a weekly overview to an analysis of the weekdays, we listed in Table 21 the average number of transports per day of the week. From Table 21 and Figure 43, it can be concluded that the transportation workload is rather stable across the working days, with a decline on day 3 (Wednesday), which is logical, as Flamco schedules maintenance every Wednesday morning. It also seems to be that, on average, somehow large batches start on Tuesdays, thereby increasing the intralogistics workload temporarily.

Table 21: Numerical details on average daily intralogistics workload

Day number	Total number of transports	Average number of transports	Finished goods	Raw materials	Returns
1					
2					
3					
4					
5					
6					
7					

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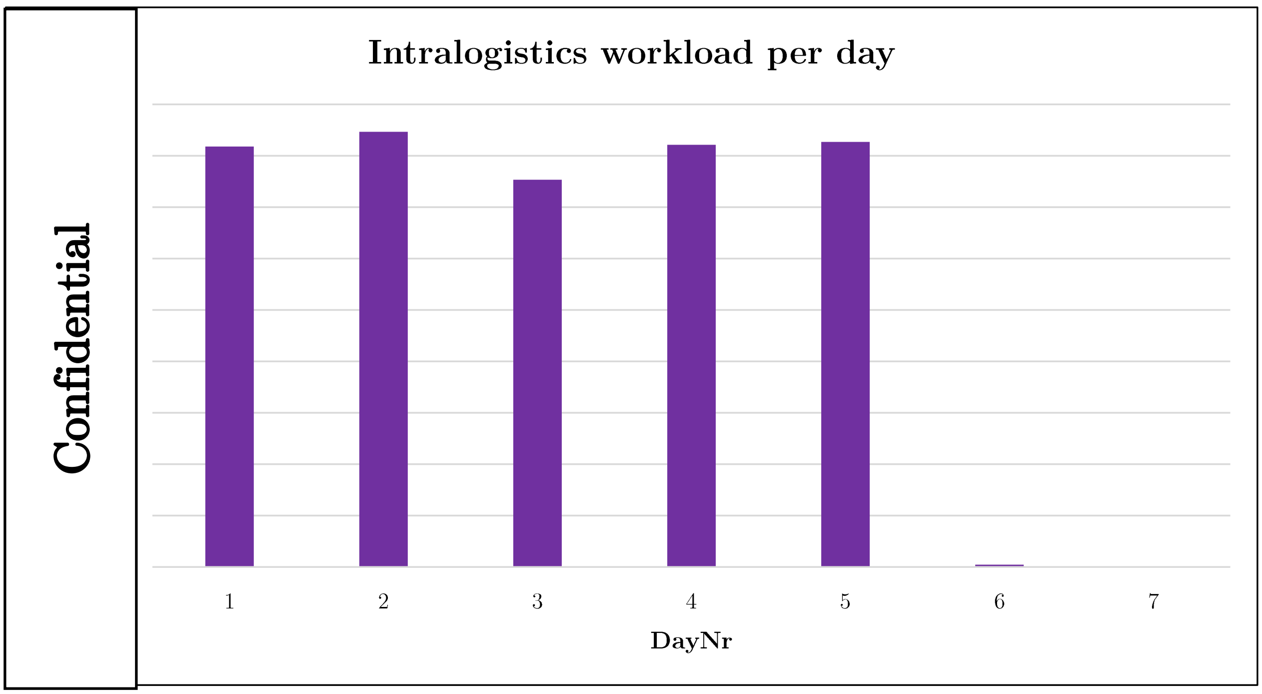

Figure 43: Average intralogistics workload per day of the week (with 1=Monday, 2=Tuesday, etc.)

If we then again divide the average daily workload over the vehicles (see Figure 44), we see that every vehicle has a rather stable amount of pallets it transports on a day. Yet, the differences among vehicles are remarkable. Note that the vehicles dedicated to the BVL respectively the OEM line work the same amount of hours. The vehicle supplying the BVL, transports daily ±2.5 times as much pallets as the vehicle of the OEM does; taking also into account the fact that the fourth vehicle (working for all lines and only during the dayshift) probably helps the BVL vehicle most of the time, i.e., due to its highest workload and thereby occupancy.

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Figure 44: Average daily intralogistics workload divided over the vehicles (in number of transports)

Besides distinguishing between vehicles executing transportation tasks, we could of course also split the daily workload in flow type. If we do so, see Figure 45, it is remarkable to see that the amount of raw materials brought into the factory is stable around x pallets a day. The return flow is on an equal level, which means that the average total number of raw material pallets in the factory is rather stable over time. However, the mix may vary and peaks might occur.

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Figure 45: Average daily intralogistics workload divided over the flow types (in number of transports)

As a last step, we can zoom in to the level of a shift. We examine every shift of the week, taking the average over the whole year across multiple replications. What we then see in Table 22 and Figure 46, is the following.

First, the night shifts are considerably less busy then the day and evening shifts, which is due to the fact that a certain production line does not work the shift night. If it would also start working in a 3-shift schedule, the situation showed in Figure 47, can be expected. This would mean that the average workload per shift is levelled with a number of transports in the bandwidth of [x1, x2].

Second, looking at the differences within a shift, there is a considerable gap between the maximum number of transports (occurred once in a replication) and the global average (taken over multiple weeks and replications). To give an example, for the dayshift on Monday, on average, the number of transports is equal to x. However, there has been a dayshift on Monday in which there were y pallets transported. That is more than twice the work. However, in the default setting this is not a problem, as for each of the four vehicles used, the percentage of time driven full does not exceed 30%.

Table 22: Numerical details on average intralogistics workload per shift

<table>
<tr><th>Shift number</th><th>Shift</th><th>Minimum number of transports</th><th>Average number of transports</th><th>Maximum number of transports</th></tr>
<tr><td>1</td><td>Monday Night</td><td rowspan="17" colspan="3">Confidential</td></tr>
<tr><td>2</td><td>Monday Day</td></tr>
<tr><td>3</td><td>Monday Evening</td></tr>
<tr><td>4</td><td>Tuesday Night</td></tr>
<tr><td>5</td><td>Tuesday Day</td></tr>
<tr><td>6</td><td>Tuesday Evening</td></tr>
<tr><td>7</td><td>Wednesday Night</td></tr>
<tr><td>8</td><td>Wednesday Day</td></tr>
<tr><td>9</td><td>Wednesday Evening</td></tr>
<tr><td>10</td><td>Thursday Night</td></tr>
<tr><td>11</td><td>Thursday Day</td></tr>
<tr><td>12</td><td>Thursday Evening</td></tr>
<tr><td>13</td><td>Friday Night</td></tr>
<tr><td>14</td><td>Friday Day</td></tr>
<tr><td>15</td><td>Friday Evening</td></tr>
<tr><td>16 17 18</td><td>Saturday</td></tr>
<tr><td>19 20 21</td><td>Sunday</td></tr>
</table>

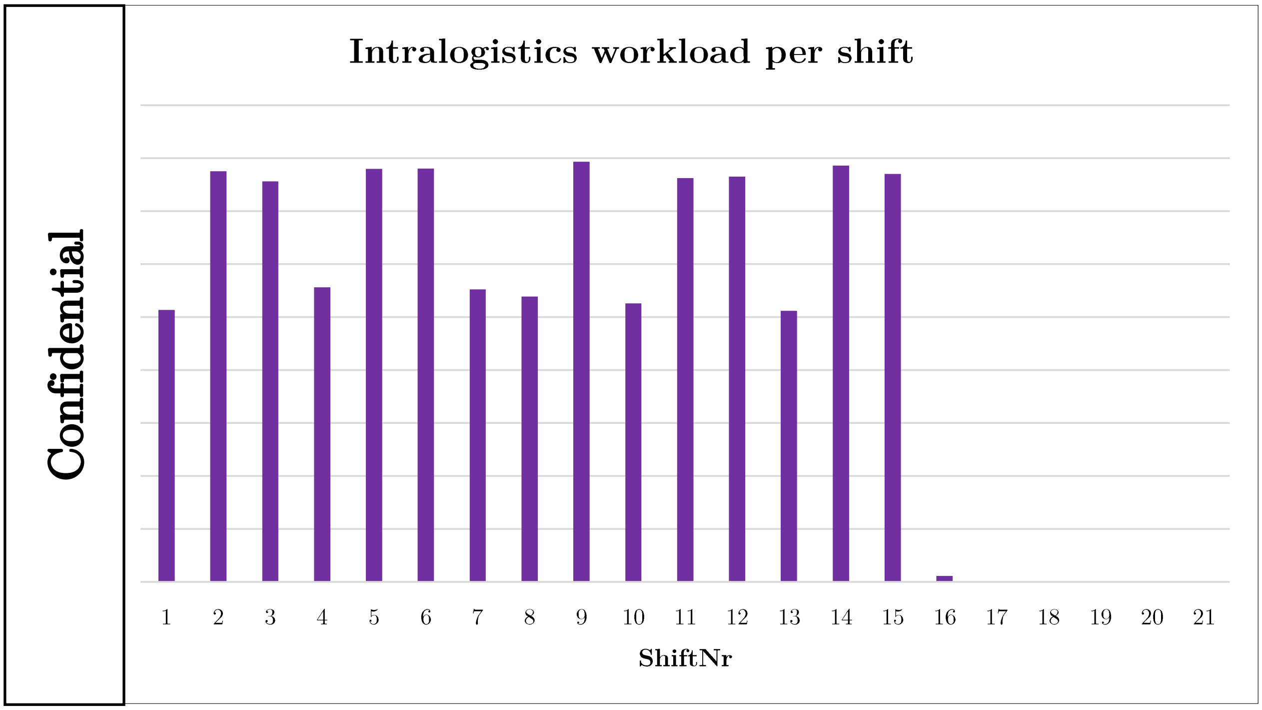

Figure 46: Average intralogistics workload per shift of the week (1=Monday Night, 2=Monday Day, etc.)

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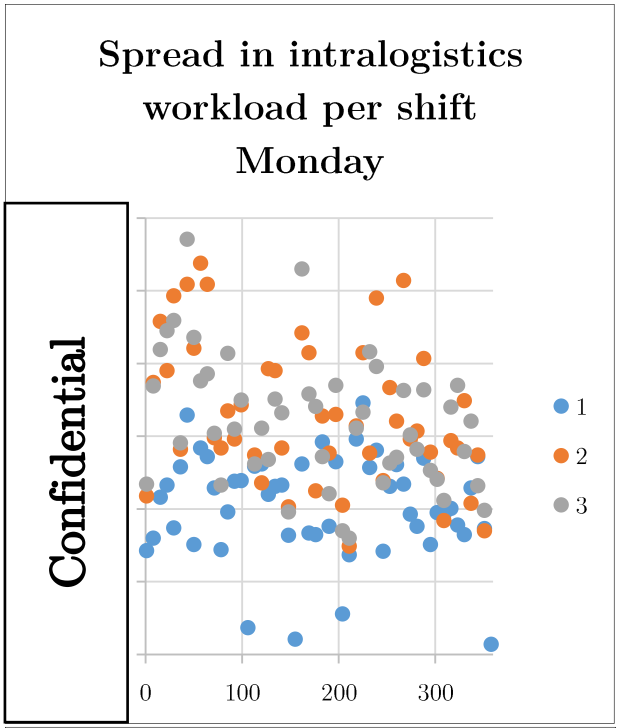
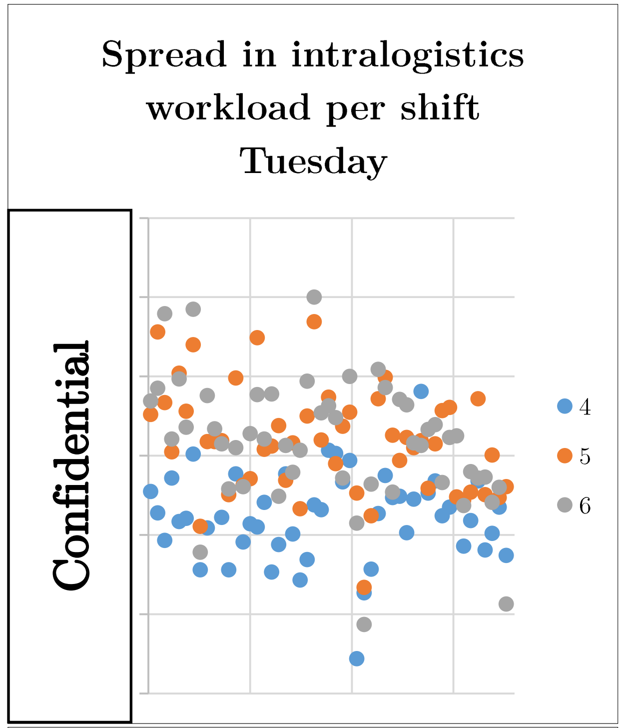
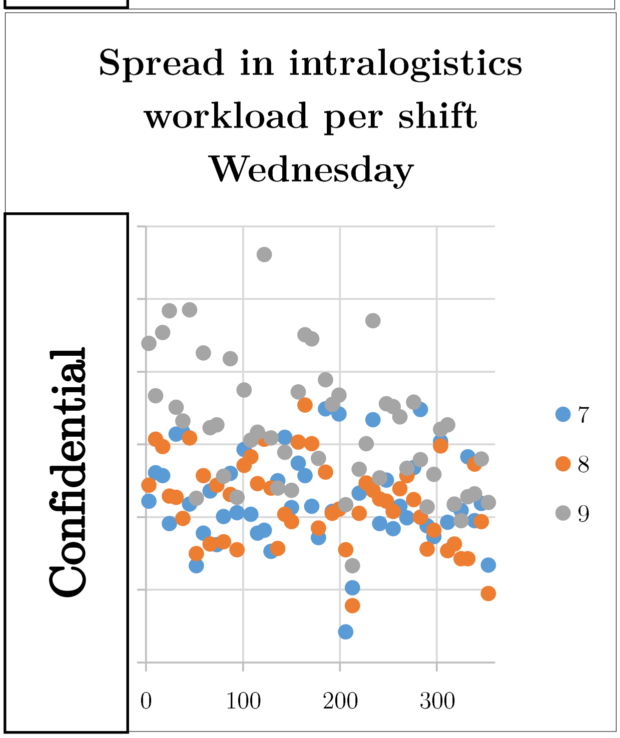
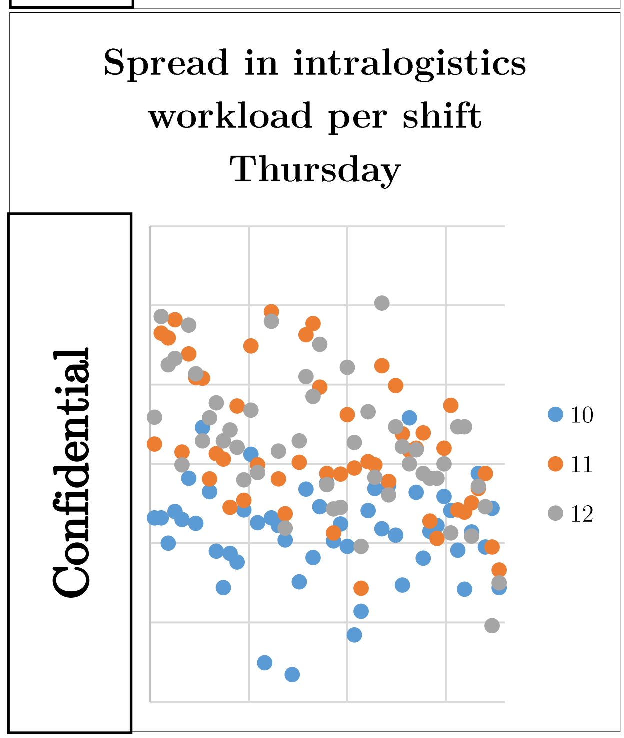
Figure 47: Average intralogistics workload per shift of the week in case production capacity is increased


Spread in intralogistics workload per shift Monday
Confidential
0
100
200
300
1
2
3


Spread in intralogistics workload per shift Tuesday
Confidential
4
5
6


Spread in intralogistics workload per shift Wednesday
Confidential
0
100
200
300
7
8
9


Spread in intralogistics workload per shift Thursday
Confidential
10
11
12

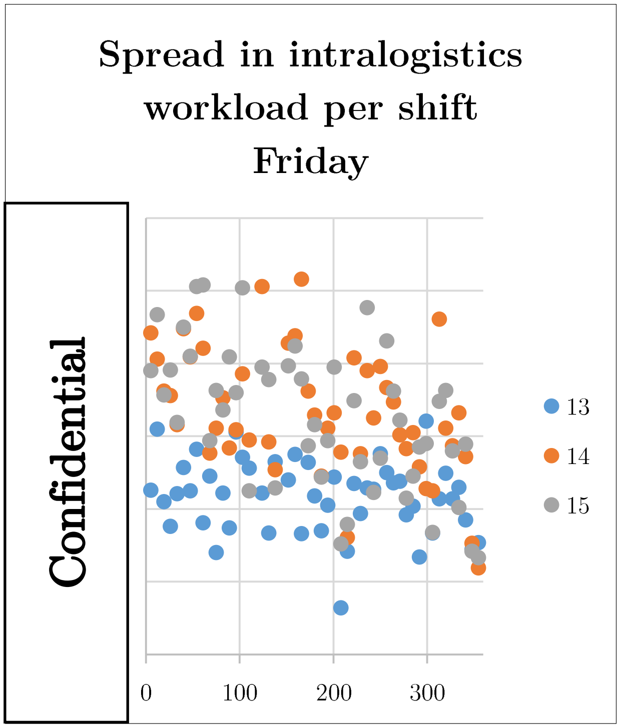


Figure 48: Spread in intralogistics workload per weekday per shift

6.1.2 Vehicle utilisation: effects of resource pooling, fleet size and prioritising tasks

In order to investigate how much intralogistics capacity (e.g., no. of forklifts) Flamco currently needs and how we can improve that, we kept track of the utilisation of vehicles under different circumstances. We define utilisation as the percentage a vehicle drives full, i.e., with a pallet. However, as the utilisation of vehicles depends heavily on variables for which assumptions have been made, i.e., the distance travelled and the driving speed, we do not know if the output numbers (utilisations) are accurate. Yet, regardless of the accuracy of the utilisation, the impact of interventions (e.g., resource pooling or a changed priority rule) should still be visible. So, to make things clear, we asked ourselves the following what-if questions:

Note that in the current situation, each production line has its own dedicated vehicle (working the same hours) to supply the line. In addition, during the dayshift, a fourth vehicle supports the dedicated vehicles.

1. What if we do nothing, leaving the current situation as it is? What vehicle utilisations can we expect?
2. What happens if a certain production line goes from a 2-shift to a 3-shift schedule?
3. What happens if we pool resources and every vehicle works, only during dayshift, for every production line? And when doing this, do priority rules for choosing the next transportation task matter?
4. What if we change the fleet size, i.e., the number of vehicles supplying the factory?

The results are displayed below.

Table 23: Comparison of vehicle utilisations when X goes from 2 to 3 shifts

Experiment	**Vehicle type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Working in shifts	BVL	MGV	OEM	Day only	Day only	Day only	Day only	GVL
	Priority rule	Flow Type	Flow Type	Flow Type	Flow Type	Nearest	FCFS	Conso-lidate	Flow Type
Total vehicle capacity: 4	*Capacities of vehicle types*	1	1	1	1	0	0	0	0
% of time driving full per vehicle (veh. 1 to 4)		**0.231**	**0.077**	**0.059**	**0.094**				
Total vehicle capacity: 4	*Capacities of vehicle types*	1	1	1	1	0	0	0	0
% of time driving full per vehicle (veh. 1 to 4)		**0.181**	**0.172**	**0.067**	**0.090**				

As one can see in the top of Table 23, we can expect vehicle utilisations in the current situation that lie between 6% and 23%, which seems rather low. The vehicle dedicated to the BVL is the busiest, whereas the vehicle of the OEM is occupied the least of the time. When a certain production line goes from 2 to 3 shifts, the utilisations also change quite a bit. The vehicle dedicated to the BVL becomes less busy, which is surprising, but can be explained by the fourth vehicle, which apparently starts helping out the BVL vehicle more often. In addition, the MGV vehicle becomes much busier, yet still has an utilisation below 20%. The OEM vehicle also becomes busier.

Now, what happens if we pool resources? That one can see in Table 24. Note that we use two times 4 vehicles, of which the utilisations are denoted in the first 4 columns of the table, with at the top of the table the non-pooling situation and in the bottom of the table the scenario in which we pool the resources. What can be concluded, is that in the situation with pooling, the first vehicle is by far the busiest, then the second, then the third, and lastly the fourth vehicle. This is exactly corresponds with the ranking of the vehicles (vehicle 1, 2, 3 and 4), which is logical, as the simulation model just picks the first suitable vehicle in case more than one vehicle suits the job. As a result, one can conclude that in only 3% of the time, there are 4 tasks available to execute at the same time. The rest of the time, the fourth vehicle does not have to anything. Even though, there might be overcapacity in both the pooling and non-pooling scenario, it seems that in the pooling scenario, we use our resources more efficiently. Furthermore, in the pooling situation, the share of work done by each vehicle is stable over the weeks, regardless of how much work there is to do in a certain week. See Figure 49, and Figure 39 to compare.

Table 24: Comparison of vehicle utilisations in a pooling and non-pooling scenario

Experiment	**Vehicle type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Working in shifts	BVL	MGV	OEM	Day only	Day only	Day only	Day only	GVL
	Priority rule	Flow Type	Flow Type	Flow Type	Flow Type	Nearest	FCFS	Conso-lidate	Flow Type
Total vehicle capacity: 4	*Capacities of vehicle types*	1	1	1	1	0	0	0	0
% of time driving full per vehicle (veh. 1 to 4)		**0.231**	**0.077**	**0.059**	**0.094**				
Total vehicle capacity: 4	*Capacities of vehicle types*	0	0	0	4	0	0	0	0
% of time driving full per vehicle (veh. 1 to 4)		**0.250**	**0.131**	**0.060**	**0.029**				

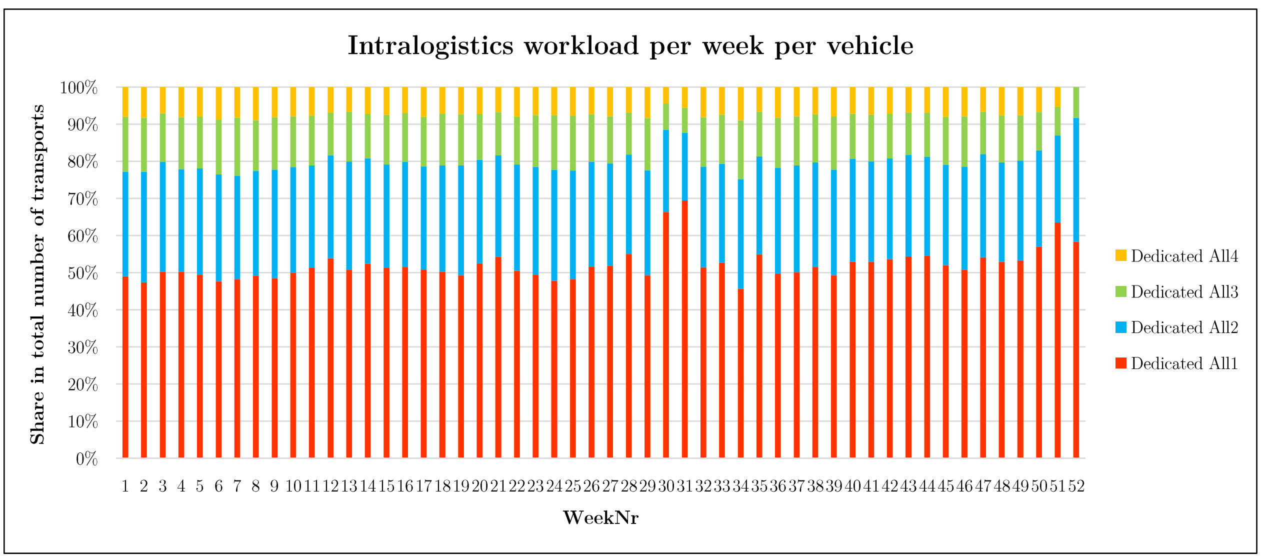


Figure 49: Average weekly intralogistics workload divided over the vehicles (in percentage)

Now we discussed the positive effect of resource pooling, it may even get better when we use other (smarter) priority rules to choose transportation tasks. The results of this are displayed in Table 25. The conclusion is simple, a priority rule does not matter, at least not in this situation where we seem to have overcapacity.

Table 25: Comparison of vehicle utilisations under different priority rules (pooling scenario)

Experiment	**Vehicle type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Working in shifts	BVL	MGV	OEM	Day only	Day only	Day only	Day only	GVL
	Priority rule	Flow Type	Flow Type	Flow Type	Flow Type	Nearest	FCFS	Conso-lidate	Flow Type
Total vehicle capacity: 4	*Capacities of vehicle types*	0	0	0	4	0	0	0	0
% of time driving full per vehicle (veh. 1 to 4)		**0.250**	**0.131**	**0.060**	**0.029**				
Total vehicle capacity: 4	*Capacities of vehicle types*	0	0	0	0	4	0	0	0
% of time driving full per vehicle (veh. 1 to 4)		**0.250**	**0.133**	**0.060**	**0.030**				
Total vehicle capacity: 4	*Capacities of vehicle types*	0	0	0	0	0	4	0	0
% of time driving full per vehicle (veh. 1 to 4)		**0.249**	**0.131**	**0.059**	**0.029**				

Previously, we mentioned overcapacity, so we now decrease the vehicle capacity and see what happens. In Table 26, we can see that the lower the number of vehicles the higher the utilisation, which is intuitive. It also seems as if one vehicle could do the job for the entire factory. This makes us question our own model and assumptions. But, on the other side, what happens today is that one guy drives a forklift during day time, supplying the most of the materials to the edges of a production line, after which normal operators put materials right next to machines. And, we do not know how busy operators are with that. If you ask, everybody is always busy, but it may be that indeed only one vehicle is enough, as long as this vehicle knows the moment it delivers something, where it should go next. And currently, that is not the case, this layer of communication is simply non-existent.

Table 26: Comparison of vehicle utilisations under different fleet sizes (pooling scenario)

Experiment	Vehicle type	1	2	3	4	5	6	7	8
	Working in shifts	BVL	MGV	OEM	Day only	Day only	Day only	Day only	GVL
	Priority rule	Flow Type	Flow Type	Flow Type	Flow Type	Nearest	FCFS	Conso-lidate	Flow Type
Total vehicle capacity: 4	*Capacities of vehicle types*	0	0	0	0	4	0	0	0
% of time driving full per vehicle (veh. 1 to 4)		**0.250**	**0.133**	**0.060**	**0.030**				
Total vehicle capacity: 3	*Capacities of vehicle types*	0	0	0	0	3	0	0	0
% of time driving full per vehicle (veh. 1 to 3)		**0.253**	**0.139**	**0.069**					
Total vehicle capacity: 2	*Capacities of vehicle types*	0	0	0	0	2	0	0	0
% of time driving full per vehicle (veh. 1 to 2)		**0.267**	**0.172**						
Total vehicle capacity: 1	*Capacities of vehicle types*	0	0	0	1	0	0	0	0
% of time driving full per vehicle (veh. 1 to 1)		**0.383**							

6.1.3 Traffic indications

To give an idea of the interaction between different parts of the factory, we use the performance table *TracksTravelled*. Recall that this tables contains a from/to-matrix registering all travels from one point to the other, or in our instance, from one P/D-area to the other. In the remaining of this section, we display the most important travel frequencies using the same kind of matrix type tables; and, we discuss each line briefly.

Note that the amount of travels have a proportional relation with the traffic on a certain factory route. In this section, we only show the most important travel frequencies, i.e., those that also say something about the volumes of the in- and output materials of a specific production line.

This means that here we ignore the fact that there are plenty of ways (e.g., task prioritising strategies) to arrive at a certain point in the factory – to either pick something up or to deliver something. However, this does influence the traffic intensities within the factory. Therefore, we provide a complete overview of the travel history in Appendix 0. This of course also indicates the total traffic that can be expected at different places in the factory and on different factory routes.

Table 27: Overview of the important average yearly travel frequencies for the BVL

To / **From**	BVL_ Rondellen	BVL_ Klemringen	BVL_ Membranen	BVL_ Karton	BVL_FG_ Warehouse
BVL_ FinishedGoods					**X**
BVL_RM_ Rondellen	**3101**				
BVL_RM_ Klemringen		**2012**			
BVL_RM_ Membranen			**3569**		
BVL_RM_ Karton				**2330**	

As one can see in Table 27, a travel from the end of the BVL production line to the finished goods warehouse occurs much more often than a travel from the incoming goods warehouse to a raw materials P/D-area at the production line, i.e., the ratio is more than x : 1. This was already emphasised in the section about the intralogistics workload, but now it is quantified using yearly travel numbers. It is estimated that for the BVL, we move around x pallets with finished goods into the finished goods warehouse.

Talking about raw materials, the total lies around 11000. Within that, the ranking in terms of travel frequency is as follows: first, the diaphragms (in Dutch: *Membranen*); second, the discs (in Dutch: *Rondellen*); third, the carton (in Dutch: *Karton*); and fourth, the clamping rings (in Dutch: *Klemringen*). These figures are assumed to be quite accurate, as the underlying data, i.e., amounts per pallet, is gathered with great care. Nevertheless, deficiencies might occur at steel materials, as these pallet amount have been generally harder to estimate.

A graphical representation of Table 27 is given in Figure 50. Note that all raw material streams below Carton have a fictitious thickness.

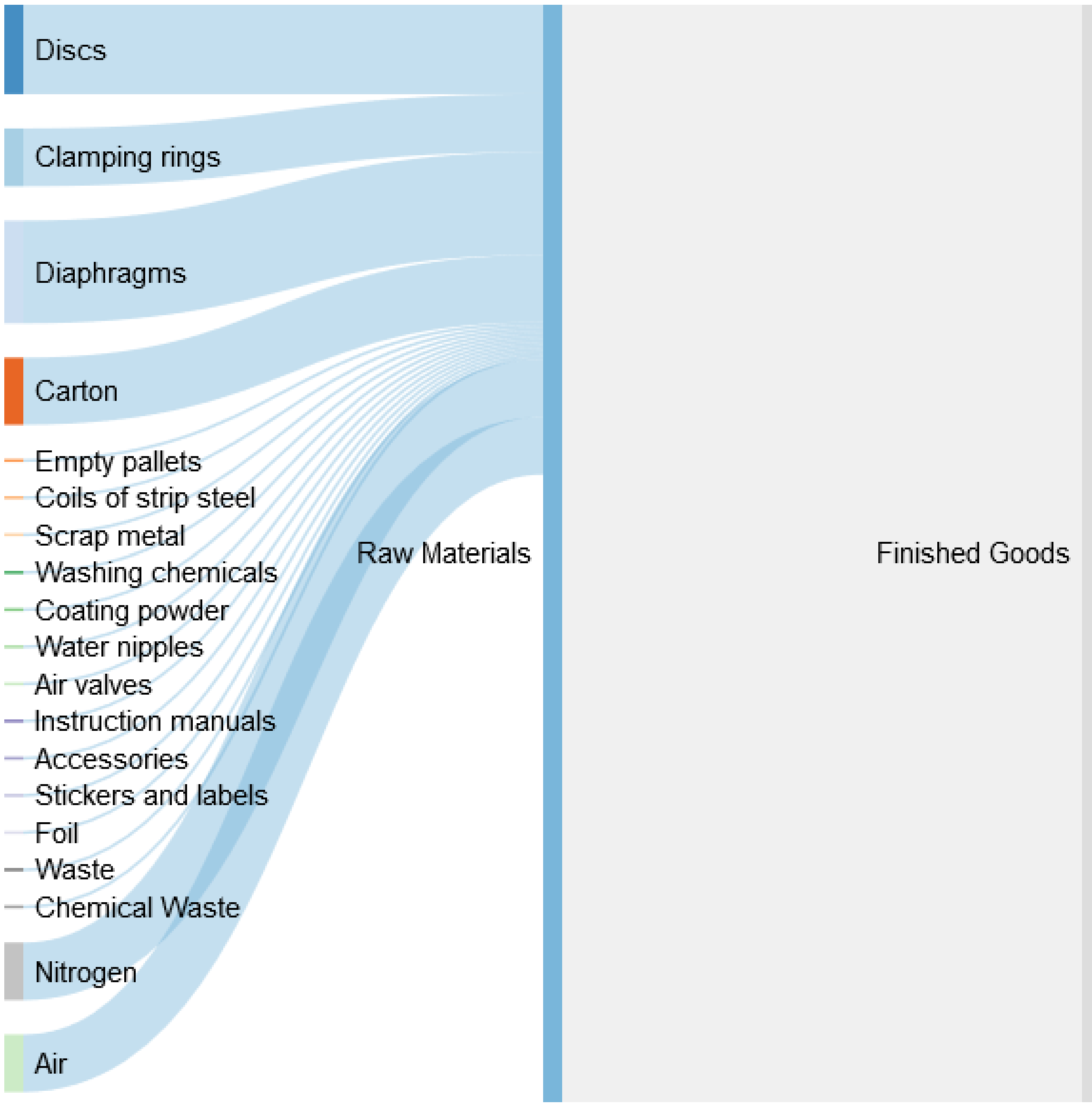


Figure 50: Sankey diagram BVL (current situation)

To continue with the MGV. Again, as one can see in Table 28, a travel from the end of the MGV production line to the finished goods warehouse occurs much more often than a travel from the incoming goods warehouse to a raw materials P/D-area at the production line, i.e., the ratio is more than x : 1. This was already emphasised in the section about the intralogistics workload, but now it is quantified using yearly travel numbers. It is estimated that for the MGV, we move around x pallets with finished goods into the finished goods warehouse.

Table 28: Overview of the important average yearly travel frequencies for the MGV

From \ To	MGV_ Rondellen	MGV_ Mantels	MGV_ Membranen	MGV_ Karton	MGV_FG_ Warehouse
MGV_ FinishedGoods					**X**
MGV_RM_ Rondellen	**555**				
MGV_RM_ Mantels		**868**			
MGV_RM_ Membranen			**1412**		
MGV_RM_ Karton				**80**	

Talking about raw materials, the total lies around 3000. Within that, the ranking in terms of travel frequency is as follows: first, the diaphragms (in Dutch: *Membranen*); second, the mantles (in Dutch: *Mantels*); third, the discs (in Dutch: Rondellen); and fourth, the carton (in Dutch: Karton). These figures are assumed to be somewhat less accurate than for the BVL, as the underlying data, i.e., amounts per pallet, was scarce. Still, there has been tried to gather data with great care. Nevertheless, deficiencies might occur at steel and carton materials, as these pallet amount have been generally harder to estimate. Again, we summarised Table 28 in a Sankey diagram displayed in Figure 51.

Figure 51: Sankey diagram MGV (current situation)

Table 29: Overview of the important average yearly travel frequencies for the OEM

From \ To	OEM_ Platines	OEM_ Klemringen	OEM_ Membranen	OEM_ Karton	OEM_FG_ Warehouse
OEM_ FinishedGoods					**X**
OEM_RM_ Platines	**1821**				
OEM_RM_ Klemringen		**1197**			
OEM_RM_ Membranen			**1720**		
OEM_RM_ Karton				**198**	

As one can see in Table 29, a travel from the end of the OEM production line to the finished goods warehouse occurs much more often than a travel from the incoming goods warehouse to a raw materials P/D-area at the production line, i.e., the ratio is more than x : 1. This was already emphasised in the section about the intralogistics workload, but now it is quantified using yearly travel numbers. It is estimated that for the OEM, we move around x pallets with finished goods into the finished goods warehouse.

Talking about raw materials, the total lies around 4000. Within that, the ranking in terms of travel frequency is as follows: first, the discs (in Dutch: *Rondellen*); second, the diaphragms (in Dutch: *Membranen*); third, the clamping rings (in Dutch: *Klemringen*); and fourth, the carton (in Dutch: *Karton*). These figures are assumed to be quite accurate, as the underlying data, i.e., amounts per pallet, is gathered with great care. Nevertheless, deficiencies might occur at steel materials, as these pallet amount have been generally harder to estimate. The amount of carton is rather low due to the fact that OEM vessels are generally packed into boxes or pallet cages. Even though, all streams denoted under Carton in are fictitious, one can clearly see a difference with the other two lines, i.e., the OEM line needs a relatively large amount of raw material pallets to produce one pallet of finished goods. This is mainly due to the fact that OEM vessels are rather small, and so, a lot of vessel fit into one box, whereas the raw material pallets differ in size, but not in pallet amount from the other two lines.

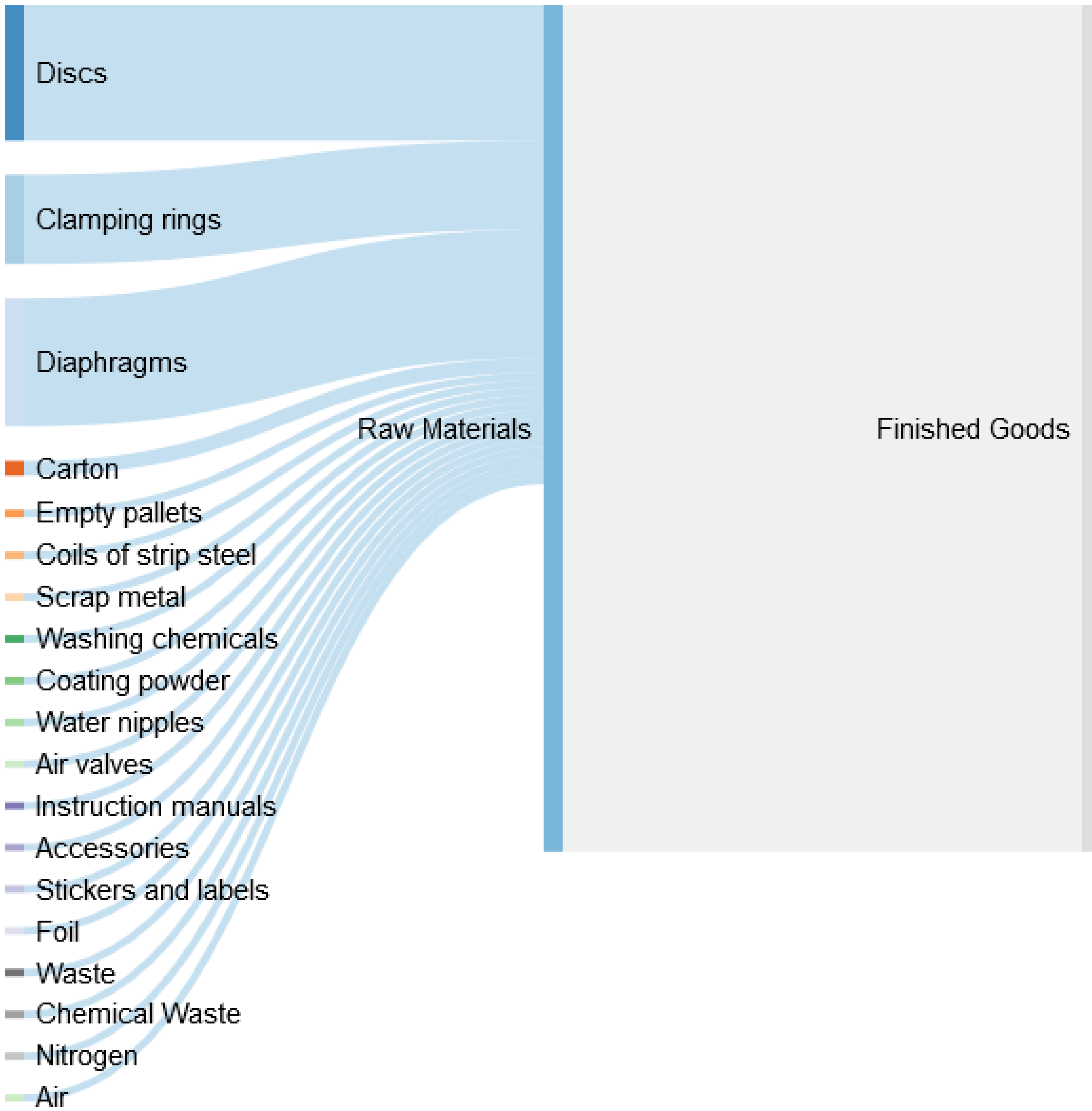


Figure 52: Sankey diagram OEM (current situation)

Table 30: Summary of important average yearly travel frequencies across the production lines

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When summarising the travel frequencies, we end up with Table 30. It clear that the BVL should receive the most attention, but also the amounts of steel and diaphragms brought to the OEM line catch eye. Still, doing things the smart way when it comes to finished goods will yield the most savings.

In addition, one should critically review the intralogistics workload that comes with the packaging of the MGV. The model reports just 80 pallets a year, but in reality, apart from carton, one needs a lot of empty pallets to store the MGV vessels on. This, we did not report here, but can be estimated using the number of finished goods pallets. The relation will not be 1 to 1, but can be calculated using the pallet amounts of finished goods and the production numbers of the different products. We expect that the fraction of pallets per finished product can certainly exceed 0.5, as all 790 articles demand their own pallet. Note that the same reasoning holds for the packaging of the OEM, where one also needs empty pallet boxes, cages, et cetera.

6.1.4 Space requirements for material buffers

In order to make the trade-off between supply/retrieve frequency and storage buffer space on the production floor, we made simulation runs varying the *SupplyInAdvanceTime*. Recall that the supply in advance time determines how far in advance materials are brought into the factory; timing depends on the estimated durations of the production batches currently in the production pipeline.

For each production line, the results are captured in two figures, displaying the average and the maximum size of a P/D-area (in no. of pallets). Note that both the average and maximum is an average taken over multiple replications, so especially the maximum could have been even worse, i.e., higher. However, the model is not very sensitive to this phenomenon, i.e., it would only concern a few pallets (<5) difference.

What can be seen across Figure 56 - Figure 61, is that the total space requirements for material buffers decrease when the supply in advance time decreases. However, it is not a linear decrease. The decrease of the *average* number of pallets per P/D-area is also more radical than that of the *maximum*; the latter seems to flatten from 12 hours and below.

For the BVL, in the default case of 24 hours supply in advance time, the raw material buffers at the line are expected to be together ± 50 pallets. This almost doubles to ± 90 pallets when the supply in advance time is doubled to 48 hours. Decreasing the supply in advance time to just an hour means that one would need, on average, space for less than 15 pallets. However, we know from inventory management that the saw tooth diagram, of which an example can be found in Figure 53, shows highs and lows instead of a single average.

Hence, when looking at space requirements, we need to take into account the peaks in material buffer, i.e., the moment that an amount of new materials (Q) is just yet delivered.

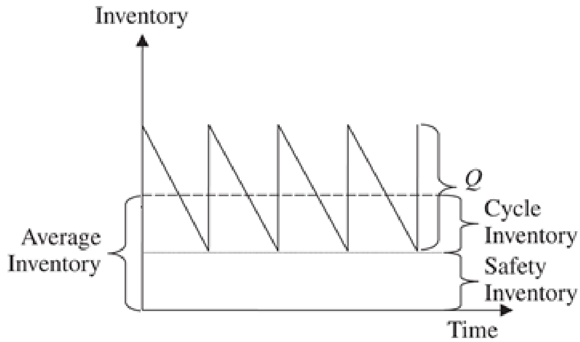

Figure 53: Example of a simple saw tooth diagram (inventory management)

The model output shows a similar saw tooth pattern. In Figure 54 and Figure 55, we take the P/D-area *BVL_Rondellen* as an example. Data originates from the first replication, for which we consider the average inventory levels over the whole period (a year) and zoom in on a random month, i.e., week 4 to 8. For the other P/D-areas, similar saw tooth patterns can be seen. Also, the maximum inventory levels show similar patterns, only the inventory levels are shifted up.

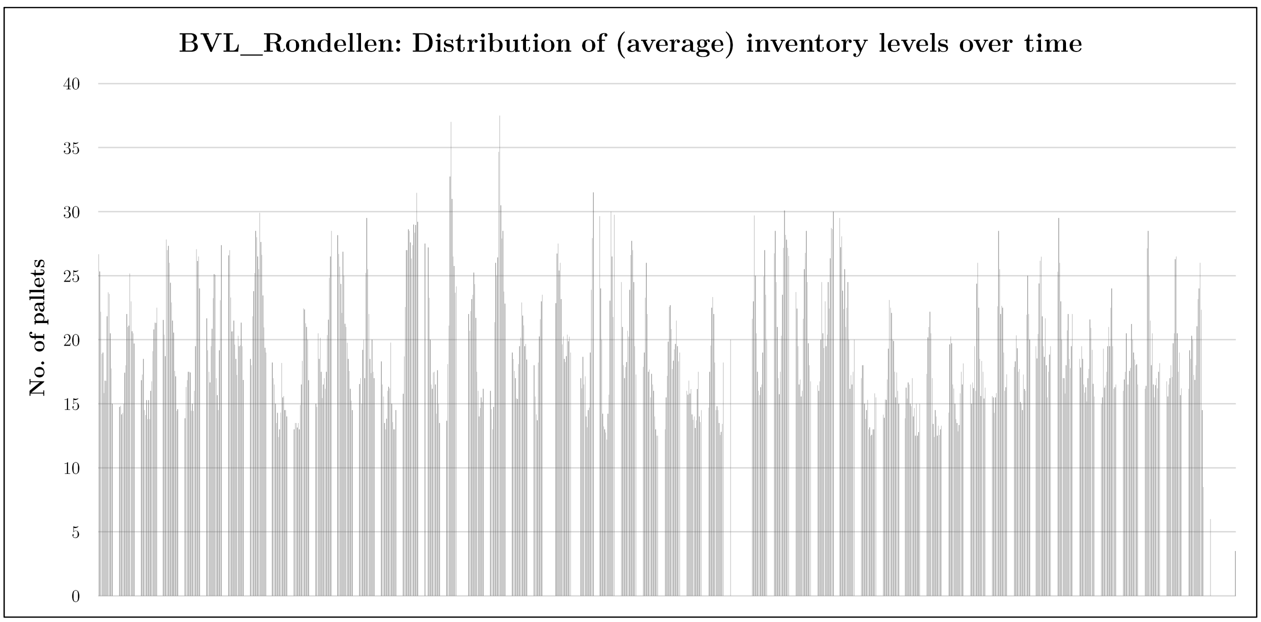

Figure 54: Example of distribution of inventory levels over time [a year]

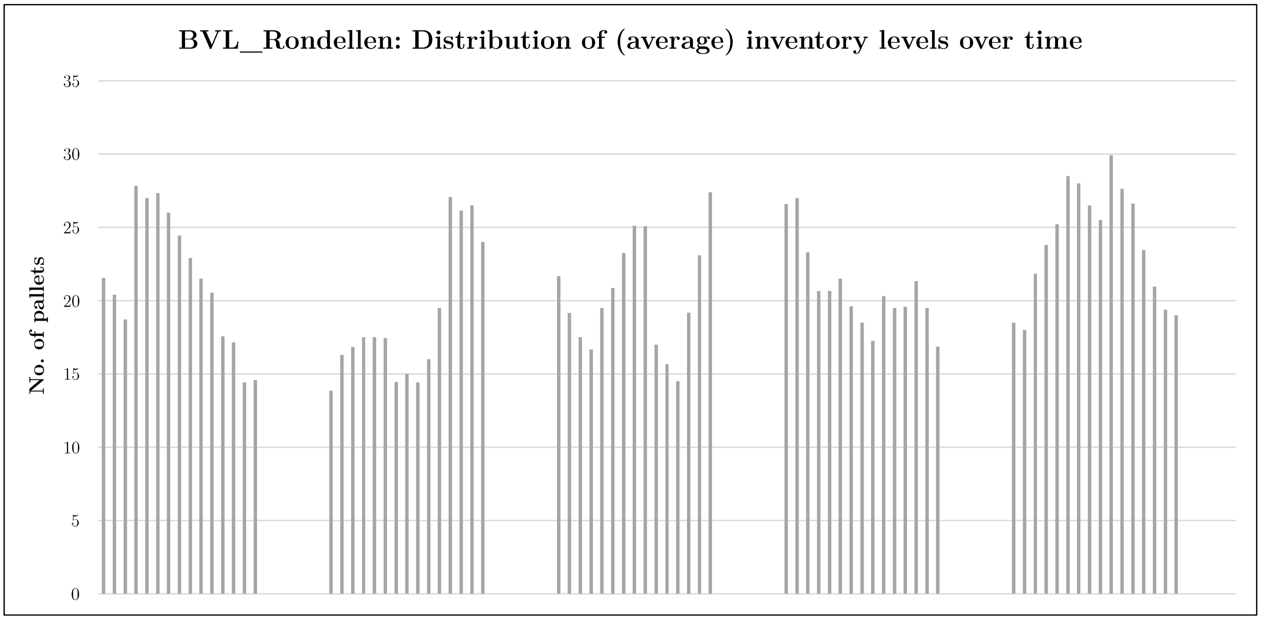

Figure 55: Example of distribution of inventory levels over time [week 4-8]

So, coming back to the maximum inventory levels for the BVL, this would mean that in the default case of 24 hours supply in advance time, the raw material buffers at the line are expected to not exceed 150 pallets (see Figure 57). Note that such maximum inventory levels are most likely to be reached in a situation, in which there are (more than) enough vehicles to supply the lines, because adding a large production batch to the production pipeline then has its immediate effects on the amount of materials on the production floor.

For the MGV and OEM, similar comments can be made. However, compared to the BVL, the pallet amounts are smaller for both lines. This is due to a lower production speed (MGV) and raw materials being smaller in size (OEM), which both decrease the number of pallets needed.

When going from 2 to 3 shifts a day for a certain production line, one can see in Table 31 what one could expect in terms of change in material buffer size.

Table 31: A production line from 2 to 3 shifts - differences in material buffers

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It is advised to take a look at the figures below to see what the trade-off between supply/retrieve frequency and the needed buffer space at a production line looks. The frequency with which raw materials should be supplied to the production floor is a decision which is up to Flamco to make. The figures below can be seen as decision support. Besides space, intralogistics capacity (i.e., vehicles and/or labour) is a vital criterion of course.

The frequency with which finished goods should be retrieved from the production lines depends on the production speed and the available (end-of-line) buffer space, e.g., on a roller conveyor. As it has been proved in earlier sections that the finished goods stream is by far the dominating stream, it could be wise to invest in some buffer space, as it provides opportunities to level the intralogistics workload on a micro-level.

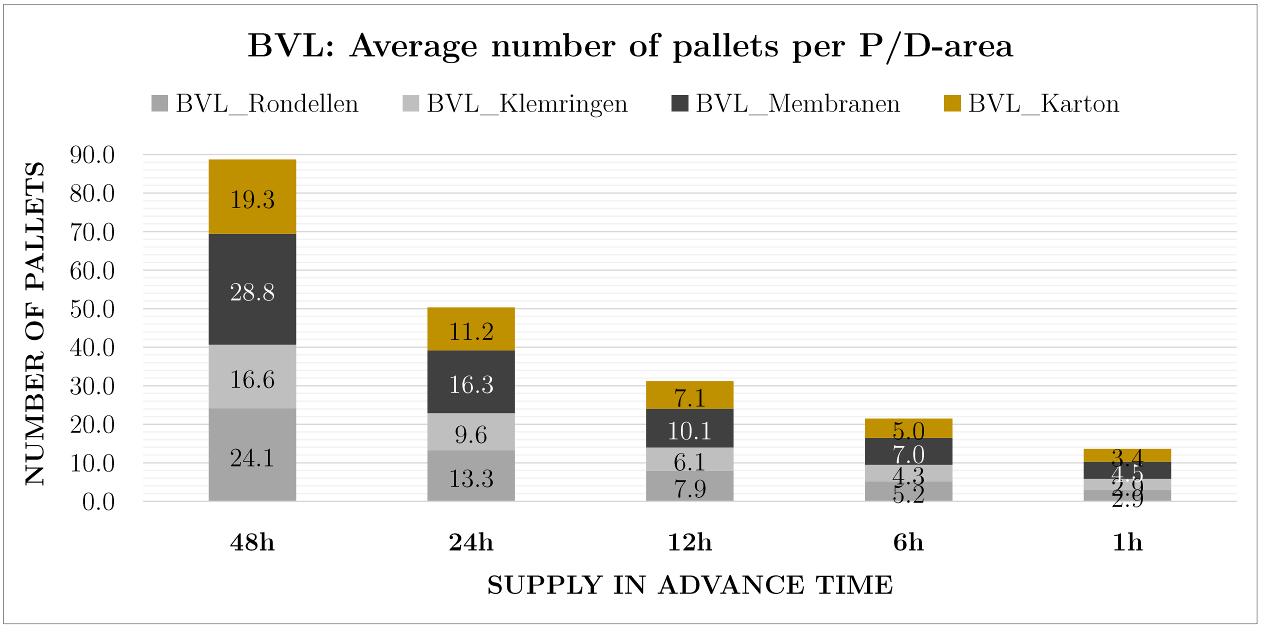

Figure 56: Average material buffer sizes BVL for different supply in advance times

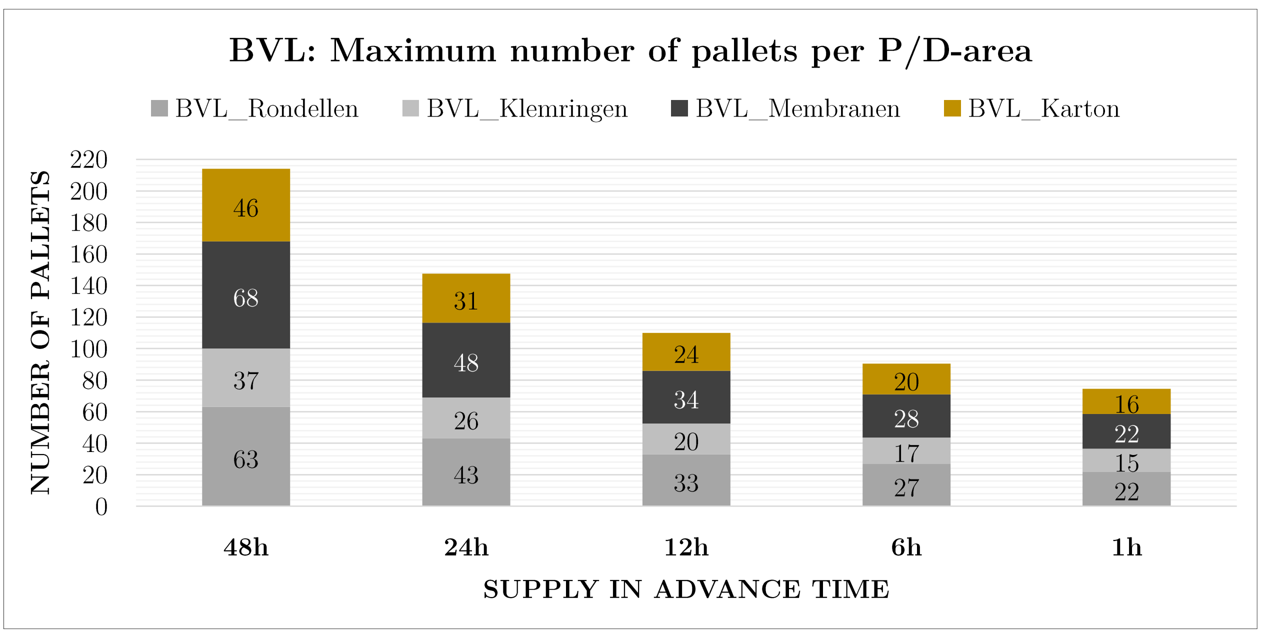

Figure 57: Maximum material buffer sizes BVL for different supply in advance times

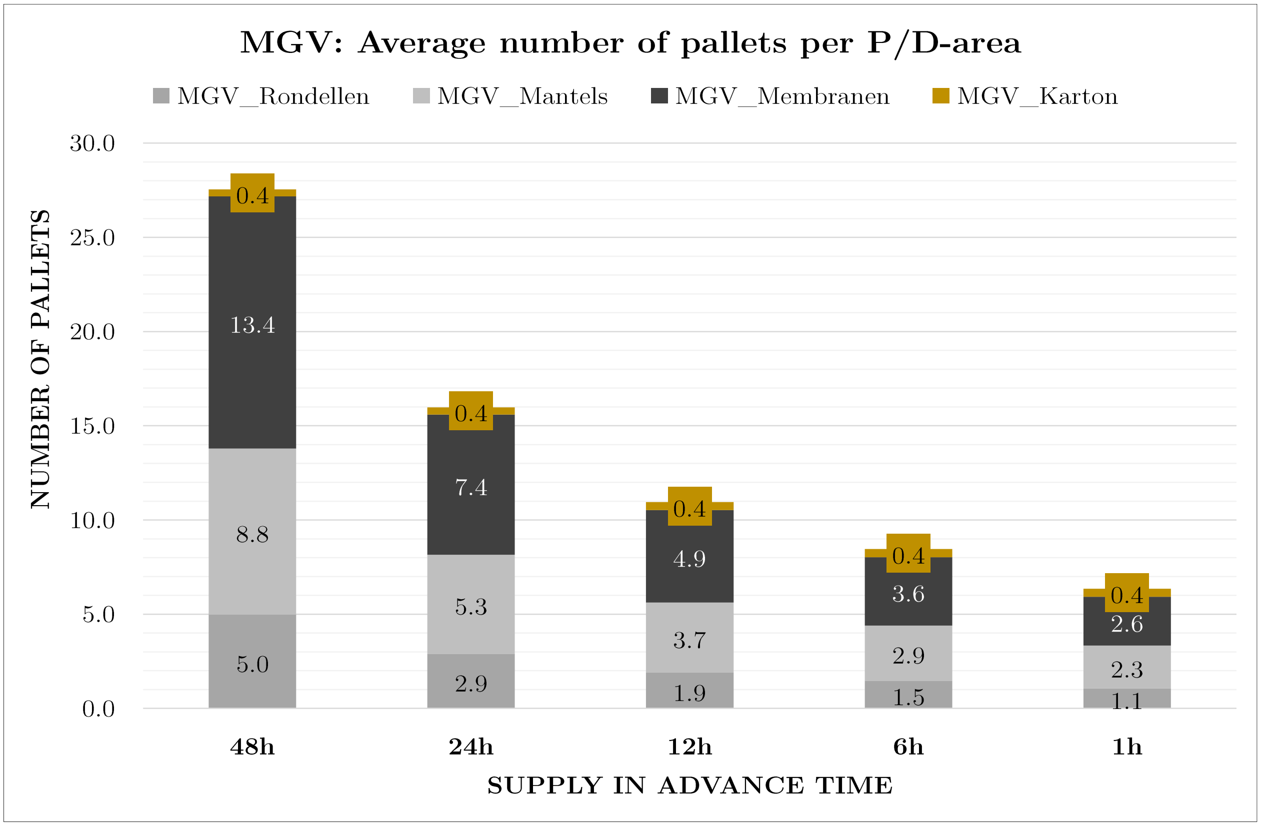

Figure 58: Average material buffer sizes MGV for different supply in advance times

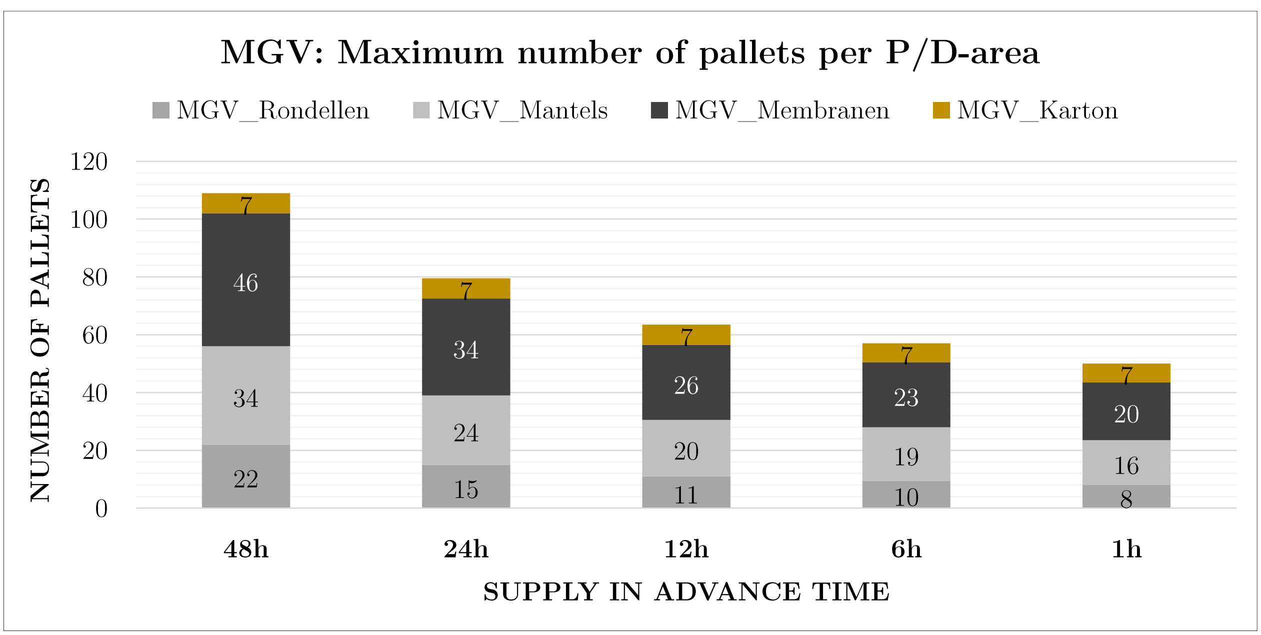

Figure 59: Maximum material buffer sizes MGV for different supply in advance times

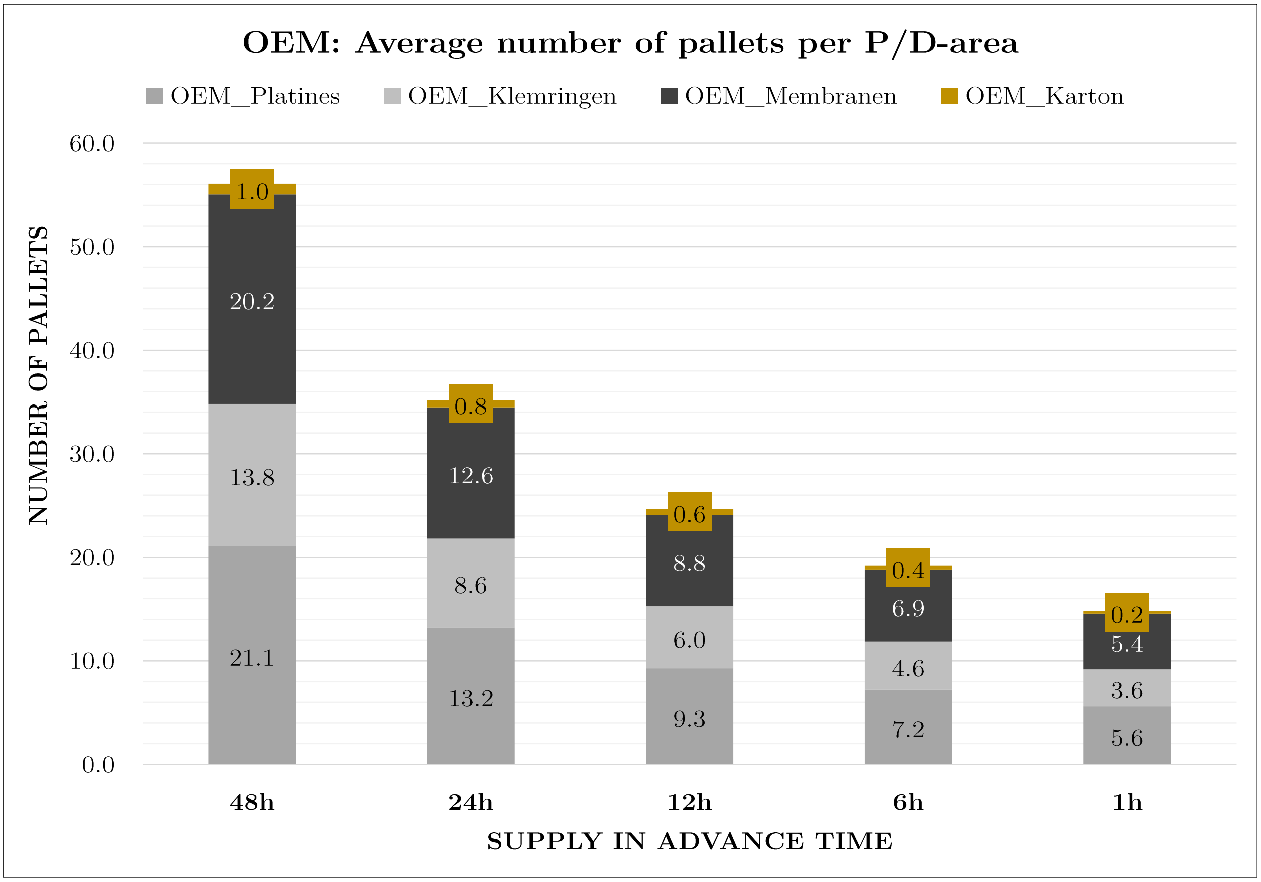

Figure 60: Average material buffer sizes OEM for different supply in advance times

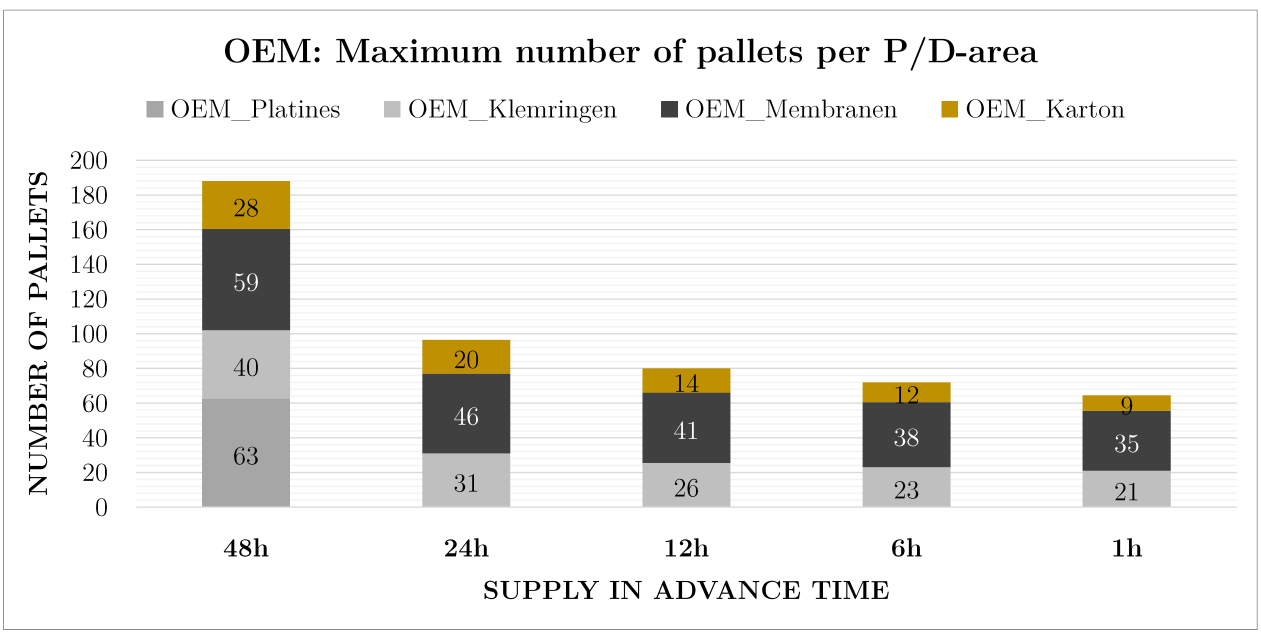

Figure 61: Maximum material buffer sizes OEM for different supply in advance times

6.2 Intralogistics and the future: expectation and performance

In the previous section, we examined Flamco's current factory operations in Bunschoten. Now, we go into detail of what could be expected from a future situation. To do so, we first discuss the expected changes in the system and how these are incorporated in the simulation model. Second, we elaborate on how the performance of a plausible future situation differs from the current situation. The data in this section originates from experiments 15-20, as were defined in section 5.3.2.

6.2.1 Towards an expectation of the future

Ideally, one would take here the current situation as a starting point, seeing what is still possible in terms of expansion within the current factory. However, we can be short about this, as it is confidential. One could create room by supplying production less in advance, but this would solve maybe the current lack of storage space, it would certainly not create enough room for, e.g., a new production line. In addition, Flamco is planning to move out of its current facility in let's say 3 years, so it is unlikely that until then large investments will be made to, for example, change the factory layout.

Therefore, it is much interesting to look at what Flamco expects in terms of future demand scenarios, what their planned actions are, and how that influences the intralogistics.

Regarding the demand scenarios, Flamco expects to grow continuously and with a yearly percentage of x1-x2%. This growth is expected across all product groups, and hence, all production lines. Even though capacity limits are confidential, all lines can be improved in terms of reliability and speed. Growth plans that go beyond the organic growth in the current product portfolio are confidential.

As Flamco is planning a new facility in greenfield, decision support on layout and dimensioning of the new building is welcome. As these kinds of investments are made for a considerable period of time, at least the dimensioning of the building should be such that future growth is facilitated. As a result, it does not make too much sense to investigate all kinds of in-betweens, Flamco prefers to know what can be expected when in the future four production lines will work full throttle, i.e., 3 shifts a day. Regarding the layout, Flamco has a concept layout plan, of which the details are today still confidential.

Hence, we choose to, for now, agree on the concept layout plan of Flamco and see what it would mean if Flamco starts producing in the planned layout with four production lines, and working in a 3-shift schedule at all lines. Note that simulating this new situation will yield travel frequencies that quantify the interactions within the factory, which allows Flamco to solve a Facility Layout Problem based on this quantitative input.

The default number of vehicles we use in the new case, is in line with the current situation and set equal to five, i.e., four vehicles dedicated to a production line (working also the same hours) and one vehicle dedicated to all lines, yet working only the day shift. The default supply in advance time is 24 hours. If it is not mentioned explicitly, we show experiment results corresponding with the default settings. Evidently, we also vary factors to analyse the system, but when we compare those results with the standard case, we will refer to this explicitly.

In addition, it is good to mention that the new layout, displayed in Figure 62, is not only different, but also larger in size. Production lines are situated in different locations, and so are the P/D-areas, resulting in different driving distances as well.

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Figure 62: Impression of the simulation model with the new planned layout

6.2.2 Changes in intralogistics workload

On a weekly basis, in the expected future situation, Flamco transports around x pallets, which is a y% increase compared to the z pallets of the current situation. The increase is mainly caused by the new production line. The fluctuations in weekly workload can be seen in Figure 63. This also shows us that, due to the increased workload, the fluctuations (e.g., due to holidays) are also automatically bigger.

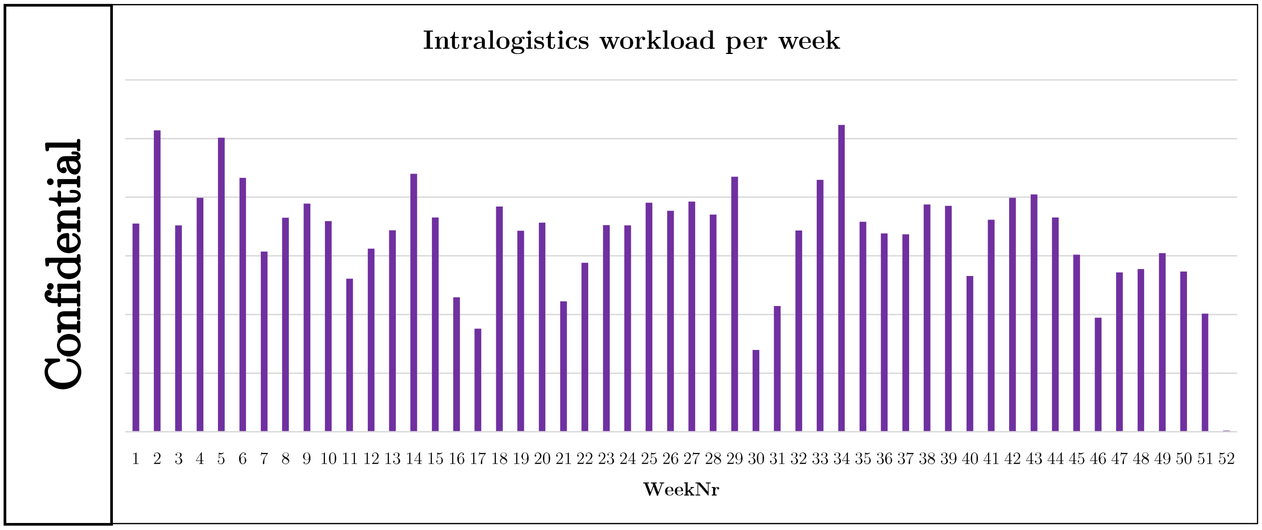

Figure 63: Average intralogistics workload per week

When dividing the total intralogistics workload over the vehicles that did the work, see Figure 64, one can see that the fifth vehicle (dedicated to all production lines) proves itself again useful, as it levels the workload of the other vehicles taking up a total of 20% of the work. Next to that, the vehicles dedicated to the largest lines, BVL and X, take up another 20-25% a week. The OEM and MGV divide the remaining percentage, where the product group at the MGV seems to have a large influence on the workload.

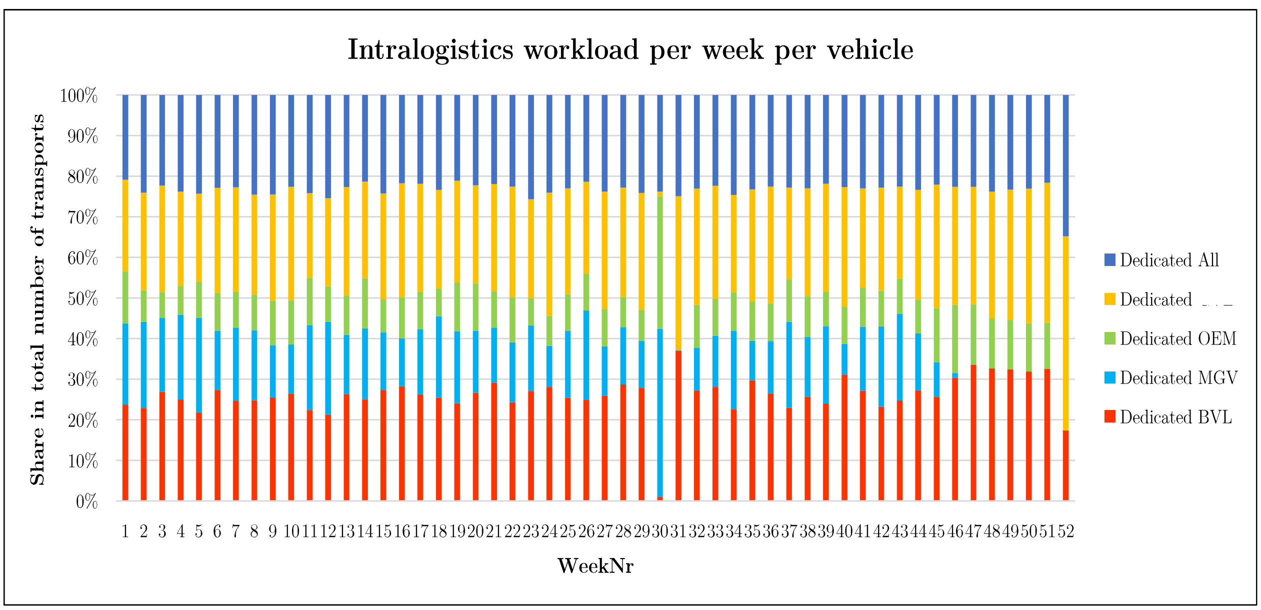

Figure 64: Average weekly intralogistics workload divided over the vehicles (in percentage)

In addition to dividing the workload over the different vehicles, we can also split and assign the workload to the different flow types, i.e., finished goods (FinGoods), raw materials (RawMat), and return flows (Returns).

We see the same division as in the current situation. According to Figure 65, x1-x2% of the work is due to pallets containing finished goods.

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Figure 65: Average weekly intralogistics workload divided over the flow types (in percentage)

Then, shifting from a weekly overview to an analysis of the weekdays, we listed in Table 32 the average number of transports per day of the week. From Table 32 and Figure 66, it can be concluded that the transportation workload is rather stable across the working days, with a small decline on day 3 (Wednesday) due to scheduled maintenance.

Table 32: Numerical details on average daily intralogistics workload

<table>
<tr><th>Day number</th><th>Total number of transports</th><th>Average number of transports</th><th>Finished goods</th><th>Raw materials</th><th>Returns</th></tr>
<tr><td>1</td><td colspan="5" rowspan="7">Confidential</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td></tr>
<tr><td>5</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td></tr>
</table>

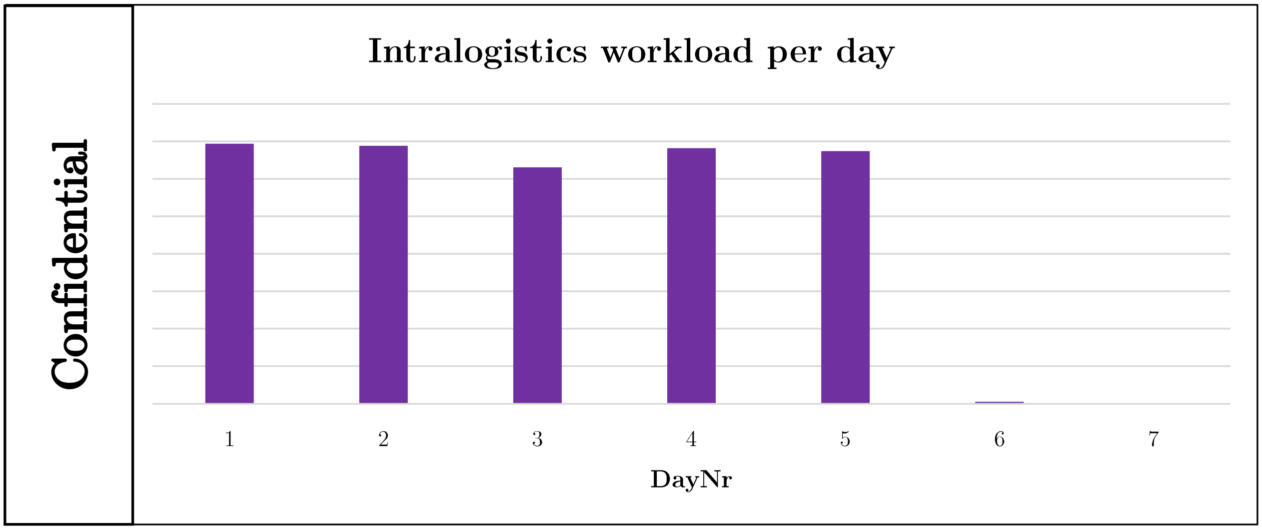

Figure 66: Average intralogistics workload per day of the week (with 1=Monday, 2=Tuesday, etc.)

Dividing the average daily workload over the vehicles (see Figure 67), we see just like in the current situation that every vehicle has a rather stable amount of pallets it transports on a day.

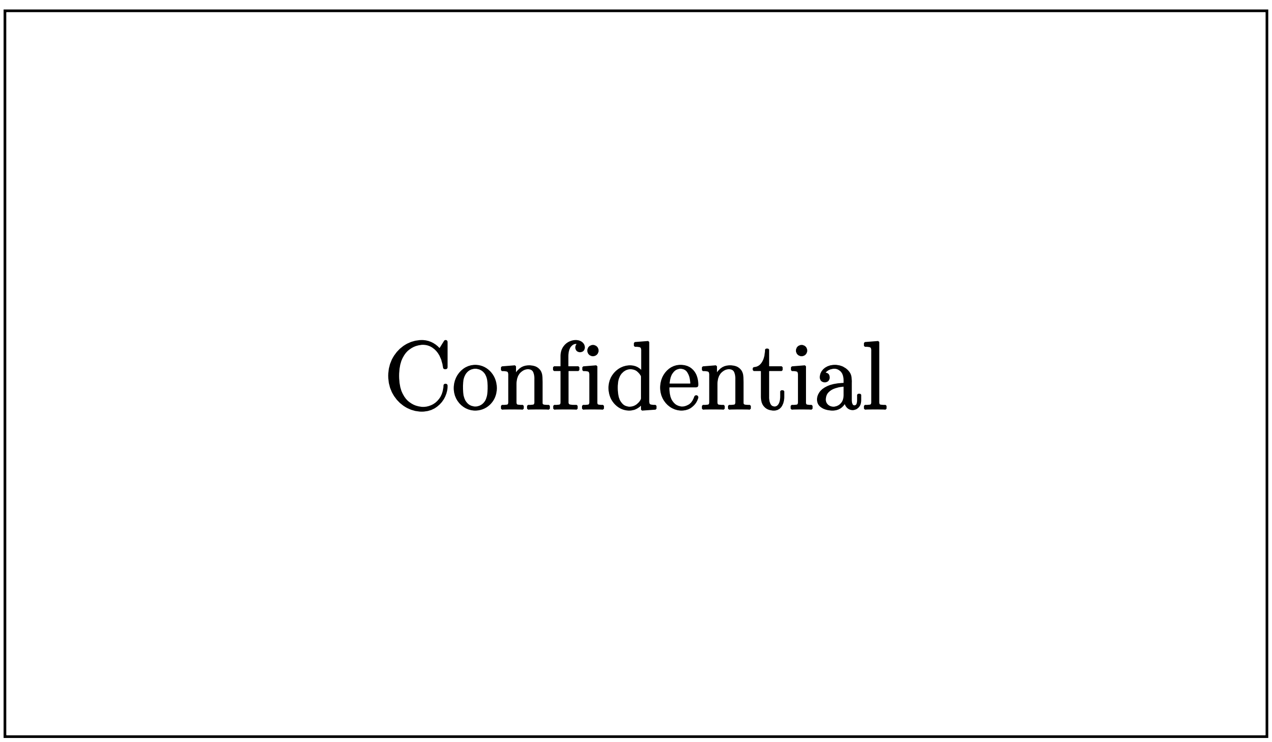

Figure 67: Average daily intralogistics workload divided over the vehicles (in number of transports)

Besides distinguishing between vehicles executing transportation tasks, we could of course also split the daily workload in flow type, see Figure 68. One can see that around x pallets finished goods are brought into the warehouse daily. All lines work 24 hours a day, so on average this means ±x pallets per hour arrive in the finished goods warehouse. Here, capacity should also be sufficient to store or cross-dock the pallets. Furthermore, Flamco can now determine if a stream of x pallets is ‘continuous enough’ to implement an automated solution here.

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Figure 68: Average daily intralogistics workload divided over the flow types (in number of transports)

Last but not least, we examine the workload on a shift level. In Table 33 and Figure 69, we see that the average workload per shift levels out around x pallets per shift. Where in the current situation we still had a bandwidth of x pallets in the average workload, now the long term average workload is even more flattened out. Yet, looking at the differences within a shift, there is a considerable gap between the maximum number of transports (occurred once in a replication) and the global average (taken over multiple weeks and replications). To give an example, for the dayshift on Monday, on average, the number of transports is equal to x. However, there has been a dayshift on Monday in which there were y pallets transported. This could potentially lead to problems if the intralogistics capacity is based on the average workload. To provide some more insight into this, we show the spread in workload using scatterplots in Figure 70.

Table 33: Numerical details on average intralogistics workload per shift

<table>
<tr><th>Shift number</th><th>Shift</th><th>Minimum number of transports</th><th>Average number of transports</th><th>Maximum number of transports</th></tr>
<tr><td>1</td><td>Monday Night</td><td rowspan="17" colspan="3">Confidential</td></tr>
<tr><td>2</td><td>Monday Day</td></tr>
<tr><td>3</td><td>Monday Evening</td></tr>
<tr><td>4</td><td>Tuesday Night</td></tr>
<tr><td>5</td><td>Tuesday Day</td></tr>
<tr><td>6</td><td>Tuesday Evening</td></tr>
<tr><td>7</td><td>Wednesday Night</td></tr>
<tr><td>8</td><td>Wednesday Day</td></tr>
<tr><td>9</td><td>Wednesday Evening</td></tr>
<tr><td>10</td><td>Thursday Night</td></tr>
<tr><td>11</td><td>Thursday Day</td></tr>
<tr><td>12</td><td>Thursday Evening</td></tr>
<tr><td>13</td><td>Friday Night</td></tr>
<tr><td>14</td><td>Friday Day</td></tr>
<tr><td>15</td><td>Friday Evening</td></tr>
<tr><td>16 17 18</td><td>Saturday</td></tr>
<tr><td>19 20 21</td><td>Sunday</td></tr>
</table>

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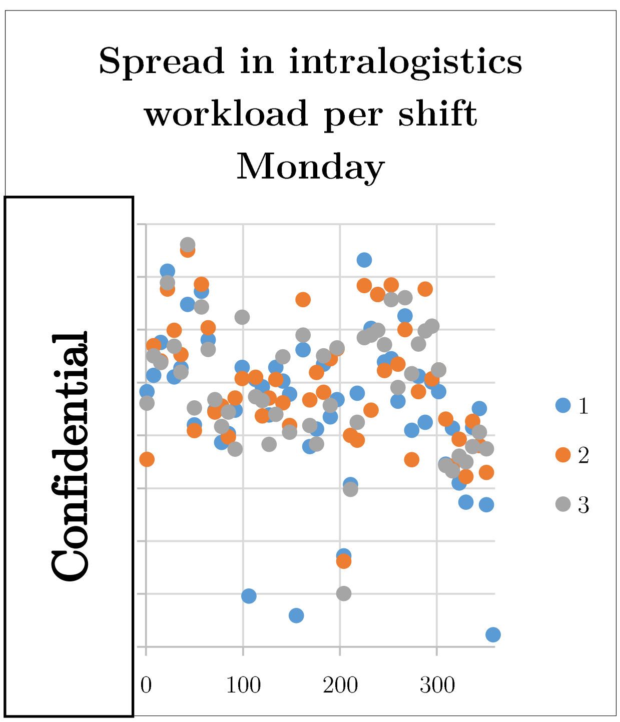
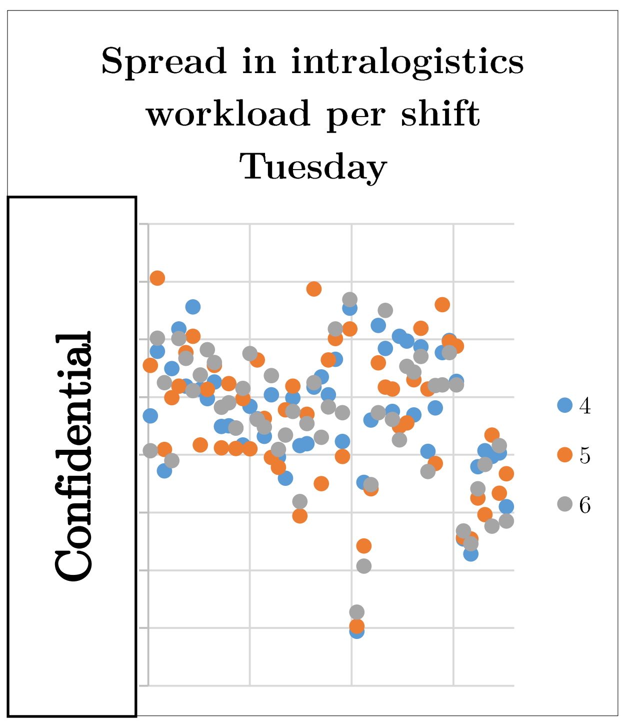
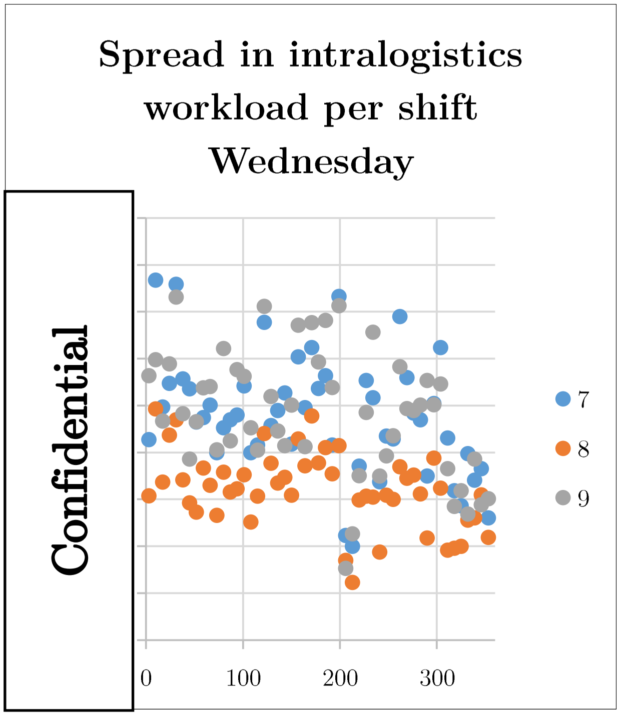
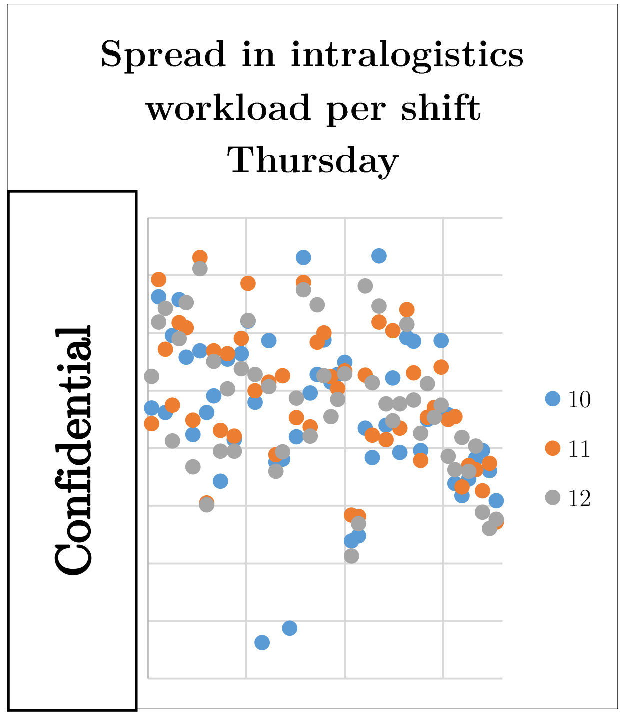
Figure 69: Average intralogistics workload per shift of the week (1=Monday Night, 2=Monday Day, etc.)









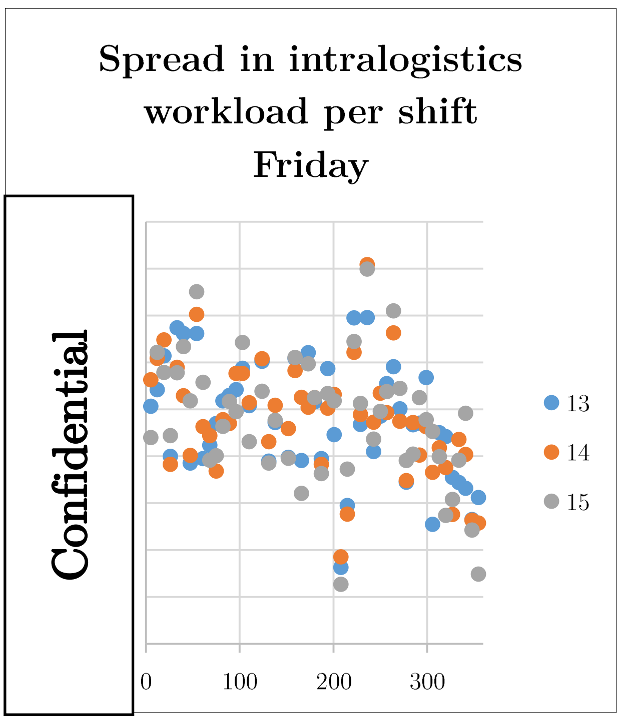


Figure 70: Spread in intralogistics workload per weekday per shift

6.2.3 Changes in traffic indications

Similar to the current situation, we list here the most important travel frequencies per production line. A complete overview of the travel history in Appendix 0.

Table 34: Overview of the important average yearly travel frequencies for the BVL

From \ To	BVL_ Rondellen	BVL_ Klemringen	BVL_ Membranen	BVL_ Karton	BVL_FG_ Warehouse
BVL_ FinishedGoods					**X**
BVL_RM_ Rondellen	**3113**				
BVL_RM_ Klemringen		**2017**			
BVL_RM_ Membranen			**3580**		
BVL_RM_ Karton				**2337**	

The future situation for the BVL is not supposed to differ from the current situation. For the sake of completion, we show the important travel frequencies in Table 34, which only differ slightly from Table 27 due to chance. Further comments can be found in section 6.1.3.

Table 35: Overview of the important average yearly travel frequencies for the MGV

To / **From**	MGV_ Rondellen	MGV_ Mantels	MGV_ Membranen	MGV_ Karton	MGV_FG_ Warehouse
MGV_ FinishedGoods					**X**
MGV_RM_ Rondellen	**761**				
MGV_RM_ Mantels		**1172**			
MGV_RM_ Membranen			**1910**		
MGV_RM_ Karton				**110**	

To continue with the MGV. As can be seen in Table 35, a travel from the end of the MGV production line to the finished goods warehouse occurs much more often than a travel from the incoming goods warehouse to a raw materials P/D-area at the production line, i.e., the ratio is more than x : 1. This was already emphasised in the section about the intralogistics workload, but now it is quantified using yearly travel numbers. It is estimated that for the MGV, we move around x pallets with finished goods into the finished goods warehouse.

Table 36: Overview of the important average yearly travel frequencies for the OEM

From \ To	OEM_ Platines	OEM_ Klemringen	OEM_ Membranen	OEM_ Karton	OEM_FG_ Warehouse
OEM_ FinishedGoods					**X**
OEM_RM_ Platines	**1834**				
OEM_RM_ Klemringen		**1201**			
OEM_RM_ Membranen			**1739**		
OEM_RM_ Karton				**199**	

As one can compare Table 36 to Table 29, there are only differences due to chance. Hence, we kindly refer to 6.1.3 for more comments.

Table 37: Overview of the important average yearly travel frequencies for the X

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Table 38: Summary of important average yearly travel frequencies across the production lines

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Then, also for the future situation, when summarising the travel frequencies, we end up with Table 38. It clear that the BVL (and X) should receive the most attention, but also for the MGV, the amount of steel and diaphragms and steel catches eye also. As said before, also the amounts of steel and diaphragms brought to the OEM line are remarkable. Still, doing things the smart way when it comes to finished goods will yield the most savings.

In addition, it also still holds that one should critically review the intralogistics workload coming with the packaging of the MGV. The model reports just 110 pallets a year, but in reality, apart from carton, one needs a lot of empty pallets to store the MGV vessels on.

Furthermore, the model now assumes the X to be something that is still confidential, but cannibalisation effects, differences in materials, et cetera et cetera, might lead to different figures.

6.2.4 Changes in space requirements for material buffers

Similar to the current situation, Figure 71 until Figure 76, show that the total space requirements for material buffers decrease when the supply in advance time decreases. Moreover, the figures for the BVL and OEM are equal to the ones showed in section 6.1.4, i.e., only some small deviations due to chance. As a result, we do not further elaborate on these results, but to say that the X figures are left out of the report, because they are still confidential.

Compared to the current situation, when adding a shift to a certain production line, the average buffer sizes scale roughly with the 33% capacity that is added. However, when looking at the maximum buffer sizes, there is a subtle difference, as for the lower supply in advance times (12h or less), there is almost no difference between the buffer sizes of a 2- or 3-shift schedule. Hence, a short supply in advance time reduces the risk of pallets piling up at a P/D-point, which seems intuitive. Still, it is important to repeat that adding an extra shift means on average larger buffers at the production lines, regardless of the supply in advance time. Furthermore, the relation between the average buffer size and the number of shifts seems to be linear.

All in all, everything that is stated above does not necessarily provide an answer on with what frequency the raw materials should be supplied to the production floor. This is because we think our research should be decision supporting, leaving the final decision to Flamco. Evidently, besides space, intralogistics capacity (i.e., vehicles and/or labour) is an important decision criterion.

Also, for the frequency with which finished goods should be retrieved from the production lines, a reasoning similar to 6.1.4 holds.

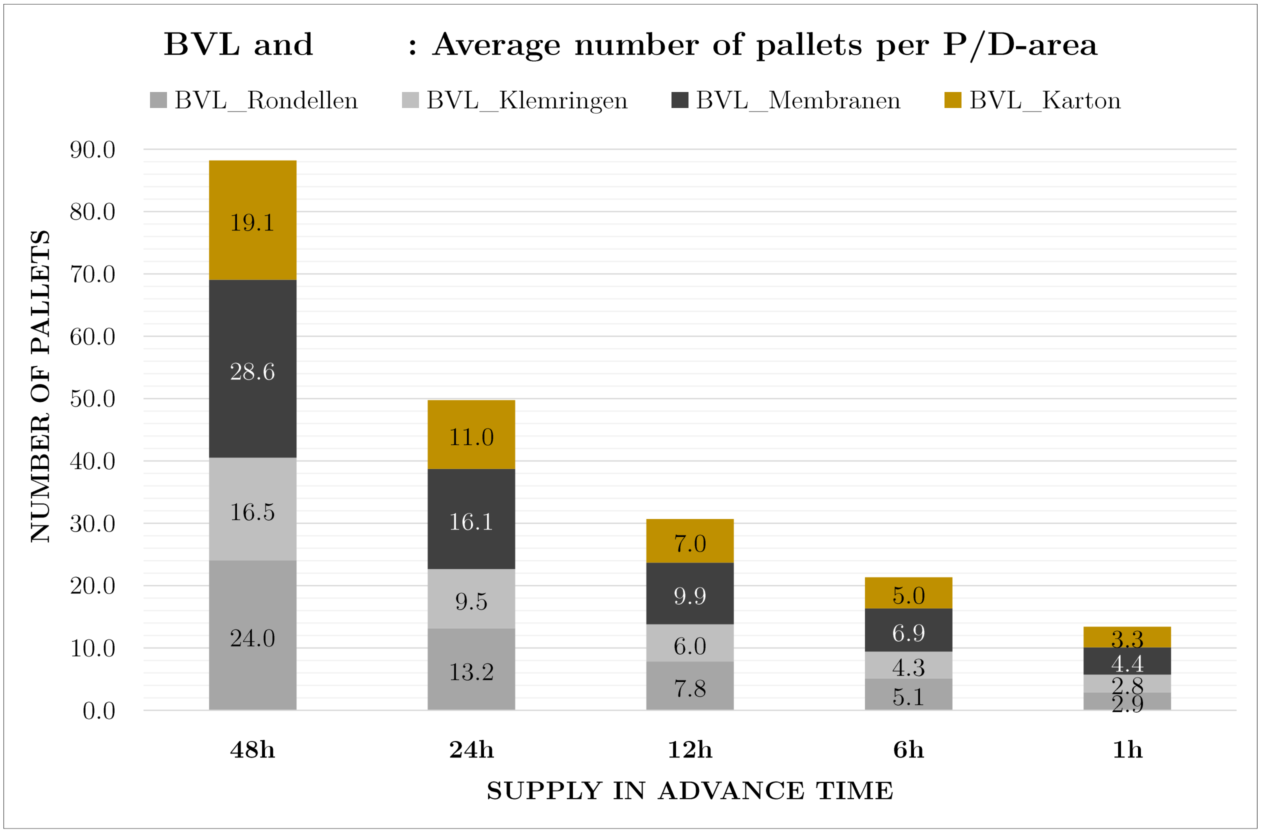

Figure 71: Average material buffer sizes BVL and X for different supply in advance times

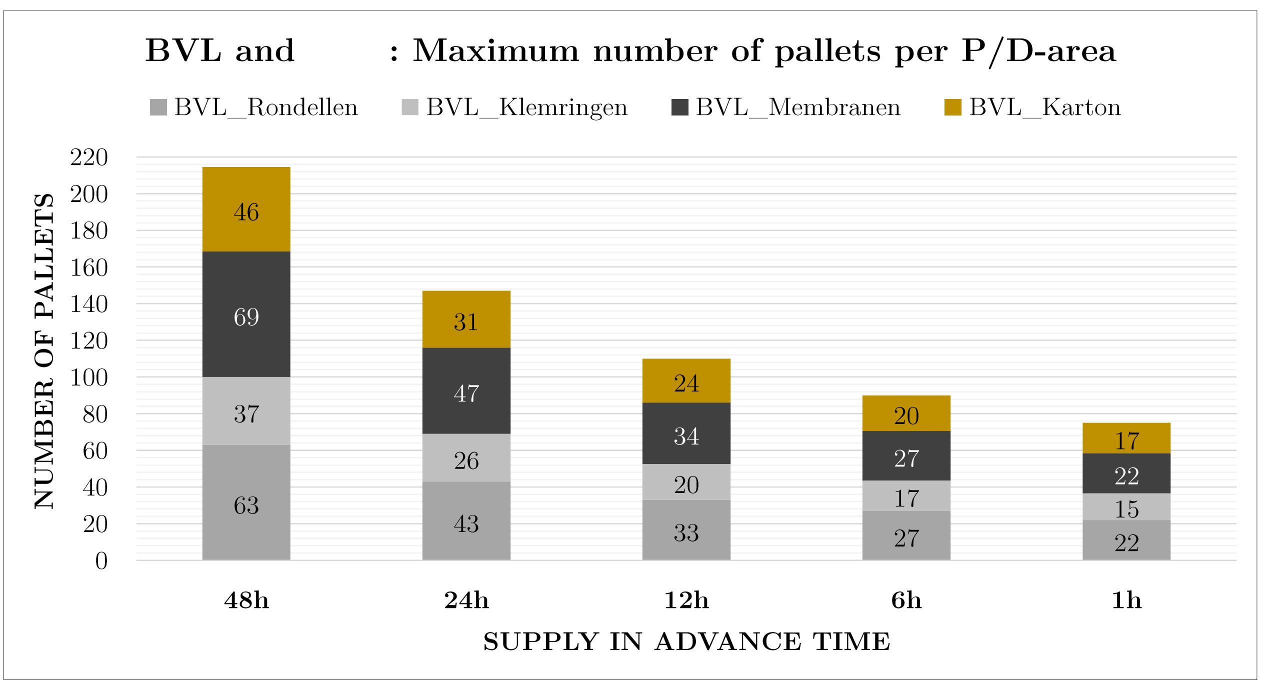

Figure 72: Maximum material buffer sizes BVL and X for different supply in advance times

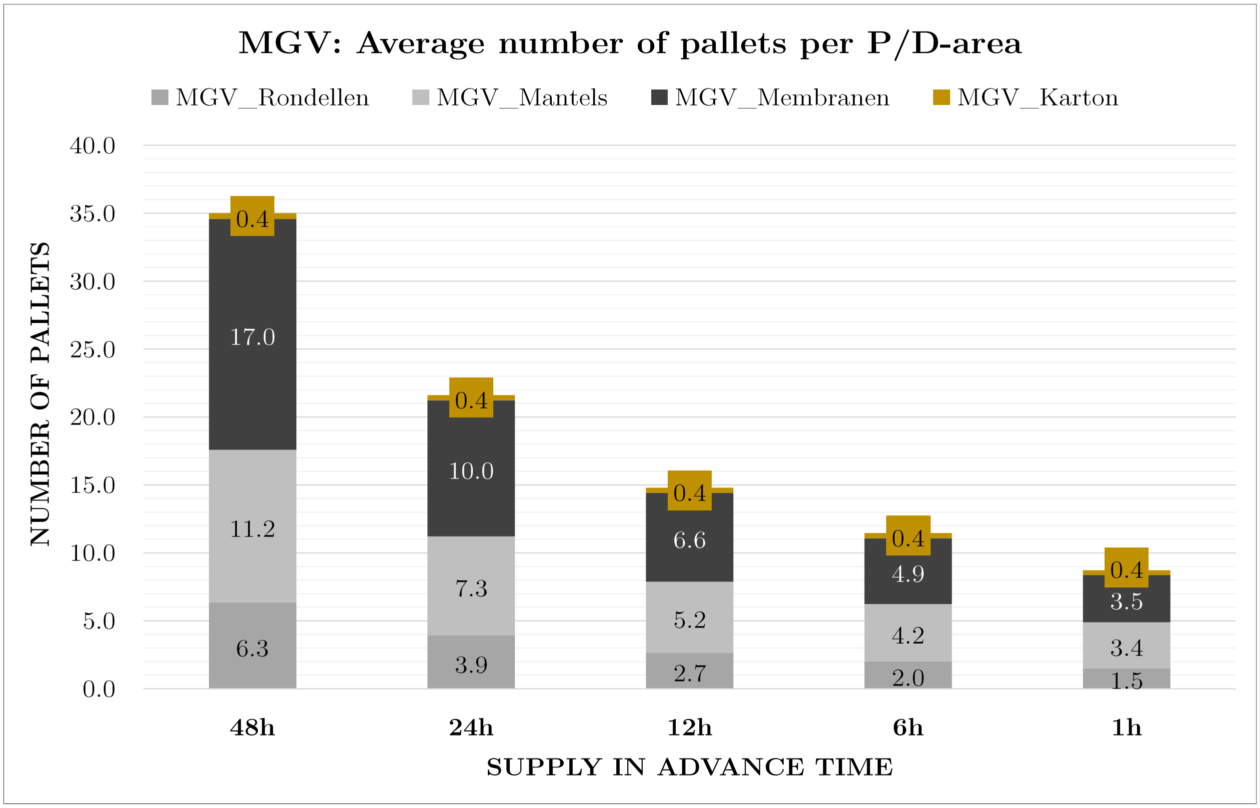

Figure 73: Average material buffer sizes MGV for different supply in advance times

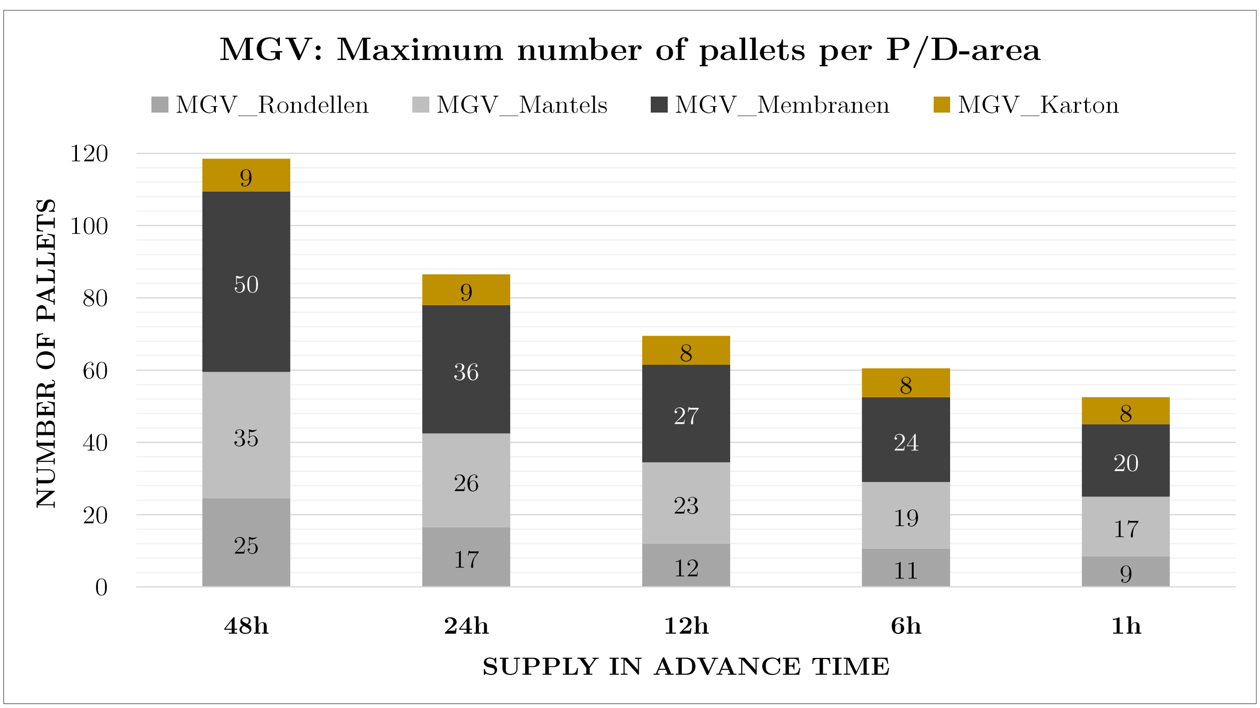

Figure 74: Maximum material buffer sizes MGV for different supply in advance times

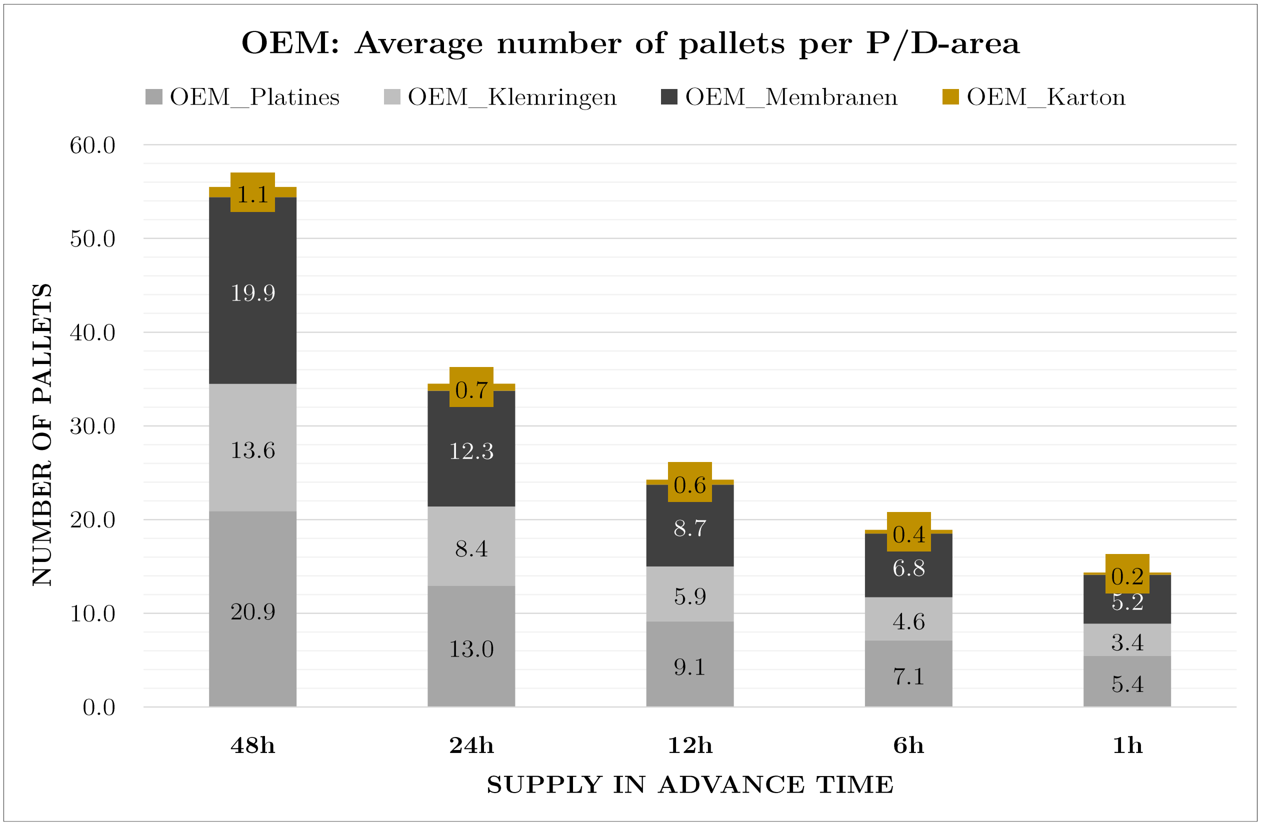

Figure 75: Average material buffer sizes OEM for different supply in advance times

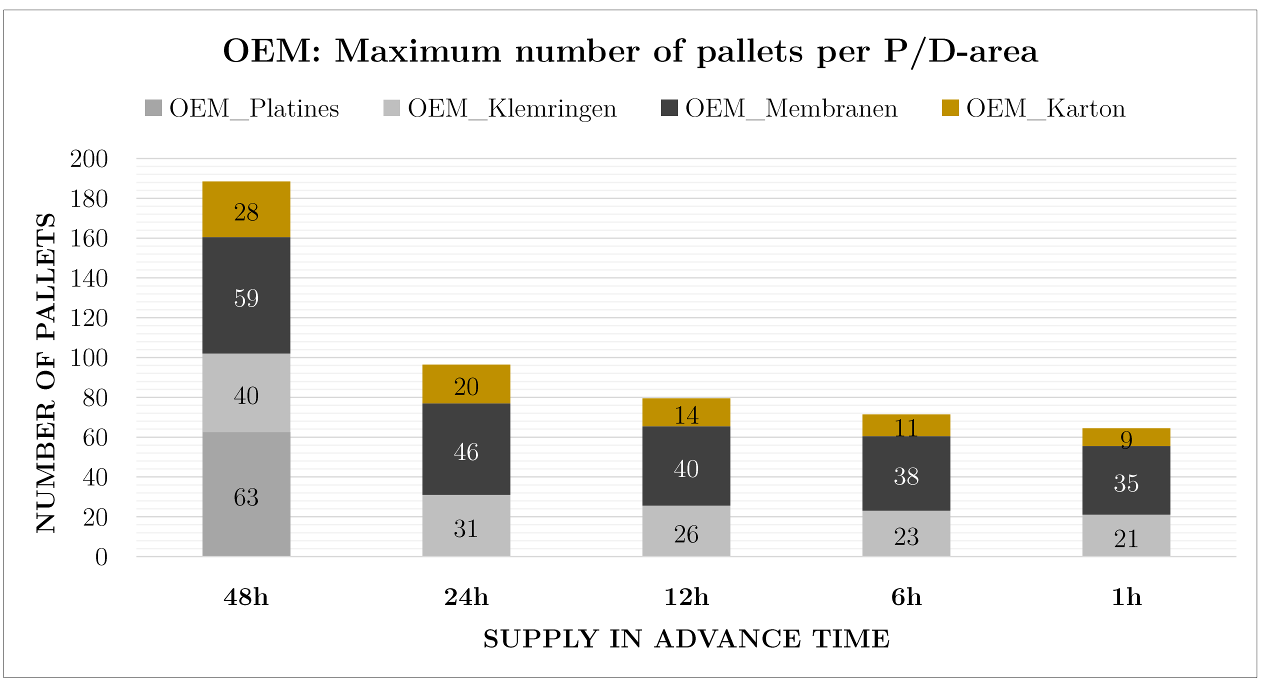

Figure 76: Maximum material buffer sizes OEM for different supply in advance times

6.3 Sensitivity analysis

In this section, we look at some factors in the model to see their impact on the model results. In, e.g., section 6.1.4, we elaborated already thoroughly on the impact of the SupplyInAdvanceTime. Here, we analyse how sensitive the model is to changes in the driving speed and handling time of AGVs. According to section 5.3.2, we use experiments 1 and 6-9 for this. A similar analysis was performed in (Vavrík, Gregor, & Grznár, 2017) *to help on deciding which vehicles should be acquired. Even though the priority of the stakeholders lies more on designing a proper layout than on capacity planning right now, we still investigate the impact of these factors to maybe do some capacity analysis with the model at a later point.*

Our sensitivity analysis on the factors vehicle Handling Time (HT) and Driving Speed (DS) is summarised in Table 39. We use the current situation as a basis, looking at the vehicle utilisations to see the impact of the factors. In the default case, which is used in all of our other analysis, we use a HT of 30 seconds and a DS of 6 km/h. In our sensitivity analysis, we in- or decrease these numbers by 50%.

Table 39: Sensitivity analysis vehicle handling time and driving speed

	Experiment	**Vehicle type**	**1**	**2**	**3**	**4**
	Sensitivity analysis	*Working in shifts*	BVL	MGV	OEM	Day only
		Priority rule	Flow Type	Flow Type	Flow Type	Flow Type
	Total vehicle capacity: 4	*Capacities*	1	1	1	1
Double Fast	HT 10 sec DS 9 km/h	**% of time driving full**	**0.16**	**0.04**	**0.04**	**0.05**
Default	HT 30 sec DS 6 km/h	**% of time driving full**	**0.22**	**0.06**	**0.05**	**0.09**
Slow HT	HT 60 sec DS 6 km/h	**% of time driving full**	**0.19**	**0.06**	**0.05**	**0.11**
Slow DS	HT 30 sec DS 3 km/h	**% of time driving full**	**0.31**	**0.10**	**0.11**	**0.26**
Double Slow	HT 60 sec DS 3 km/h	**% of time driving full**	**0.30**	**0.10**	**0.11**	**0.25**

Looking at the table above, the DS seems to be the only factor of influence. Utilisations clearly increase when the DS is lowered, and vice versa. On the contrary, nothing, but changes due to chance and stochasticity in the simulation model, seem to happen when the HT is changed. Conclusion, the vehicle utilisation is sensitive to the driving speed and insensitive to the handling time, which may be due to the fact that the driving time dominates clearly over the handling time.

6.4 Conclusion on results

In this chapter, we experimented with the simulation model and analysed the results in an attempt to answer the related research question(s) about the intralogistics performance in the current and in a future situation. Main causes of difference among the experiments conducted are factory layout, intralogistics capacity, production capacity, supply in advance time, pooling of resources and priority rules to choose transportation tasks.

The intralogistics workload fluctuates over the weeks, with an average of x1 transports in the current situation and y1 in a foreseeable future situation. Peaks to x2 respectively y2 pallets transported per week are proven possible. The average daily workload is rather stable in both situations, with a dip on Wednesday due to scheduled maintenance. The same holds for shifts.

The question of how much intralogistics capacity Flamco needs, is hard to answer. In our simulation runs, the current intralogistics capacity proved to be more than enough to handle the current intralogistics workload, i.e., utilisation for all vehicles below 25%. However, we tested and therefore know that the driving speed (and hence, the distances) are the main determinants of the required fleet size. For these two variables, we made assumptions that could be inaccurate. Hence, we are hesitating in giving an advice on intralogistics capacity. What we however can say is that pooling resources can definitely yield a situation, in which resources are used more efficiently.

The trade-offs between supply/retrieve frequency and the needed buffer space at a production line, has been investigated by varying the so-called *SupplyInAdvanceTime*. One can clearly see relations between the *SupplyInAdvanceTime* and the average and the maximum total material buffer on the production floor. From 12 hours downwards, the total material buffer does not decrease that much anymore. Probably because of the fact that one production batch often accounts for multiple production hours, yielding a situation in which there are always a certain minimum number of pallets present on the production floor. The other way around, increasing the *SupplyInAdvanceTime* from 24 hours to 48 hours in the current situation, yields the average material buffer to grow with 80%.

The frequency with which finished goods should be retrieved from the production lines depends on how one will retrieve the goods. The simulation model has given estimates of the number of finished goods pallets coming off the lines (per week, per day, per shift). Now it is up to Flamco to make a choice in end-of-line buffer space, retrieving goods by forklifts or guiding the ‘continuous’ stream of pallets into the finished goods warehouse using, e.g., a roller conveyor.

Last but not least, what happens in the intralogistics system depends largely on what happens in the production system. However, we validated the production system with success, so this should not be an issue. It remains however important that the pallet amounts, which are used to calculate the number of required pallets for a certain production batch, are accurate. Next, there are two variables having a large impact on, e.g., utilisation of vehicles, namely driving speed and driving distance.

7 Implementation

In the previous chapters, we analysed the current situation at Flamco Bunschoten and came up with a model to investigate what benefits alternative factory configurations could have in the operations of the future. However, talking to many people throughout the company and observing daily operations yields additional insight, resulting in this chapter addressing the practical side of what has been discussed so far.

Within Flamco, the journey to Future Flamco has had its kick-off by, amongst other things, the Operational Excellence initiatives of Aalberts Industries, the forthcoming relocation of the main production facility, and also this research. Yet, to make sure the road to Future Flamco will not be a too bumpy ride, there are some practical steps that management could start thinking of today. A summary of roughly six months of talking to people and observing what happens within Flamco is presented below.

7.1 General comments

Regardless of the results and insight the simulation has provided in the previous chapter, there are some general comments to make when it comes to operational excellence and Smart Industry within Flamco.

When looking at Flamco now, one sees a company that needs to stretch its resources to cope with growing customer demand. Production lines need to work in overtime or even scale up capacity with a (night) shift. However, the production facility itself does not grow and operators start to complain about a lack of storage space. As a result, materials are placed everywhere in the factory; and more and more temporary storage locations are created close to the line to be still able to changeover the production lines fast instead of digging through piles of pallets or cages searching for the materials needed for the next batch of products. The driving lanes, where forklifts drive or manoeuvre and people walk, are busier or even become rather dangerous as forklift drivers simply drive faster to keep up with the required production pace.

It is quality that characterises Flamco in the HVAC market, but the means to deliver high quality need to be sustained. Flamco can present itself as a shiny red Ferrari, but an excellent driving experience is only maintained when the engine keeps running smoothly. Therefore, from an operational excellence perspective, it is time to critically review processes associated with the (manufacturing) operations and involve the people that now stretch themselves to keep delivering the famous Flamco quality.

Evidently, the boards of Aalberts Industries, AI Hydronic Flow Control, and Flamco itself have ideas on how to proceed and make the business future-proof. Nevertheless, this research has come up with some suggestions that are not all directly related to the solution design, yet are worth mentioning.

In Chapter 3, we discussed the fact that expansion vessels are standardised and relatively low-tech products, produced in relatively high quantities and sold against relatively low margins. This means that there is a continuous pressure to cut costs. One way to do so is to reduce expensive labour and automate processes. Thinking also about Smart Industry, working towards a highly automated manufacturing environment could yield a competitive advantage. Imagine fully automated production lines supplied by AGVs and monitored by a combination of computer-based algorithms (e.g., for machine control, production planning and predictive maintenance) and a team of technical operators with specialist knowledge. Imagine that it is then possible to for example integrate a fully automated OEM line with the information systems of large OEM customers to become a strategic partner and, e.g., improve product quality, enhance supply chain visibility, and facilitate Vendor Managed Inventory.

For a highly automated manufacturing environment to happen, two matters need to be resolved. First, the production lines need to reliably produce a predictable output (making it plannable). When machines break down all of a sudden and/or often, production is interrupted so many times that the organisation around the production line (i.e., operators, material supply, et cetera) is forced to be flexible. Then, a highly automated production line, controlled by algorithms, is rather rigid and does not seem to fit well.

Second, regardless of the type of expansion vessel, the production process needs to be standardised to a (very) high degree to make sure robots and machines can handle it. Furthermore, the more standardised the process, the simpler the operation that needs to be executed by a robot often is, which also means that the acquisition costs of the robot(s) will probably be relatively low.

When taking the highway to fully automating the production, one should bear in mind some risks, especially because Flamco finds itself in a situation where it is certain that it is going to build a new facility. Danger is then that one then wants top-of-the-bill, e.g., AS/RS, robots, AGVs, software tools, the whole package. Yet, the information on which one is building, is outdated the moment the actual purchase of equipment will take place. It is a risk to base investment decisions on information that is 2-3 years old, in a business that grows 10-15% a year and in various product directions.

From a risk management perspective, it would be wiser to start simple, i.e., still doing a lot of manual work, and step-by-step replace manual labour with automation. Doing this in a systematic and structured way means that there need to be process engineers that have a day job on enhancing the reliability and efficiency of the production lines. Increasing capacity here could certainly pay-off, as there is still a lot of improvement potential when it comes to (getting insight in) the dynamics and bottlenecks of the production system. In addition, the value inhabited in the OEE data gathered over the years is still unexploited. One could, e.g., start to calculate how batch sizes, the amount of setups, and the total downtime evolve over time.

7.2 Suggestions for practical steps to take

Building further upon the general comments made in the previous section, we here present a set of practical steps that could potentially add value to the business.

Sensors. A first practical step that also falls into the Smart Industry philosophy, is placing sensors on the different stations at the production lines. These sensors should automatically measure, e.g., machine processing times, the vessel that is produced, and so on. As sensors are normally rather cheap, this is a low hanging fruit that could provide us with lots of useful data. To give an example, measuring processing times helps us with, amongst other things, identifying the bottleneck in the process, balancing the line to avoid excessive WIP, and making a production planning that everybody can work with.

More attention to OEE registration. Besides applying sensors to the production lines and exploiting the OEE data that it is currently available, it might be also beneficial to create a standard protocol for registering what happens in production. To be able to quickly make meaningful analysis afterwards, it is useful to have unpolluted data stored in a standardised format. Suppose, one wants to register downtime. There not only should be a data column for the amount of downtime, but also for the type of vessel currently produced, the machine that failed, the failure type (code), the deployment of technical services (y/n), et cetera. In line with applying sensors to the lines, one could think of automatic OEE registration as a next step.

Create clarity in production norms. To date, Flamco uses three types of production norms, i.e., a planning norm for the production planning, a cost price norm for accounting purposes and to indicate when the factory operates break-even, and an OEE norm reflecting the maximum production output possible. In the experience of the researcher, who has been an outsider at first, it might be helpful to clarify these norms and choose one norm as base, e.g., the OEE norm. To achieve a feasible 'planning' norm, one could use a variable (per vessel/article) called 'production efficiency', which then fluctuates between 0 and 1. Production efficiency can be registered over time and adjusted if the level used for planning is structurally too high or too low. The cost price norm is a fixed norm, so also a fixed percentage of the OEE norm. By comparing this fixed percentage with the 'production efficiency' percentages, one could keep track of the margins made by the factory.

Usefulness of buffering vessel halves outside the BVL line. To date, it is standard procedure to buffer vessel halves outside the BVL line when the *Dieptreklijn* (DTL) produces at a higher pace than the chain conveyor can handle. On the other hand, during a long setup of the DTL, vessel halves are added manually to the chain conveyor, provided there are vessel halves and other materials available to extend the previous or coming batch. This whole operation is claimed to increase the production output, but it cannot be denied it also can sometimes be a hassle. A suggestion to simplify, and thereby increase the usefulness of this operation, has to do with the Single Minute Exchange of Die (SMED) method, as adding vessel halves only adds to the business if it is done fast and smooth. Think of what happens if one only has one fixed fast-moving product to changeover to and produce during long setups and/or failures. This would yield a situation, where one has only a small buffer of one particular vessel halve outside the line (and a small and fixed buffer of the auxiliary raw materials). This not only reduces space, it also saves people from continuously checking if all materials are indeed available to perform the changeover action. It simplifies the process considerably, making it also more suitable for further optimisation later on, as only one question remains, i.e., how large should the 'stand-by' buffer of vessel halves and auxiliary materials be. To organise this efficiently, one could think of a fixed buffer of vessel halves, clamping rings, diaphragms, and carton; somewhere close to the line and stored in lanes making it easy to retrieve materials once needed. The only decision that is then left to make when a setup or failure takes (too) long, is whether or not the BVL should be changed over for a short while, i.e., until normal production can be resumed. This decision should be made by the shift leader in consultation with the technical service and the production planner.

Parallel processing BVL AWL. In a discussion with the production planner, we came up with the thought to decouple the *Afwerklijn* (AWL) from the *Bandvatenlijn* (BVL). Decoupling the AWL would enable the production of larger batch sizes of one vessel size; and the produced vessels could be then customised based on the actual customer demand by setting the vessel pre-pressure at a later point in time. The expected benefits are increased line efficiency, less setups and a much easier production planning. In short, decoupling the AWL creates a finishing-on-demand situation, which makes the production process as a whole more flexible - potentially yielding a faster customer response. In addition, capacity can be increased rather easily by adding testing cabins and a packing machine (modularity).

Single Minute Exchange of Die (SMED) for the MGV coating line. Currently, the MGV coating line is responsible for coating MGV vessels, Air+Dirt products, and some OEM vessels. All three production lines face growing demand. Changing colour on the MGV coating line is a time-consuming process, as there is only one spraying cabin - that needs to be cleaned and set up to proceed with another colour. Planning the coating of vessels on this coating line is merely an ad-hoc process.

When the MGV line is running smoothly, the MGV vessels occupy all of the coating line, thereby also determining the spraying colour. Often, only a failure of the MGV line can create a hole for Air+Dirt or OEM products to be coated. Otherwise, those products need to be coated in overtime (mostly on Saturdays) or externally. Note that Air+Dirt and OEM products can only be inserted in the coating line, if the right colour is sprayed.

One can imagine that, due to a smoothly running MGV (which is also necessary to cope with growing customer demand) or a 'wrong' colour, WIP builds up fast when it comes to semi-finished MGV, Air+Dirt, and OEM products. This increased WIP is then not only a problem for the MGV coating line, it also has negative effects in the rest of the factory, e.g., even more issues regarding storage space, pallet cages that are hogged, et cetera.

In order to relieve some of the pressure on the MGV coating line, one could invest in one more spray cabin, such that the coating line can change the spraying colour fast (just like the BVL). This would not require too much space, yet makes the coating line more flexible, the ad-hoc coating planning at least somewhat easier, and buys us time to come up with a sustainable solution in a future factory.

Focus on outbound stream of goods. An expansion vessel contains, apart from some steel and a rubber diaphragm, mainly air. This means that a rather small volume of raw materials creates a rather large volume of finished goods. Hence, from an intralogistics perspective and regardless of the simulation results, the outbound stream of goods deserves the most attention. Combining the outbound streams of the different production lines results in a daily stream of around x pallets of finished goods. This amount of intralogistics could certainly be worthwhile trying to automate using, e.g., a conveyor belt into the finished goods warehouse.

Storage policies raw materials. To date, materials are stored nearly everywhere, i.e., in the incoming goods warehouse, the production floor, and sometimes just there where there is space left. The incoming goods warehouse does not use strictly defined storage locations or a Warehouse Management System (WMS). This has been decided in the past, because the turnover of the warehouse is high. Materials that are brought into the warehouse are mostly transported to the production floor and used there within a week. However, this is not always the case; and, in many cases there is some leftover material, as production cannot finish exactly all the discs, clamping rings, diaphragms, and carton. The production floor has predefined storage locations, but the material amounts at various locations in the factory do not always correspond exactly with the SAP ERP system. Therefore, regardless of how the new factory and warehouses are organised in the future, it might be useful to further structure the warehouses and production floor using, e.g., predefined storage locations, lanes and policies. Leftover pallets with raw materials (e.g., with discs or clamping rings) should be stored such that they are in front, used or supplemented / replenished the next time a product is produced that uses these raw materials. This way, one does not end up with many almost empty pallets that nobody pays attention to anymore.

Cross-isles in new factory layout. From an intralogistics perspective, it might be convenient to have, in addition to the driving spaces between the production lines, a number of cross-isles that go right through the production lines. These cross-isles could be used to deliver raw materials that are needed in the middle of the line (and account for a considerable intralogistics workload) in a more economical way. In our opinion, the cheapest option to apply cross-isles, is to exploit the height of the building and let the chain conveyor track go higher up into the sky, thereby making room for transporting vehicles to drive underneath.

7.3 Conclusion on implementation

To conclude the chapter that had only few connections with prior chapters, we provide a bullet-point list summarising the (practical) advices given – all with the aim of working towards a smart and automated Flamco.

People

- ✓ On the short term, focus on people, as operators are still the ones that produce in the near future, have ideas, and want to be involved.
- ✓ Spread the message: "We want to do things smarter, instead of with less people." Flamco grows, so even though automation would replace some operator tasks, plenty of work will still be there.
- ✓ Invest in people's education. Operators that have the capabilities of understanding the technical details of the production process should be encouraged and facilitated to deepen this technical knowledge. We believe the operator of tomorrow is a technical operator that is able to interfere in production when computers run out of options to cope with a problem.
- ✓ Employ process engineers that structurally work on enhancing the reliability and efficiency of the production lines. Let them continuously search for the bottleneck in the process, thereby also exploiting the OEE data gathered.

Technical

- ✓ Focus on increasing the reliability of the production lines. In 2017, the percentage of downtime for the BVL, MGV, and OEM was respectively x%, y%, and z%.
- ✓ Machine breakdowns are not the end of the world, as long as the output is predictable.
- ✓ Start paying even more attention to data gathering, e.g., OEE data. Investigate the options to gather data automatically, e.g., through connected sensors on machines. Focus strongly on gathering data consequently and in a standardised format, as this simplifies things substantially and contributes massively to actually using the data, e.g., for data analysis and/or for aligning processes and machines (especially in a Smart Industry setting).

Logistical

- ✓ Focus on automating the outbound stream of goods first, as this stream is a) larger than the inbound stream of goods (expansion vessels mainly contain air), b) more standardised in terms of pallet type and pallet dimensions, and c) after converting the current finished goods warehouse into a new high-bay warehouse with possibly an AS/RS, there is a lot of improvement potential when it comes to storage and retrieval strategies, e.g., order-oriented slotting and cross-docking.
- ✓ Consider implementing (strictly) predefined storage spaces and lanes. Apply storage policies to prevent raw materials from wandering through the factory and leftover pallets from being left behind. One main storage location per material might simplify not only intralogistics, but also inventory management, e.g., reduced discrepancies between the stock levels in SAP and on the floor.

8 Conclusions

In this chapter, we summarise the most important things that have been discussed in the report so far. We briefly repeat the answers given to each of the research questions and give an outlook on what is to happen next, i.e., recommendations and suggestions for further research. We also briefly reflect on (the relevance of) what we have done in this research.

8.1 Conclusions

Until now, Flamco did not know what happens in their largest production facility in terms of intralogistics. Performance could have been measured in some way, but this was not the case. Not a problem if production goes smoothly and one makes a profit. However, difficulties arise when one needs to (re)design the internal logistics processes, which happens to be the case, as Flamco needs to move its operations to a new facility - to be build in greenfield.

After a thorough (data) analysis of Flamco's current operation, we saw in simulation a method that could help solving the problem mentioned above, making up for the gap in (quantitative) data on intralogistics performance. We modelled the entire factory in Siemens Plant Simulation, putting in the historical production planning to validate the model and calculate the intralogistics performance of Flamco now. In addition, we anticipated on the scenario of increased customer demand, in which the new and larger factory - having a different layout and an additional production line - should help out. Also here, we measured the intralogistics performance that can be expected, providing the vital input to solve the Facility Layout Problem to create a near-optimal layout in the new factory. Furthermore, we assist in dimensioning the new facility by giving insight into the expected storage space needed at the production lines to temporarily store (raw) materials.

Note that building the simulation model also forced us to analyse both the production system and the intralogistics system thoroughly. This also added value, because it pointed out various aspects that could be improved and of which some clearly relate to the concepts of Smart Industry.

Coming back to measuring the intralogistics performance, we summarise the two situations in Table 40, displaying the weekly workload in number of pallets transported.

Table 40: Summary weekly intralogistics workload

<table>
<tr><th>Case</th><th>Minimum</th><th>Average</th><th>Maximum</th><th>Standard deviation</th></tr>
<tr><td>Current situation</td><td colspan="4" rowspan="2">Confidential</td></tr>
<tr><td>Future situation</td></tr>
</table>

Dividing this workload over the vehicles, one sees that, in the current and future situation, four respectively five vehicles are more than enough to do the job. Especially the last vehicle, working for all lines during the dayshift, is useful to level the workload of the other vehicles. This suggests that pooling resources might yield an improvement, which has been confirmed in our analysis in section 6.1.2.

In order to identify the (raw) materials that add the most to the intralogistics workload, we made several Sankey diagrams, of which Figure 77 is a complete overview, reflecting the yearly workloads. Note that the stream of finished goods is much larger than the stream of raw materials and/or returns, so the main focus should be on efficiently organising the stream of finished goods from the end of production lines to the finished goods warehouse.

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Figure 77: Sankey diagram (complete overview of the current situation)

The lack of storage space on the production floor could be improved by supplying production less in advance. See 6.1.4 and 6.2.4 for the related figures. In addition, asking what is really necessary to (temporarily) store close to a production line in combination with renewed attention to standard storage procedures would certainly help.

However, Flamco expects to grow substantially, which makes the current facility in Bunschoten not sustainable. As a result, it will move to a to-be-build-in-greenfield facility, acquiring also a new production line to cope with increased customer demand across all product groups. As such large investments are not often made, the design of such a new facility should be 'right', meaning well-dimensioned and with proper factory layout. To this end, we also simulated what it would look like in the future, all production lines pulling full gas to meet customer demand. An overview of the expected yearly intralogistics workloads per production line can be seen in Figure 78.

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Figure 78: Sankey diagram (complete overview of the expected future situation)

So, to finalise our conclusions, we repeat and answer our main research question for the last time.

"What is the current intralogistics performance, what does a smart organisation of intralogistics related processes look like in a future business environment, and what performance can be expected from it?".

We can answer this question by saying that we now know the quantitative details of the intralogistics at Flamco Bunschoten, i.e., the (expected) workload, travel frequencies, and space requirements.

We also know that to smartly organise the factory, we should put an emphasis on information and communication, which is also fully in line with Smart Industry. As an example, pooling resources (e.g., forklifts) is smart in terms of intralogistics, but only when drivers know (in real-time) what they are up to (and what the others are up to).

A lot can also be still achieved in making the production more reliable, yet the way to do so is not only by getting your hands dirty, but also by, e.g., gathering data on processing times of machines, processing it, and acting upon the resulting information through production planning or else.

"We are made wise not by the recollection of our past, but by the responsibility of our future." George Bernard Shaw.

8.2 Further research

Where we previously summarised our conclusions and recommendations, we are now going to discuss the limitations of this study and provide suggestions on how we – in the future - can further improve the research and 'solution' quality.

This research has mainly been about making up for the gap in data, data analysis, and performance measurement and management when it comes to intralogistics. The way we filled up the gap was through simulation, yielding a situation where the quality of this research depends heavily on the quality of our simulation.

To date, the simulation model is validated and able to show us the intralogistics workload under different circumstances, but the step to capacity management and optimisation is still one to make complete; and, one that could improve a lot. In order to do so, determining the required vehicle capacity, e.g., internal distances and driving speeds need to be estimated more precise. Handling times at pickup or delivery were found less important; and dominated by the driving times. Hence, to improve to model, one should pay more attention to the distance calculation, the driving speeds, and the statistics related to driving distances. This could however add a whole new layer of complexity, as traffic and collision management might become more important. If we then talk about capacity optimisation, one could do it in a static manner with pre-defined experiments, or one could choose a more dynamic way of optimising, using for example techniques like simulation optimisation (e.g., a genetic algorithm). Note that such algorithms could also be used for layout optimisation or choosing the best SupplyInAdvanceTime.

However, to come back on the distance calculation, the distances between the production floor and the incoming or finished goods warehouse could be estimated more accurately. We used rough estimations for the average distance to a specific warehouse. Of course, these distances are also influenced by (dynamic) storage policies. Especially the distance to the finished goods warehouse is important, as these travels account for more than 60% of the total.

This brings us also to the next point, which is further pooling of intralogistics resources. Until now, we deliberately separated the vehicles driving on the production floor and those of the shipping department driving back and forth in the finished goods warehouse to ship goods / load trucks. Of course, we could also merge this fleet of vehicles, giving us more room to level the total transportation workload within Flamco Bunschoten. Especially at busy times (e.g., when multiple trucks come to pick up pallets of finished goods), one could benefit from helping each other.

In this respect, one could also think of model extensions such as multiple docks to return a vehicle to, the possibility to have more destinations for one origin, and a calculation of the response time taking into account the time that a vehicle is off-duty. One could also extend the model by modelling the Air+Dirt department.

Regarding the modelling of the future business environment, in which Flamco thinks it is going to operate, one should pay attention to the cannibalisation risk that the new production line has in relation to the others. But to what extent? That is the question, especially on the mid- and short term.

Definitely, when more information and data becomes available, it is wise to review the simulation model and update it accordingly. Production lines could certainly be modelled in more detail, maybe not with the aim to improve intralogistics processes, but to improve the production itself, it could certainly add value. For the intralogistics analysis, the pallet amounts are of course vital, so if one knows more about, e.g., the pallet amounts of MGV steel, this could yield more reliable estimates of the intralogistics workload.

In this context, it could also be valuable to perform more in-depth analysis on the relation between producing a certain product group and the intralogistics workload that comes with it. We know, from our preliminary analysis, that for the MGV, the product group "790" comes with a relatively high intralogistics workload, but apart from that, we still know little.

Last but not least, in terms of Smart Industry, we strongly focussed on simulation. Things like Cyber Physical Systems (CPSs), machine-to-machine communication, and collaborative robots (AGV to AGV) disappeared quickly into the background, as Flamco is not ready for that today. Systematic data collection, in function of future big data analysis, and adding sensors (IoT) in the manufacturing process is however certainly something that could yield benefits on the short term.

8.3 Research summary and contribution

In this section, we look back, summarise what we have done in this research (without discussing any results), and see what contributions are made to the project stakeholders.

This master's dissertation has shown the build and execution of a scenario-based simulation study for the purpose of analysing the intralogistics system of Flamco's main production facility in Bunschoten as well as of a foreseeable future factory. Before drawing up the conceptual model on which the computer simulation is built, we described the research problem and approach. Extra attention was paid to the concepts of Smart Industry, as Flamco continues to automate its (production) processes, which is getting an extra boost from the Aalberts Operational Excellence programme and the fact that the company will move to a to-be-built-in-greenfield facility in a couple of years. This research was also considered a small part in planning the latter. A case study was described to get everyone familiar with the situation at Flamco Bunschoten. In addition, we performed a thorough data analysis of the current intralogistics system. A lot of missing data was gathered with great care to avoid a well-known credo in simulation, i.e., garbage in = garbage out. Based on the case study and data analysis, an extensive conceptual model was formulated; containing all relevant details of the model, i.e., in- and output, assumptions and model logic. After that, in line with Smart Industry, a computer simulation model was built in Siemens Plant Simulation. A decent model verification and validation process made sure the model does what it is supposed to do. The management of Flamco has been continuously consulted during the model building and validation process, which in the end established credibility for the model. By means of scenarios and interventions, and again in consultation with the stakeholders of the project, a set of experiments was run to evaluate important output factors of the intralogistics system, e.g., travel frequencies and material buffer sizes. Two main scenarios, i.e., the current factory layout and that of a newly planned factory, have been analysed, providing information and identifying potentials for improvements. In addition, apart from the simulation study, some practical advices were put together using the things that caught the critical eye in those 6 months of research. The thesis was finalised by conclusions, i.e., the answering of research questions as well as recommendations and an outlook on what is supposed to be next in terms of research.

Then, the contribution of this research to the different stakeholders, e.g., Flamco, the scientific world, society. Knowing that the goal of the Master's thesis was to independently execute a research and/or design-oriented project, a (scientifically) justified and structured approach should have been followed in analysing, modelling, and implementing improvements for the design and control of operational processes that belong to the Industrial Engineering and Management (IEM) domain. Talking about this research, we carried out a project that is a mix of research and design, i.e., the main deliverable is research-oriented, as it is about providing extensive insight in Flamco's intralogistics of today and tomorrow, while the way to get there, an advanced (discrete-event) simulation, is almost fully design-oriented.

The research contributes to practice in various ways. First, it comes up with data that can be used to create a close to optimal layout for a new factory build in greenfield. Second, building a simulation model means that the production and intralogistics systems are analysed and critically reflected at the same time, pointing out weaknesses for which today assumptions need to be made and for which additional data gathering and decision support can add value in the future. An example would be adding sensors to the production lines to automatically measure what happens at a production line, which is not only in line with the concepts of Smart Industry, but also adds to Flamco's operational excellence program once the data is exploited, i.e., analysed structurally by a process engineer. Third, the simulation is able to quantify the impact of changes in the production and/or intralogistics system, e.g., what happens in terms of intralogistics workload when a production line works an extra shift. This again supports the design of a new factory. Fourth, the scenario-based simulation study shows Flamco the potential of simulation, which is also a concept of Smart Industry. Model assumptions and simplifications help describe the gap between Flamco today and maybe a fully automated Flamco some future day.

The scientific contribution of this research is somewhat more complicated. As this research is tailor-made for Flamco, it is hard to generalise results whatsoever. Yet, the structured approaches in data gathering and analysis, and simulation model building, are examples of how one could shape a scenario-based simulation study. The agile way in which the model was verified and validated step-by-step - consulting the main stakeholders frequently - proved to be useful as credibility in the model was established. From an IEM perspective, it might seem as if the research mainly works with rather simple improvement suggestions and proposes rather simple solutions. However, the complexity of this research does not lie in the individual processes or solutions, it is the combination of systems (i.e., intralogistics combined with production combined with physical boundaries and planning combined with customer demand) that makes things complex to manage and see through. Furthermore, complexity lies in the fact that before this research, very little was known about the intralogistics; and if there was data on something, it was certainly not quantitative information. In addition, regarding the production system, basic information (e.g., processing times) seems to be unavailable or is scattered throughout the organisation without people knowing about it. These issues also complicate things considerably when one tries to model from scratch a larger system - consisting of multiple subsystems.

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Appendices

In the appendices one can find all necessary attachments relevant to support the main report.

A Technical details of the production processes

In this appendix, we explain the production processes of the production lines from a technical point of view.

This appendix is marked as confidential.

B Technical details of the downtime in production

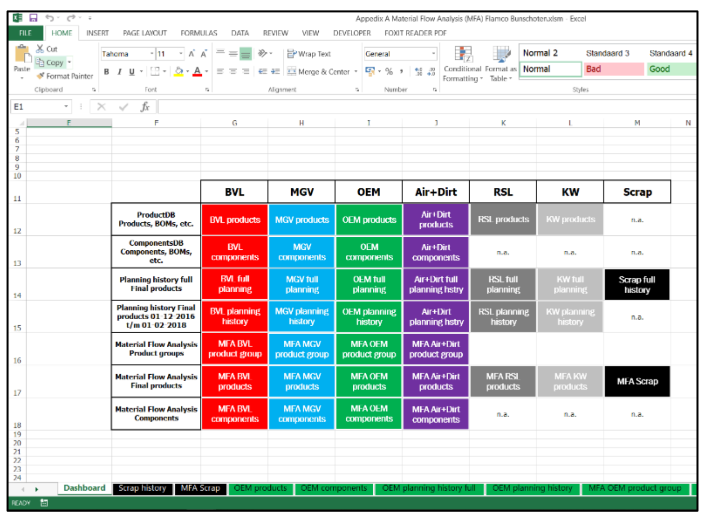
In this appendix, we explain in more detail some causes of downtime in production, e.g., the setup activities that are needed when the production line switches from one expansion vessel to the other. As, e.g., setup activities often have a technical reason, we address also the technical background.

This appendix is marked as confidential.

C Data and calculations Material Flow Analysis

In this appendix, we show the data and calculations of our material flow analysis (MFA) that was part of our systematic handling analysis (SHA) and of which the results were discussed extensively in section 3.7. The appendix is in a spreadsheet format (MS Excel).

See accompanying Microsoft Excel file. With help of the buttons in the sheet "Dashboard" one can easily navigate easily through the different sheets. Note that in every sheet, in the top left corner, there is a "Back" button, which returns the user to the sheet "Dashboard".



D Overview of all containers and pallets

In this appendix, we provide an overview of all containers and pallets that exist within the Flamco Bunschoten plant. Also, the handling equipment that is used to perform the intralogistics is listed.

Pallet type	**Euro**	**Pallet cage S**	**Pallet cage M**
Terminology Flamco	*Euro*	*Gitterbox*	*Zilveren kooi klemringen*
Picture Flamco			
Picture			
Dimensions (B x L x H)	800 x 1200 x 144	800 x 1200 x 1000	800 x 2100 x 1000

Pallet cage L	**Steel pallet**	**Throw away pallet**	**Pallet crate**
Groene kooi OEM / BVL	*Stalen pallet rondellen*	*Weggooi pallets voor VLMs, platines, klemring coil, etc.*	*Pallet krat MGV of Air+Dirt*
			
			
1400 x 2100 x 1200	800 x 1200	Depends	Depends

Euro Carton (non-stackable)	Tray	Box	Double Euro
Euro met doos membranen	*Klantspecifieke tray / box OEM (Vaillant, Tzerra etc.)*	*Klemringen box Saunier Duval en Vaillant*	*Dubbele Euro voor dozen die nog steeds uitsteken*
			
			
800 x 1200 x 1000	800 x 1200 x 1000	1000 x 1200 x 750	

Scrap bin M	Scrap bin L	Coils of steel	
Schrootbak normaal	*Schrootbak RSL*	*Coils staal (klemringen en bandstaal voor rondellen)*	
			
			
1100 x 1600 x	1550 x 2400 x	L = 1400; diameter = ±1200	

Vehicle type	Reachtruck	Forklift	
Picture			

E Technical description simulation model: Model structure

In this appendix, we describe the model structure and the important model functionalities.

Model structure in Siemens Plant Simulation

General structure

The model is built up around a series of frame objects. Each frame has its own task and place in the hierarchy of frames. We use an object orientation when modelling, which means that we create a library of 'standard' objects and built a model using instances of these library objects. Hence, when we describe the model, we continuously refer to objects, which are always the instances of the library objects. Object oriented modelling has advantages such as easy duplication of 'standard' objects, and easy model changes and maintenance due to far-reaching inheritance.

The frame *Main* is literally the main frame, from which everything starts. On this frame, one can distinguish three types of objects.

First, there are the objects that together form the Flamco factory: the *FloorPlan* frame, the *ProductionLine* frames, the *PDpoint* frames, and the *AGVparking* frames. These frames in turn all contain MaterialFlow objects (Source, Line, Buffer, etc.) and InformationFlow objects (Method, Variable, TableFile, etc.). During the initialisation phase of the simulation, we always delete all objects mentioned above and draw up the factory again. We elaborate on this when discussing the method Init.

Second, there are the methods and frames related to EventControl: *Init*, *Reset*, *EndSim*, and so on, the frame *Network*, the frame *Settings*, the frame *AGVcontrol*, the frame *Performance*, the frame *Experiments* and some additional methods and tables related to Factory Control globally.

Third, there are the so-called Movable Units (MUs) that flow through the model when simulating. There are three types of MUs in the model: the *ExpVessel* object being a customised Entity object with its own user-defined attributes, the *AGV* object being a customised Transporter object, and the *Pallet* object being a customised Container object with its own user-defined attributes.

Model (experimental) settings

All model settings are gathered in the *Settings* frame. Here, one can change a multitude of factors, e.g.,

- The production lines with their location and working hours;
- The number of PDpoints and AGVparkings (and of course there names and locations);
- The number of AGVs, dedication, default location, driving speed, and working hours;
- A distance metric can be chosen from the following set: {Euclidean, Manhattan}.

Note that the user can change the location of all PDpoints and AGVparkings interactively with help of the button *Update Distances*. First, one should define all PDpoints and AGVparkings in the designated tables (with random X and Y coordinates). Subsequently, one should initialise and reset the simulation once. After that, one can open the *Main* frame and drag all frames into the desired place. Hitting the button *Update Distances* then adjusts all settings and rebuilds the simulation.

Model initialisation and reset

The method *Init* initialises the simulation, i.e., it for example deletes and recreates all factory related objects that were mentioned earlier. The fact that *Init* rebuilds the whole factory before the start of the simulation has the strong advantage that the model is dynamic, which makes that a lot of settings can be easily changed. The method *Reset* resets the simulation by killing all MUs, emptying all tables and setting all variables back to their default value. Note that some frames contain their own *Init* and/or *Reset* methods (or alike). This is done to keep methods simple, avoid referring too much to other frames, and for practical reasons (e.g., make sure one first creates the PDpoint object instead of the AGV object, as vice versa would mean creating an AGV object in some non-existing place).

Flows of MUs through the model

The flows of MUs through the model is as follows. *ExpVessels* flow within the different *ProductionLine* frames thereby going through the production process, i.e., through Procs, Lines, Buffers, et cetera. *AGVs* flow in and between the *FloorPlan* frame, the *PDpoint* frames, and the *AGVparking* frames. *AGVs* drive on *Track* objects created in the *FloorPlan* frame. With help of *Interface* objects, these tracks connect all kind of other frames with each other, i.e., *PDpoint* frames, *AGVparking* frames, and *Buffer* objects within *ProductionLine* frames. *Pallets* host either *ExpVessels* or artificially created raw materials (to cut the number of MUs and speed up the simulation), or are empty. *Pallets* are transported from one place to another by *AGVs*.

Network and Flow control

The frame *Network* contains all details of the intralogistics network, i.e., the different nodes that can be reached by the *AGVs*, the tracks that are used to connect the nodes, and the distances from one point to the other. Furthermore, the method *CreateNetwork* actually builds the whole network (and is therefore the first thing *Init* calls).

The frame *AGVcontrol* facilitates the whole process of *AGVs* driving, executing transportation jobs/tasks/..., et cetera. Hence, this frame is covers most part of the Flow control in the model. An arriving pallet (with either raw materials or finished goods) triggers a method that lists the pallet in a to-do-list as a load to be transported from A to B. A new transportation job or task (terms may be used interchangeably) triggers the method *Check*, which logically checks if there are any vehicles free to perform a task. In case multiple tasks are available for (multiple) *AGV(s)*, a matching procedure is followed in the method *AGVgetnewtask* to choose the task with the highest priority. The methods *AGVpickup* and *AGVdelivery* take care of the physical drop-on drop-off movements of the load. A pre-defined and tactically chosen default location is used as a waiting point for *AGVs* from the moment there are no tasks that they can perform or there are off duty. The driving itself is facilitated by the tables *Network.TrackTable* and *Destinations*, i.e., each origin location has a pre-determined destination location. The methods *ChooseFactoryTrack* and *UpdateLocation* are self-explaining.

Performance measurement

The frame *Performance* collects all relevant data. Per replication, a table with output data is saved.

Experimentation

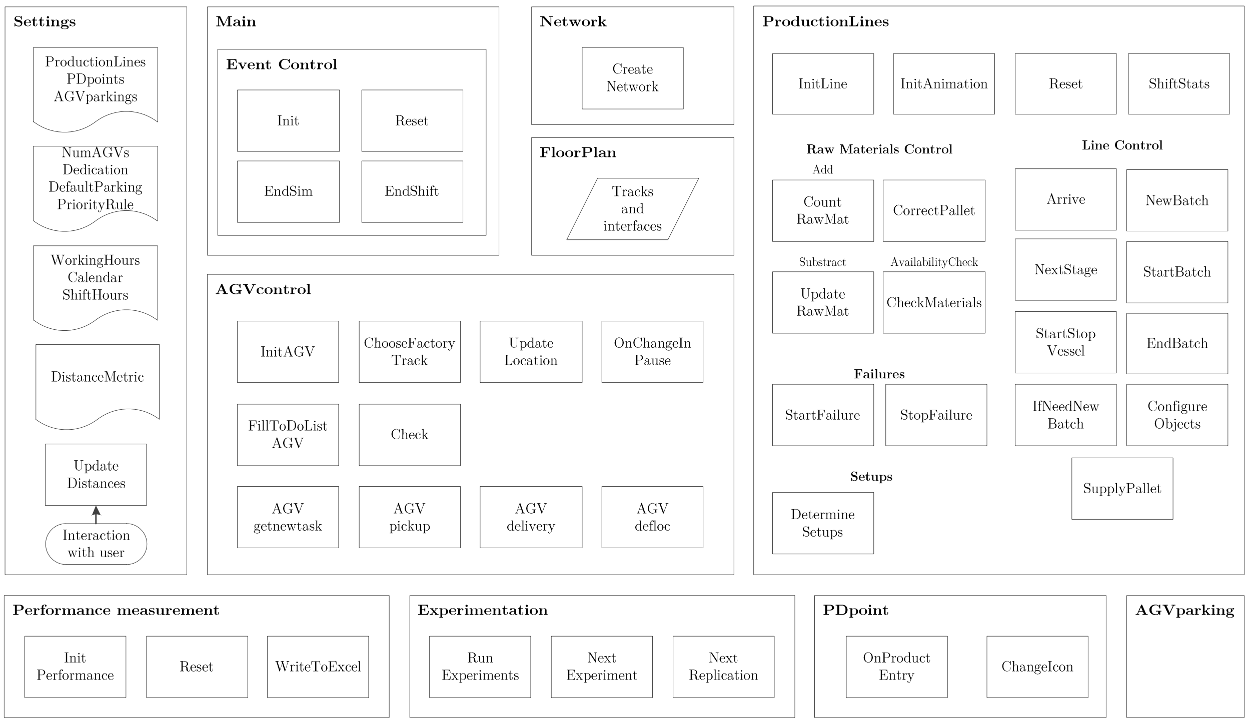
The frame *Experimentation* can be seen as a substitute for the *Experiment Manager* object of Plant Simulation. By changing the variables *NrExperiments* and *NrReplications* one sets the settings for the next round of experiments. The input settings of the experiments itself should be defined in the table *Experiments*. When everything is set, one can hit the green start button (method *RunExperiments*) to start simulating. After experimenting, output data can be automatically written to MS Excel by hitting the method *WriteToExcel* (with the MS Excel icon) in the frame *Performance*.

hydronic flow control

Flamco

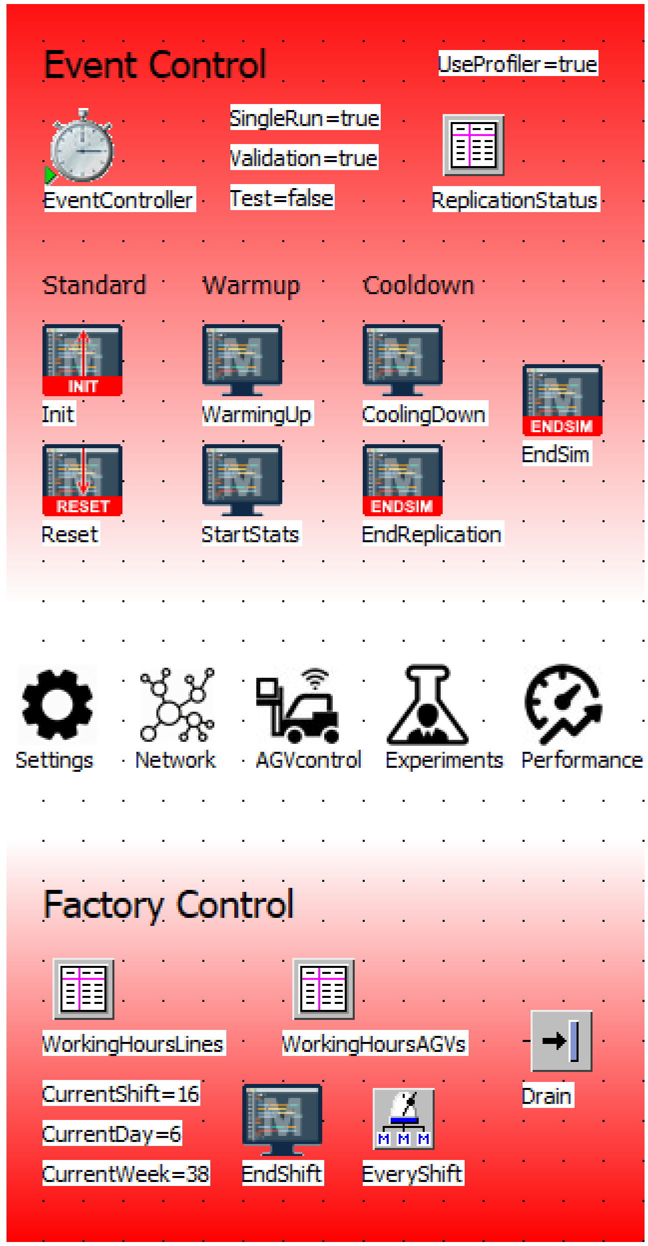
F Technical description simulation model: Methods

In this appendix, we provide an overview of all methods in the simulation model and explain the function of each of them.



Frame Main

Init



Called by: EventController

This method calls the following methods in the order of mentioning: *CreateNetwork* (frame *Network*), *InitLine* (frame *BVL*, *MGV* and *OEM*), and *InitAGV* (frame *AGVcontrol*). It also resets and activates (if used) the Profiler function of Siemens Plant Simulation to keep track of the simulating performance. Using the Profiler can be regulated with the Boolean variable *UseProfiler*.

Reset

Called by: EventController

This method resets the simulation, together with the other reset methods in the other frames. All movables are deleted, i.e., *ExpVessel* objects and *AGV* objects. The tables *WorkingHoursLines* and *WorkingHoursAGVs* are emptied. The variables *CurrentShift*, *CurrentDay* and *CurrentWeek* are set to zero.

WarmingUp

Called by: EventController

This method randomly picks a line in the production planning and adds it on top of the planning to warm up the simulation.

StartStats

Called by: EventController

This method makes sure that once the first production line finishes its warmup, statistics are gathered.

CoolingDown

Called by: EventController

This method makes sure that once the first production line finishes its entire production planning, it stops. The cooling down phase of the simulation is also started then, which means that the simulation ends once all production lines finish their scheduled production.

EndReplication

Called by: EventController

This method logs / copies all relevant output, i.e., tables with statistics, in frame *Performance*. Next, the method determines the next step of the simulation. In case of a single run, this simple means that *EndSim* is called. In case of experiments, either a new experiment and/or replication is started or the simulation is ended.

EndSim

Called by: EventController

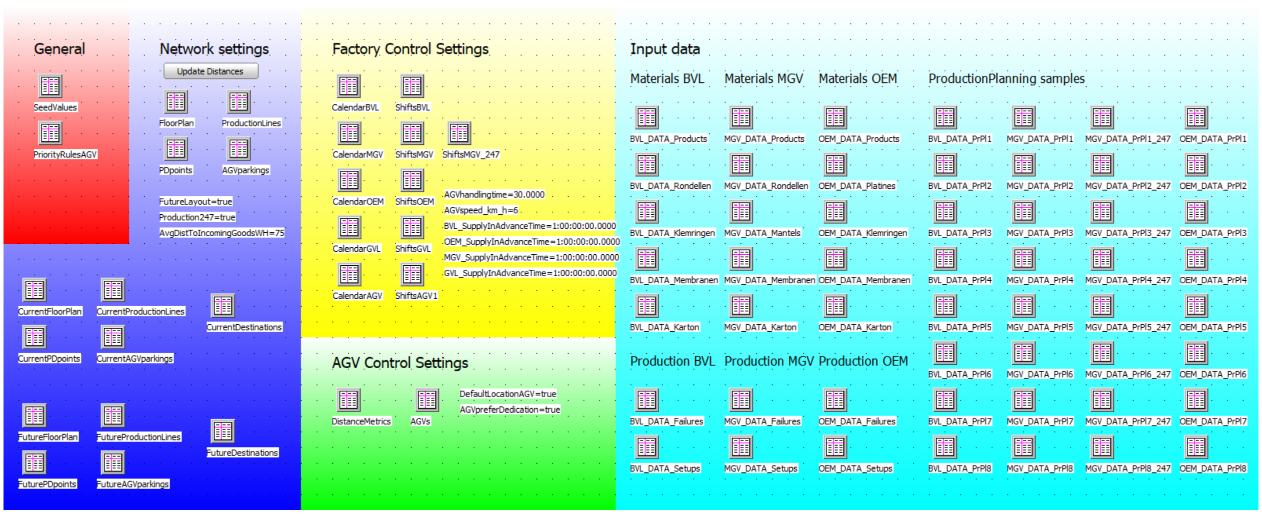
This method stops the simulation, i.e., EventController.

EndShift

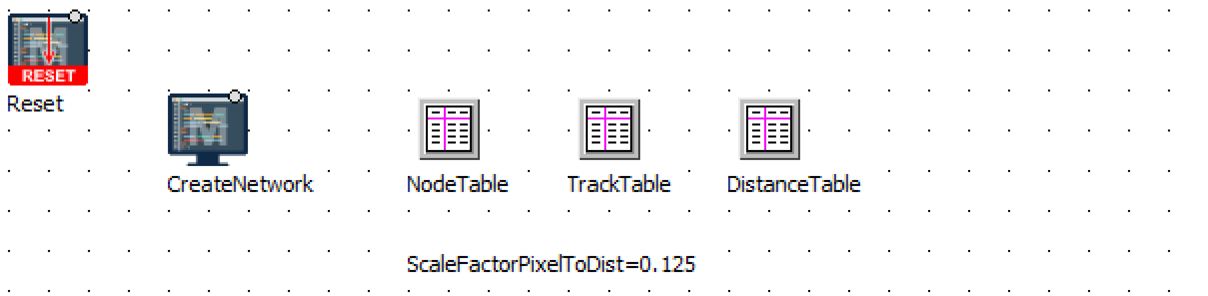
Called by: Generator EveryShift

This method updates the counters *CurrentShift*, *CurrentDay* and *CurrentWeek*. Next to that, statistics of the past shift are collected here (e.g., related to production, utilisation of AGVs and buffer sizes needed at the different points in the factory).

Frame Settings



Frame Network

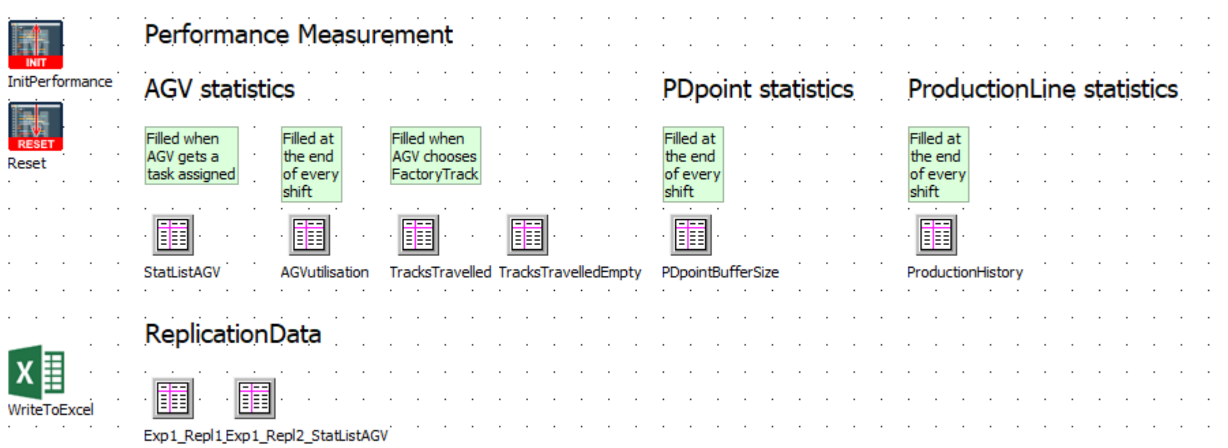


CreateNetwork

Called by: Init

This method (re)builds the whole factory. First, it deletes the *FloorPlan*, the *ProductionLines*, the *PDpoints* and the *AGVparkings*. Also, the tables on the frame *Network* are emptied. Next, all aforementioned objects are recreated. The *Interfaces* connected to the *FactoryTracks* in frame *FloorPlan* are linked to the *Interfaces* connected to the *PDpoints* and the *AGVparkings*, i.e., the *Interfaces* AGV_IN and AGV_OUT. In addition, the *Interfaces* connected to a *ProductionLine* are connected to the right *Interfaces* of the right *PDpoint*. Lastly, the animation lines of the different *ProductionLines* are taken care of.

Frame Performance



InitPerformance

Called by: Init

This method initialises the table *ProductionHistory* by creating nested lists.

Reset

Called by: EventController

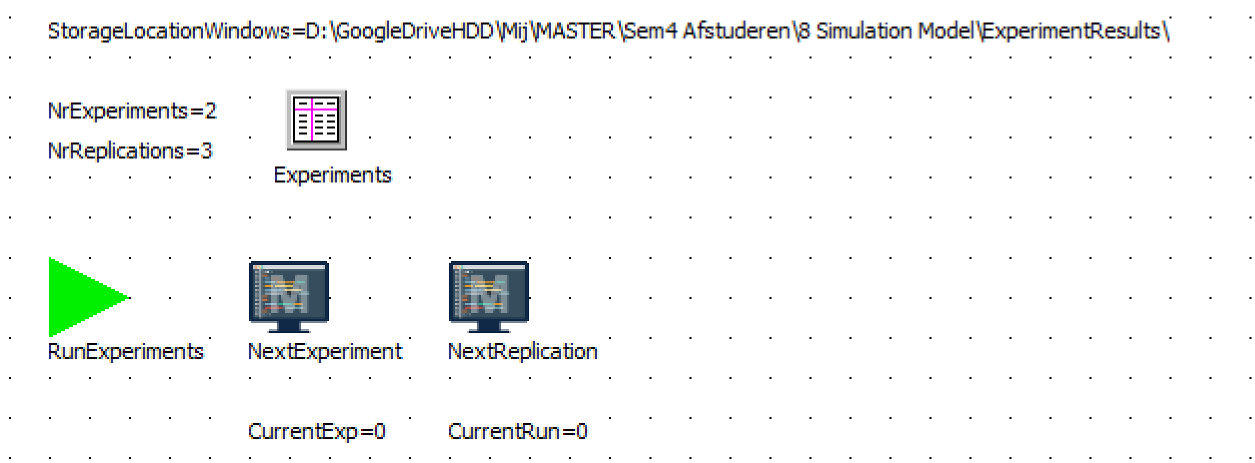
This method empties all tables with statistics.

WriteToExcel

Called by: OnClick (by user)

This method writes all tables with statistics, resulting from a round of experiments, automatically to MS Excel.

Frame Experiments



RunExperiments

Called by: OnClick (by user)

This method starts simulating a round of experiments that are defined in table *Experiments*. The method makes sure a number of experiments equal to *NrExperiments* is simulated, each with a number of replications equal to *NrReplications*.

NextExperiment

Called by: EndReplication

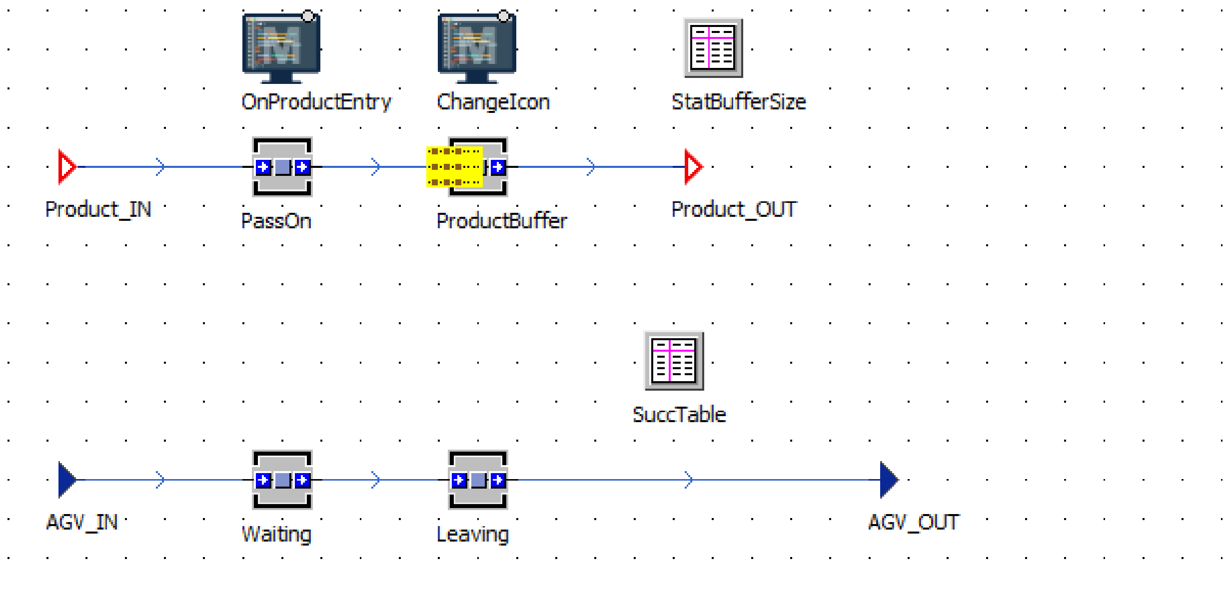
This method initialises the experimental settings for the next experiment. Next, it calls NextReplication to start the first replication of the new experiment.

NextReplication

Called by: EndReplication and NextExperiment

This method starts simulating a new replication, i.e., the simulation is stopped, reset and restarted.

Frames PDpoint



OnProductEntry

<u>Called by:</u> PDpoint.PassOn (Exit control)

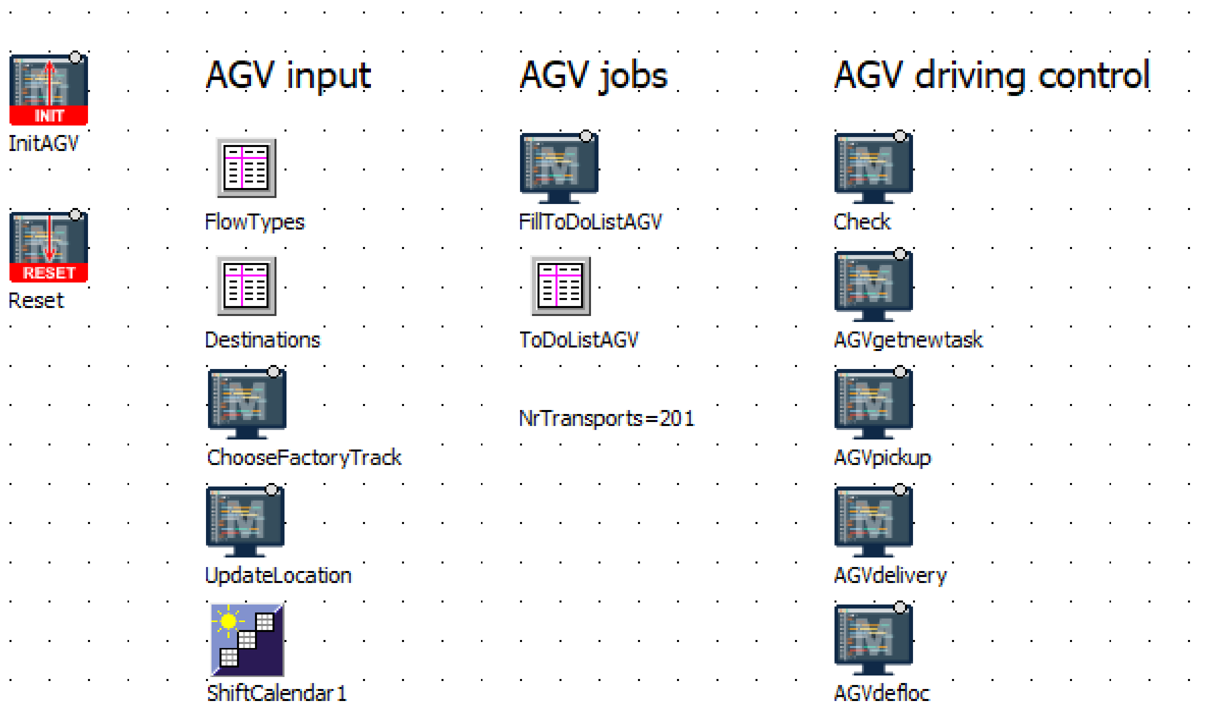
This method calls the method *FillToDoListAGV* to add the incoming pallet MU as a transportation task. The MU is then moved to the subsequent *PDpoint.ProductBuffer* to wait.

ChangeIcon

<u>Called by:</u> Observer of the attribute numMU of the PDpoint.ProductBuffer object

This method switches the icon of the *PDpoint* according to the number of MUs (pallets) that are in the *PDpoint*. This way, one can see from the frame *Main* already how many pallets there are at which locations. The method also updates, if needed, the *StatBufferSize* table in frame *Performance*, such that one can see how much space there is needed to cope with the pallets going in and out of the *PDpoint*.

Frame AGVcontrol



InitAGV

Called by: Init

This method makes sure that all AGVs are physically created in their default location as well as the corresponding ShiftCalendar objects with working hours.

Reset

Called by: EventController

This method resets the AGVcontrol frame. The ShiftCalendar objects are deleted, the to-do-list of the AGVs is emptied and the variable NrTransports is set to zero.

ChooseFactoryTrack

Called by: PDpoint.Leaving or AGVparking.Leaving (Exit controls)

This method simply searches for the track object that corresponds with the current location and the destination of the AGV. It also registers which track is chosen/travelled.

UpdateLocation

Called by: FactoryTrack objects (Entrance and Exit controls)

This method updates the AGV's user-defined attributes *curloc* and *lastloc*. If an AGV starts driving on a track, the *curloc* will be "In transit" and the *lastloc* will be the predecessor object (*PDpoint* frame or

AGVparking frame). An AGV leaving the track means that only the *curloc* will be changed into the successor object (*PDpoint* frame or *AGVparking* frame).

FillToDoListAGV

Called by: OnProductEntry (method which is the exit control of the buffer PassOn in a PDpoint)

This method lists a new transportation task on the to-do-list of the AGVs. Time of request is logged as well as the origin and destination locations of the load that needs to be transported.

Check

Called by: FillToDoListAGV, PDpoint.Waiting and AGVparking.Waiting (Entrance controls)

This method is the heart of the AGV driving control. First, the type of trigger is determined within the method. We distinguish four different triggers*: todolist, pickup, delivery, and defloc*. Second, depending on the trigger type, the method calls other methods – passing through either a table containing candidate AGVs to perform a task or only the triggering AGV.

If the trigger is *todolist*, it means that a new task is added to the todolist or an AGV has become available to get a new task assigned (either due to just finishing a delivery or changing working hours). The method *Check* loops over all AGVs and determines if they are candidate to perform a new task (i.e., they are not busy with another task, not (about to be) in transit, not off duty). Subsequently, the method *AGVgetnewtask* is called with the so-called *CandidateTable* as an input parameter.

If the trigger is *pickup*, it means the AGV has arrived at the location where it should physically pick up its load. The method *Check* simply calls the method *AGVpickup* with the AGV as input parameter.

If the trigger is *delivery*, it means the AGV has arrived at the location where it should physically deliver its load. The method *Check* simply calls the method *AGVdelivery* with the AGV as input parameter.

If the trigger is *defloc*, it means the AGV has arrived at the location where it should physically deliver its load. The method *Check* simply calls the method *AGVdelivery* with the AGV as input parameter.

AGVgetnewtask

Called by: Check

This method matches AGVs free to perform a new task to the available tasks on the to-do-list, also taking into account the dedication of the AGVs (e.g., AGV only working for one specific production line) and the prioritisation of tasks (e.g., bringing new raw materials over retrieving leftovers). It might be the case that an AGV cannot be matched to any available task; in such cases, the AGV will return to its default location.

AGVpickup

Called by: Check

This method sure that the AGV physically picks up its load and starts driving to its destination - the point of delivery. Also, the response time until pickup (i.e., the time between the task being added to the to-do-list and the actual physical pickup) is stored in *StatListAGV*.

AGVdelivery

Called by: Check

This method makes sure that the AGV physically delivers its load. In addition, statistics of the delivery are stored in the *StatListAGV* is adjusted. Also, the AGV's user-defined attributes are set back to the basic values. Lastly, in case raw materials are delivered, the method *UpdateRawMat* is called to make sure an production order starts once all raw materials are available at the line.

AGVdefloc

Called by: Check and OnChangeInPause (user-defined attribute of ShiftCalendarAGV)

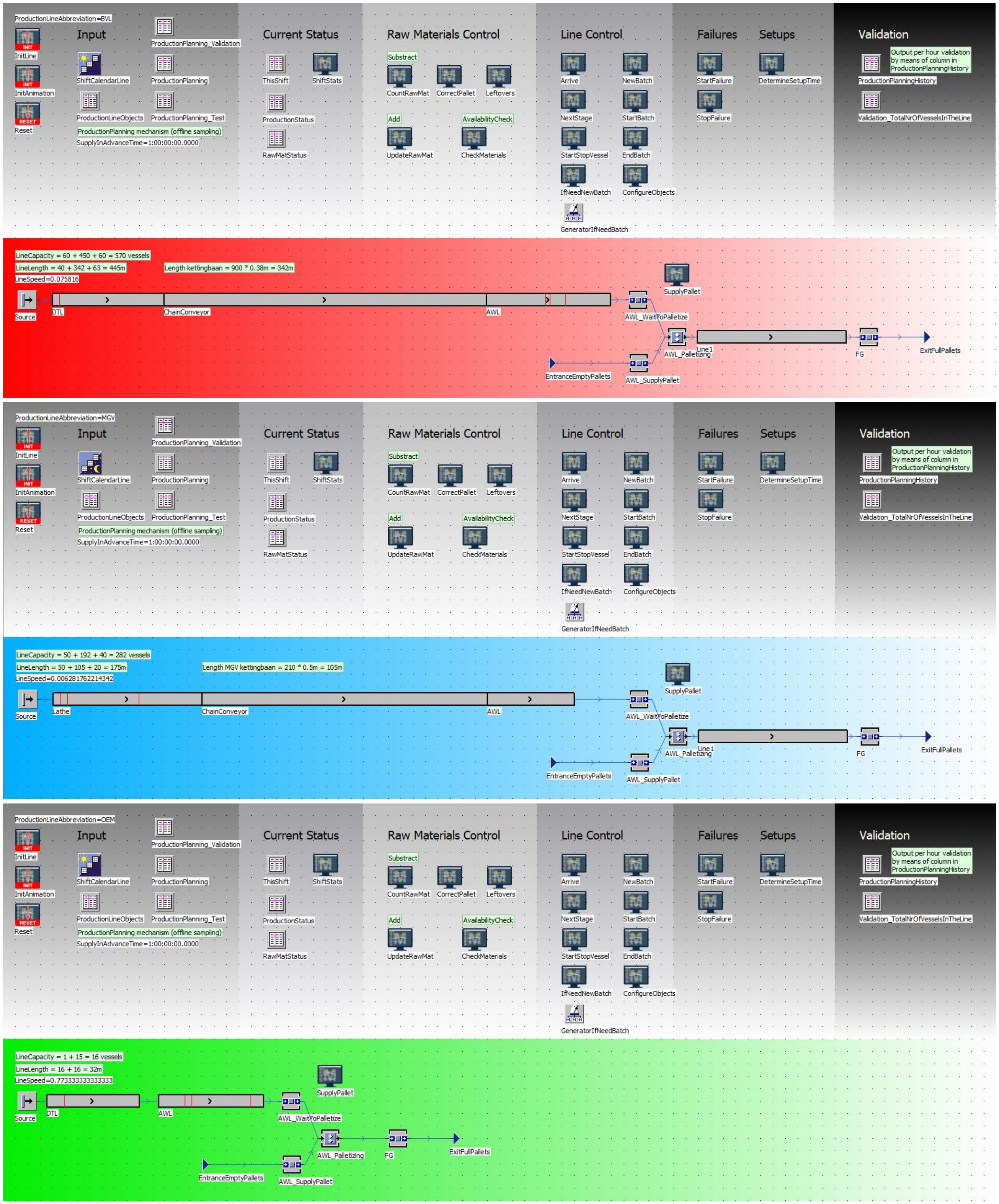
This method helps returning the AGV to its default location by setting the destination of the AGV to its default location. It becomes more complex when the AGV ends its shift (working hours set to false). In such situations, there are three scenarios: 1) the AGV has no task assigned, 2) the AGV has a task assigned, but has not yet been able to physically pick up its load, and 3) the AGV has a task assigned and has already picked up its load. In scenario 1, the AGV simply returns to its default location. In scenario 2, the AGV gives back its task (the task is put back on the to-do-list) and returns to its default location. In scenario 3, the AGV proceeds with its delivery and thereafter immediately returns to its default location.

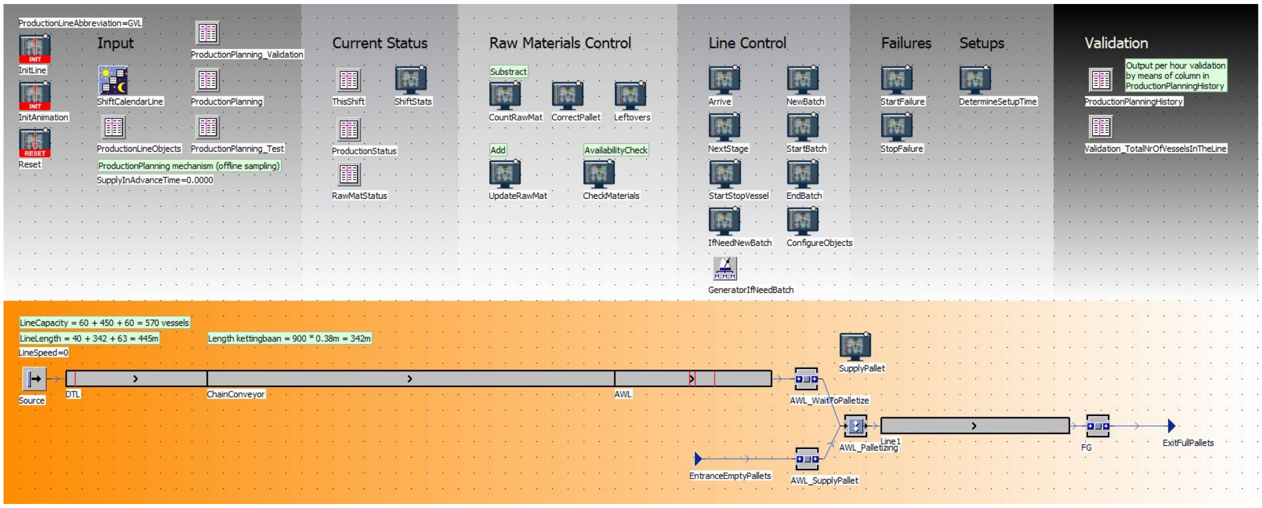
OnChangeInPause (user-defined attribute of ShiftCalendarAGV)

Called by: Observer of the attribute Pause of the ShiftCalendarAGV object

This method adjusts the table *WorkingHoursAGVs* on the frame *Main*, i.e., working hours are changed for all AGVs that are connected to the calling *ShiftCalendarAGV* object. If the working hours are set to false, the method *AGVdefloc* is called. If working hours are set to true, the method *Check* is called (trigger todolist).

Frames ProductionLine (BVL, MGV, OEM, X)





InitLine

Called by: Init

This method initialises the production line. Some empty pallets are created to later on store finished vessels on. The shift plan for the specific production line is assigned to the ShiftCalendar object, which in turn, assigns the shift hours to all relevant MaterialFlow objects. A random number is drawn to schedule the first failure of the line. The production is started by generating the first and second batch of products.

InitAnimation (inheritance cut due to different MaterialFlow objects)

Called by: InitLine

This method makes sure the MU animation is nice, i.e., there is an equal distance between the vessels flowing on the different line objects.

Reset

Called by: EventController

This method resets the production line, i.e., empties tables and resets variables.

Arrive (inheritance cut due to different raw materials)

Called by: Source (Entrance control)

This method is the entrance control of the *Source* object, which generates the *ExpVessel* MUs at a constant rate with zero interval. Too much MUs in the line are prevented by a restricted line capacity. The method fills in all necessary vessel details by assigning values to the user-defined attributes of the *ExpVessel*.

NextStage (inheritance cut due to different MaterialFlow objects)

Called by: Source (Exit control), Line objects (Exit control), This method regulates the flow of MUs through the production line. The method is triggered by different MaterialFlow objects, i.e., the *Source*, the Line objects (*DTL, ChainConveyor,* and *AWL*) and the *FG* buffer. For each trigger different actions apply. When for example the *Source* triggers, the raw materials are checked to make sure the production of a particular vessel can actually start.

StartStopVessel

Called by: CheckMaterials, StartBatch

This method adjusts the Source.ExitLocked attribute according to the availability of raw materials for a specific *ExpVessel* that wants to enter the production line, i.e., start production. If all raw materials are available at the line, the MU can pass through, otherwise not.

IfNeedNewBatch

Called by: Generator IfNeedNewBatch

This method determines, based on the variable *SupplyInAdvanceTime* ((experimental) factor set in frame *Settings*), if new batches need to be generated. The generator *IfNeedNewBatch* determines when the method is called (e.g., every hour), and hence, how often we check if the remaining expected production workload is still larger than the *SupplyInAdvanceTime*. When the remaining expected production workload falls below the *SupplyInAdvanceTime*, we generate a number of new batches of articles such that the expected production workload is again above the *SupplyInAdvanceTime*. The idea behind the *SupplyInAdvanceTime* is that the production is always supplied with something. Yet, at most 24 hours in advance, it is delivered to the production line.

NewBatch (inheritance cut due to different raw materials)

Called by: IfNeedNewBatch

This method has the function of creating all necessary pallets with raw materials for the next article to be produced (and for which raw materials are not yet created). Evidently, with the raw material pallets created in the designated P/D-points, also transportation requests are generated and added to the to-do-list of the AGVs. If there are ready-to-be-reused empty pallets present in the target P/D-point, the method creates the new pallets the same way as always, but in addition, an equal amount of empty pallets (if present) are deleted to compensate for the newly created pallets earlier.

StartBatch

Called by: StartStopVessel

This method registers that a new batch of products, i.e., an article, starts production.

EndBatch

Called by: InitLine and NextStage

This method registers that a batch of products, i.e., an article, ends production. RawMatStatus is also adjusted accordingly.

ConfigureObjects (inheritance cut due to different MaterialFlow objects)

Called by: StartBatch

This method adjusts the different line objects, which together account for the majority of the production line, such that the line produces at a speed that complies with all the different vessels in the line, i.e., the lowest production speed is leading. In a way, this is an assumption, so more on this can be found in 5.1.5.

ShiftStats

Called by: StartBatch, EndBatch and EndShift

This method registers the current shift (week, day, and shift), the vessels that are or have been in the line during the shift, and the shift output. At the end of each shift, this data is stored in the table *ProductionHistory* in frame *Performance*.

CountRawMat (inheritance cut due to different raw materials)

Called by: Sensors on the line objects

This method counts the raw materials that are used by the *ExpVessels* flowing through the production process. The actual subtraction of raw materials is done by the method *CorrectPallet*.

CorrectPallet (inheritance cut due to different raw materials)

Called by: CountRawMat

This method subtracts raw materials from the production line by adjusting the user-defined attributes of *Pallets* containing raw materials. Once a raw material pallet is empty, this method generates a transportation request to return the empty pallet to mostly its original location – ready to be reused. Note that within the simulation model raw materials are never physically delivered to the lines, only the pallets containing them are physically supplied. As a result, raw materials are artificial; they only exist in a counting process. This has the advantage of cutting the number of MUs in the model, which speeds up the simulation.

UpdateRawMat (inheritance cut due to different raw materials)

Called by: AGVdelivery

This method adds raw materials to the production line by adjusting the tables that are influenced by a material delivery, i.e., *ProductionStatus* and *RawMatStatus*. Its function is the opposite of *CorrectPallet*, which subtracts raw materials every time an *ExpVessel* triggers a sensor in the production line. The method calls *CheckMaterials* to make sure production continues once the 'decisive' raw materials are delivered.

Leftovers (inheritance cut due to different raw materials)

Called by: EndBatch

The method *EndBatch* checks when a batch is finished, if the raw materials going into the just finished product are also used by other products / batches / production orders currently in table *ProductionStatus* / in nested list *ProductionOrderIds* in table *RawMatStatus*. If so, nothing happens. If not, the raw material article is marked as a leftover and the method *Leftovers* is called. This method creates a return flow of these leftover

Pallets by making transportation requests for each of them. The method also marks them as empty pallet to make sure they are deleted when new materials are created. A simplification that saves a lot of programming hassle and does not have a large impact on the number of new pallets to be created, as leftovers are by definition small (remainders of a pallet) and are already utilised as much as possible during the time they are registered in table *RawMatStatus*.

CheckMaterials

Called by: NextStage, CountRawMat, UpdateRawMat, and OnChangeInPause (ShiftCalendarLine)

This method has multiple triggers. Either the trigger asks for a material availability check to proceed production (*NextStage* and *OnChangeInPause*) or the trigger can cause change in material availability for the production orders currently in sight, i.e., at the point of calling listed in table *ProductionStatus*, (*UpdateRawMat* and *CountRawMat*):

- When a particular *ExpVessel* wants to enter the production line.
  Call chain: *ExpVessel* calls *NextStage* calls *CheckMaterials*.
  Ideally, the materials are available in time and the *ExpVessel* can enter the line immediately of course.
- When a pause of the line ends.
  Call chain: *Observer ShiftCalendarLine* calls *OnChangeInPause* calls *CheckMaterials*.
  During the line pause, other parts of the factory might have continued working (e.g., AGVs). Therefore, the material availability should be updated and if possible, production should proceed.
- When a certain raw material is used up.
  Call chain: *Sensor* calls *CountRawMat* calls *CheckMaterials*.
  The method checks if the raw material in question has an impact on the currently produced production order and those to come. The material availability should be changed accordingly of course and if possible, production should proceed.
- When a pallet of a certain raw material is delivered.
  Call chain: *AGVdelivery* calls *UpdateRawMat* calls *CheckMaterials*.
  The method checks if the raw material in question has an impact on the currently produced production order and those to come. The material availability should be changed accordingly of course and if possible, production should proceed.

Hence, the method loops, within in a loop over all production orders in the table *ProductionStatus*, over all raw materials in the nested list (column *MaterialsAvailable*) of the specific production order. When all production orders are updated in terms of material availability, we determine if all raw materials for the forthcoming *ExpVessel* are available at the line, and hence, if production can proceed. The result is passed on to the method *StartStopVessel*, which takes care of the physical movement of the *ExpVessel*.

StartFailure

Called by: InitLine and StopFailure

This method starts a failure of the entire production line, i.e., it sets all *MaterialFlowObject.Failed* attributes to true. It furthermore draws a random number to determine the time that the line will be failed. After this time, the method *StopFailure* is called.

StopFailure

Called by: InitLine and StopFailure

This method ends a failure of the entire production line, i.e., setting all *MaterialFlowObject.Failed* attributes back to false. It furthermore draws a random number to schedule the next failure of the line, i.e., the time at which the method *StartFailure* is called.

DetermineSetupTime (inheritance cut due to differences in data source, i.e., OEE data)

Called by: StartStopVessel

This method determines how long a setup takes (between two batches / articles). For now, every setup on a certain production line takes the same amount of time, i.e., the average setup time – based on the OEE data of 2017.

SupplyPallet (inheritance cut due to differences in pallet amounts)

Called by: AWL_WaitToPalletize (Exit control)

This method makes sure the palletizing process of finished expansion vessels is executed properly. The amount of expansion vessels that can go on a pallet is according to the data from real life. When an article is different than its successor, the (partially) filled pallet is send away and a new empty pallet is supplied to palletize the new article on.

OnChangeInPause (user-defined attribute of ShiftCalendarLine)

Called by: Observer of the attribute Pause of the ShiftCalendarAGV object

This method adjusts the table *WorkingHoursAGVs* on the frame *Main*, i.e., working hours are changed for all AGVs that are connected to the calling *ShiftCalendarAGV* object. If the working hours are set to false, the method *AGVdefloc* is called. If working hours are set to true, the method *Check* is called (trigger todolist).

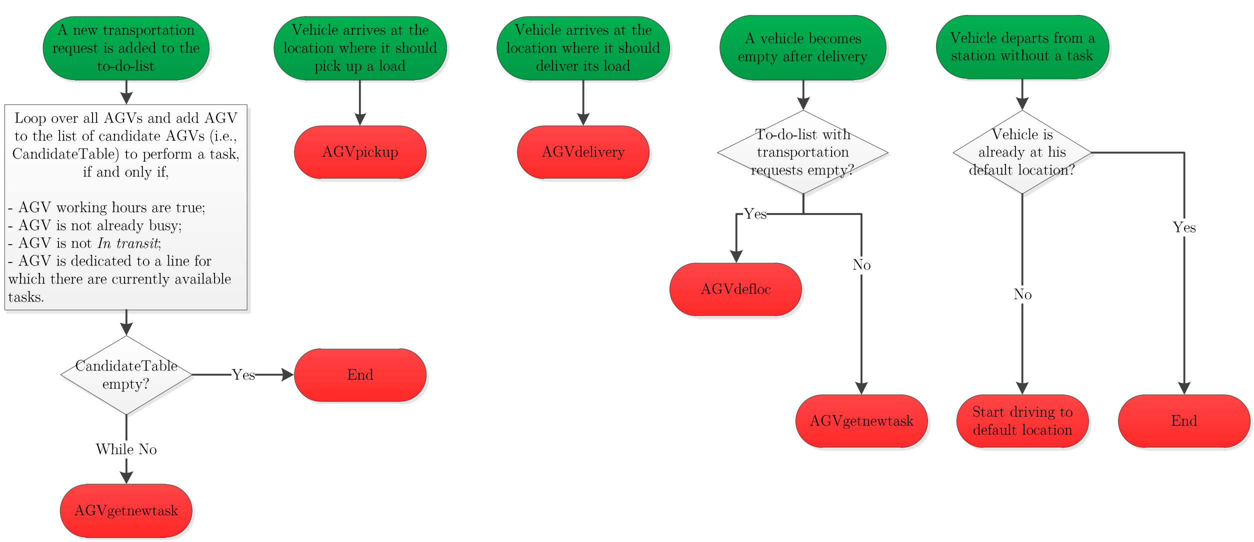
G Technical description simulation model: Logic flowcharts

In this appendix, we elaborate on section 5.1.6 by providing some detail on the model logic. We present some logic flowcharts of methods that form the heart of the simulation, i.e., the logic related to the transportation process.

The list of methods related to the transportation process:

- Check
- AGVdefloc
- AGVpickup
- AGVdelivery
- AGVgetnewtask

CHECK



CHECK

Trigger: todolist

Triggered when a new transportation request is added to the to-do-list.

Function: Determine if an AGV can perform a job, and if so, assign the right AGV to the right job.

calls subsequently:
AGVgetnewtask

Trigger: pickup

Triggered when an AGV arrives at its pickup destination.

Function: Physically pickup a load and determine the delivery destination.

calls subsequently:
AGVpickup

Trigger: delivery

Triggered when an AGV arrives at its point of delivery.

Function: Deliver load and determine if an AGV can perform a new job. If so, assign the right AGV to the right job.

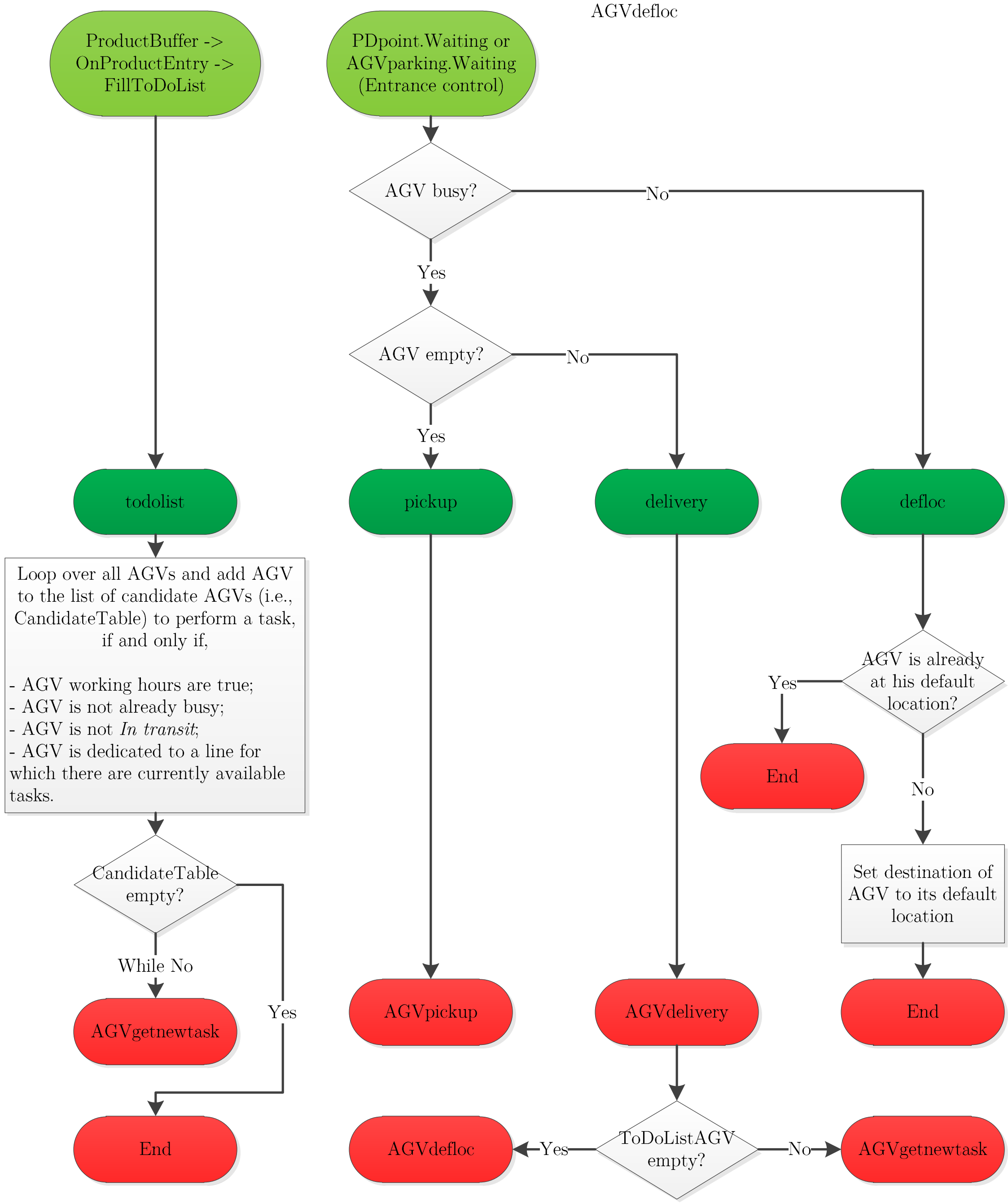
calls subsequently:
AGVdelivery
AGVgetnewtask or
AGVdefloc

Trigger: defloc

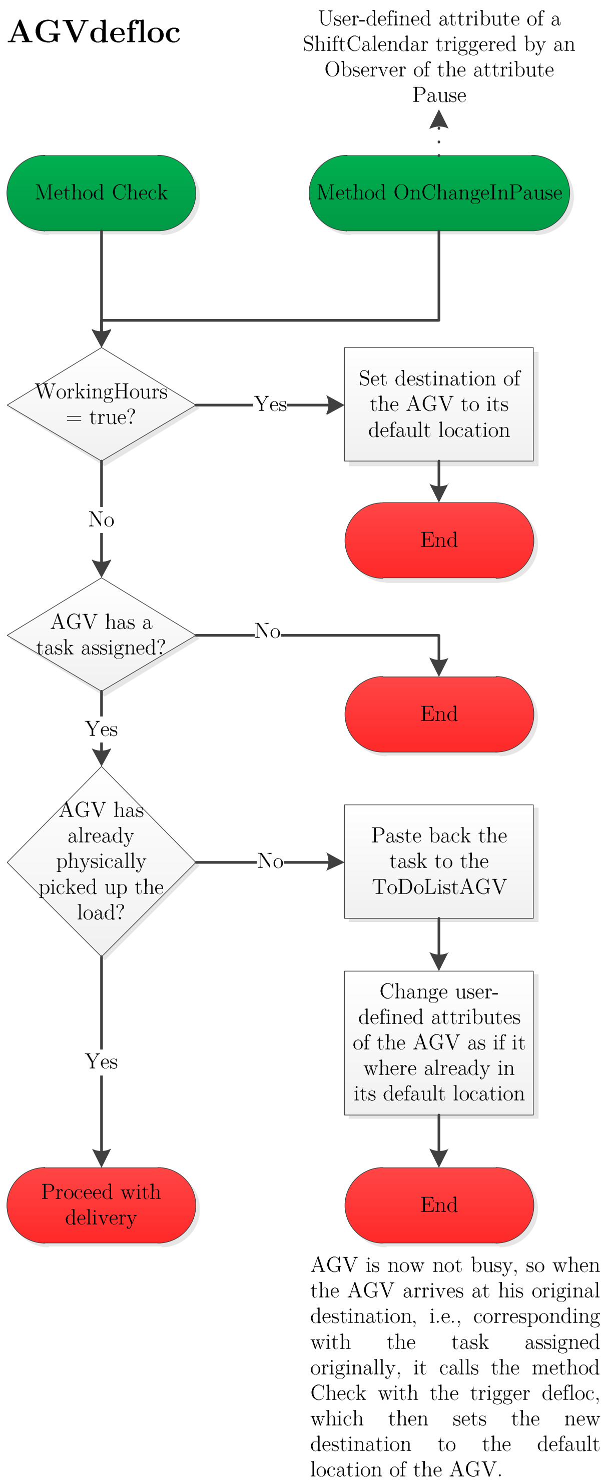
Triggered when an AGV arrives at a station and is not busy with a task

Function: If the AGV is not already at its default location, set its destination to its default location

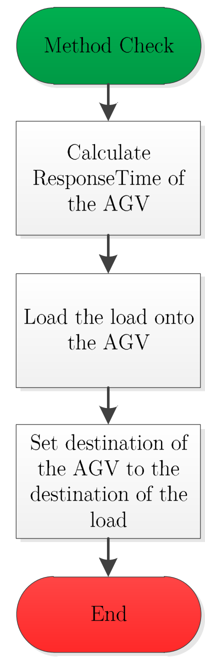
calls subsequently:
no other method



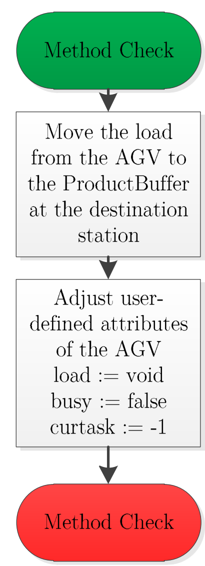
AGVdefloc



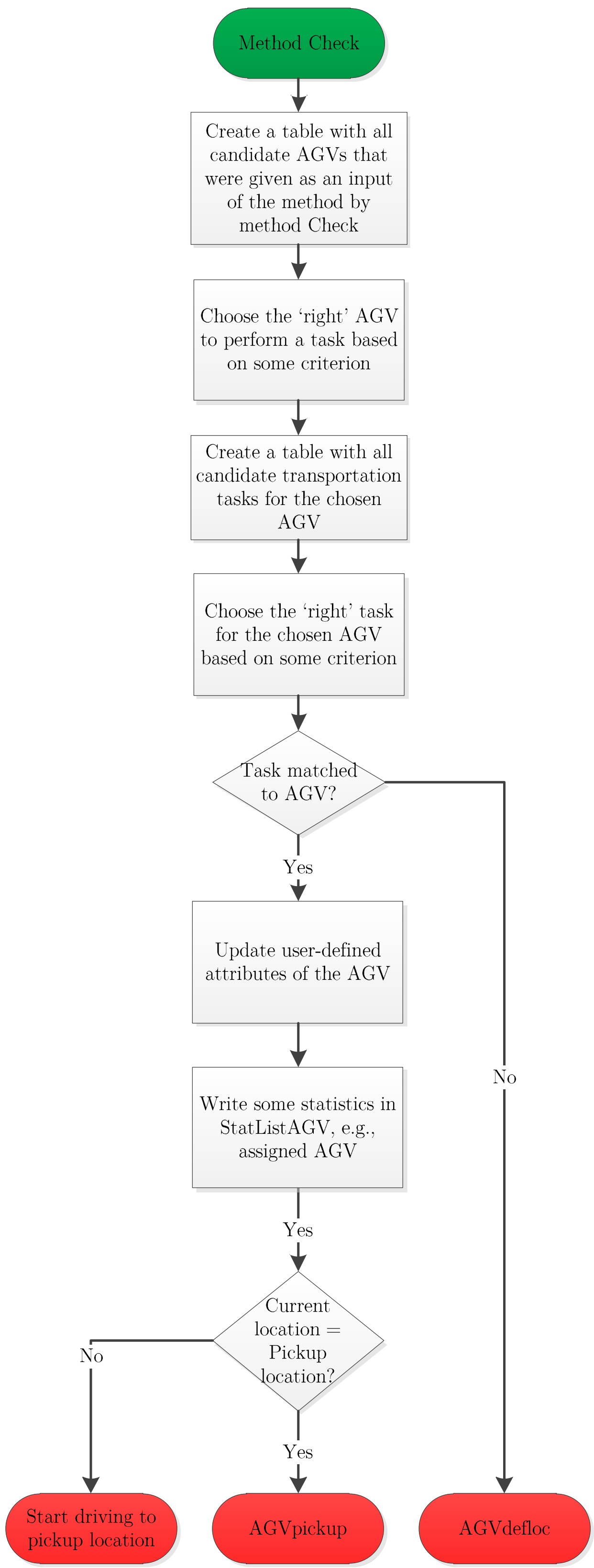
AGVpickup



AGVdelivery



AGVgetnewtask

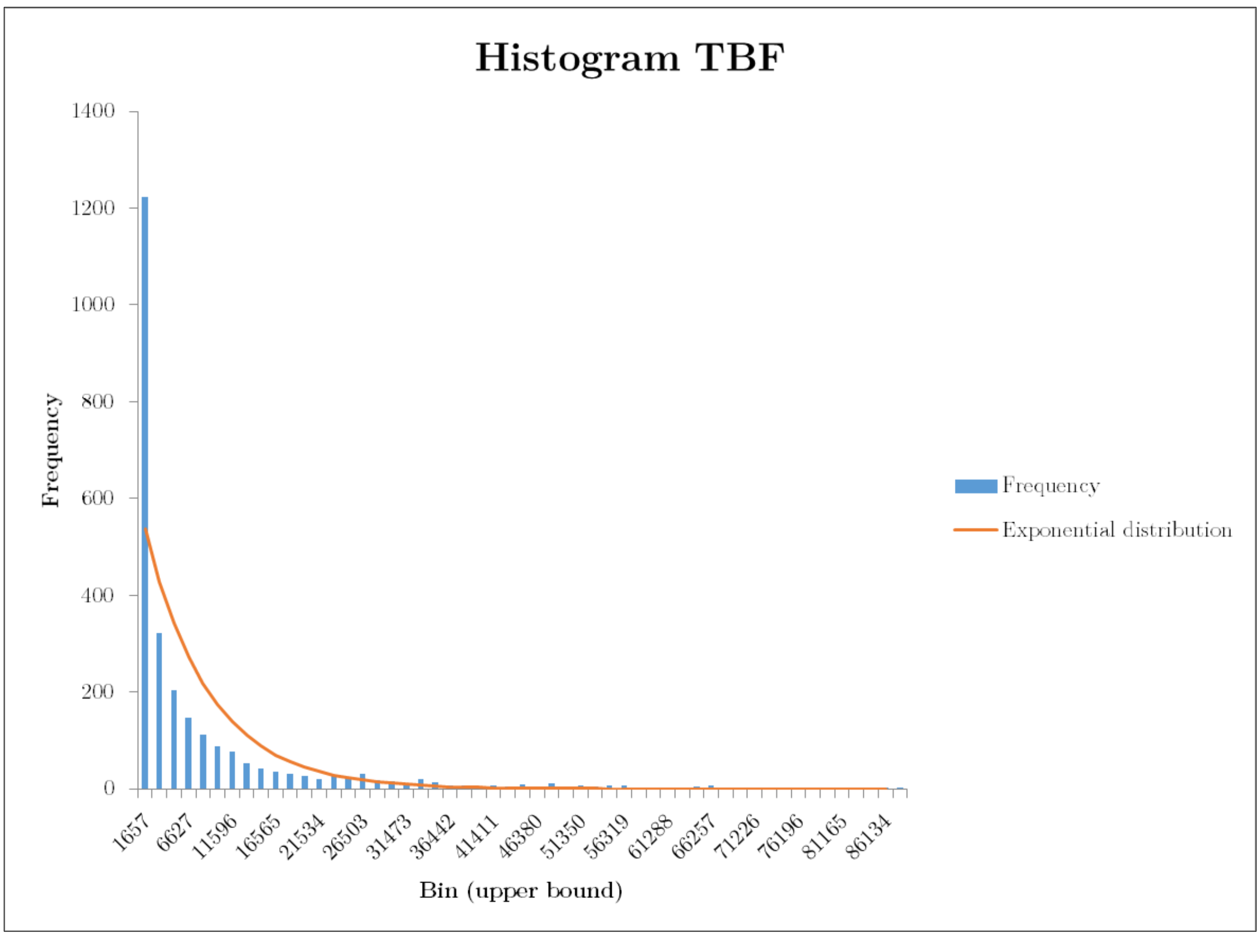


H Input data and distributions

In this appendix, we fit a theoretical distribution through the aggregated failure data and explain the sampling method to create a different production planning for each replication.

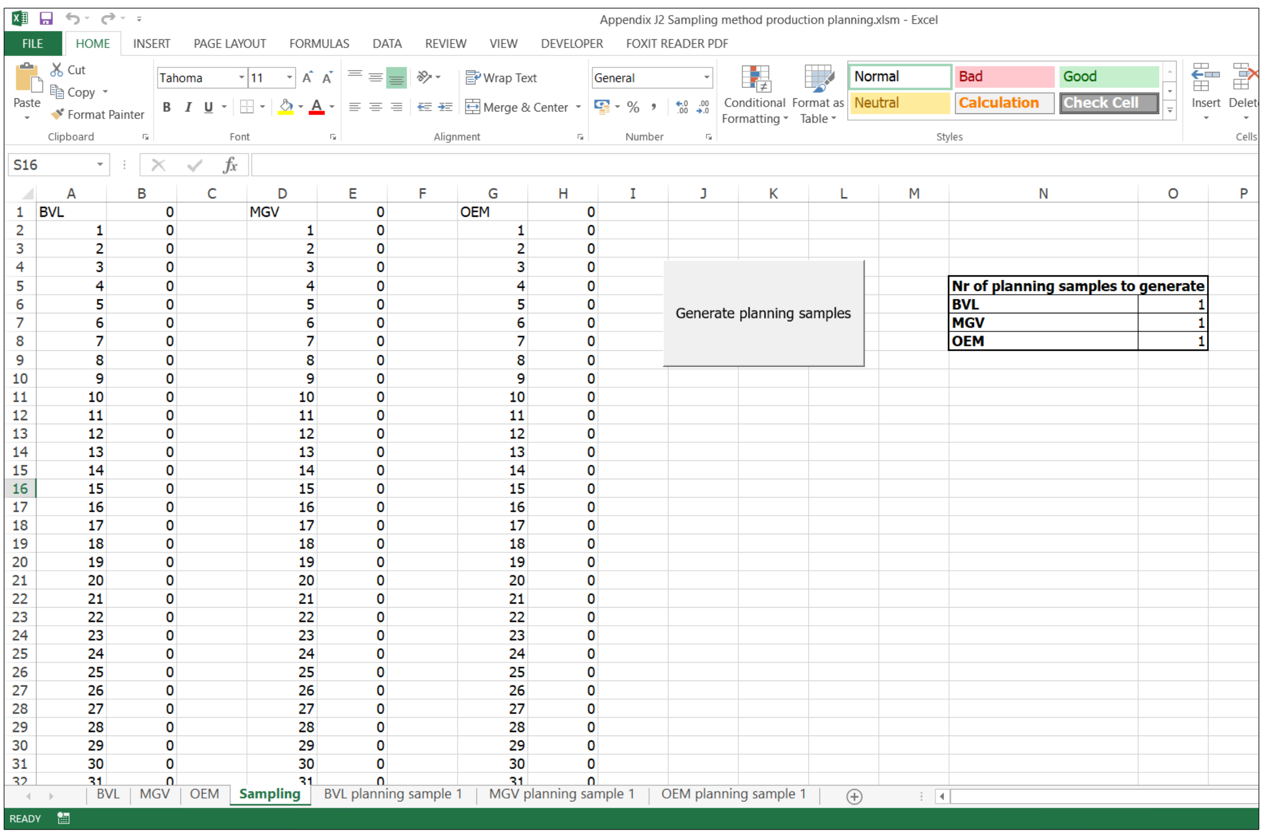
Failure data

Regarding the aggregated failure data, across all production lines, the suspected distribution for the aggregated failures is the exponential distribution. However, in all cases, a formal goodness-of-fit test (i.e., a chi-squared test) rejects the null-hypothesis saying that the data is exponentially distributed. Hypothesizing of the distribution(s) as well as the formal chi-squared test(s) is performed in MS Excel. See accompanying Microsoft Excel file "Appendix J1 Fitting a distribution for MTBF and MTTR" for the details. With help of the buttons in the sheet "Dashboard" one can easily navigate through the different sheets. Note that in every sheet, in the top left corner, there is a "Back" button, which returns the user to the sheet "Dashboard". An impression of what can be expected in the spreadsheet file, can be seen underneath. The example in this case is the histogram of the time between failures of a production line.



Production planning sampling

With regard to the sampling method to generate a new production planning, we also use MS Excel. For each production line, the sampling procedure is similar. We start from the historical production planning of 2017. This planning has a certain number of planning lines (i.e., an article number and an amount to be produced) and a number of so-called blocks. A block is a number of adjacent planning lines that share the same product group, see also the screenshots underneath. Within a block, there has been sequencing logic, which is hard to model – most probably not worth the effort. Hence, we keep blocks together to also keep the underlying sequencing logic. Now, by hitting a button, a VBA script automatically generates new production planning samples. Sampling is done proportionally, i.e., a random number between the first and the last planning line is drawn, after which the block that inhabits the planning line is added to the planning. This process goes on until all blocks are added to the planning: a new planning is now created. Note that relatively large blocks are added to the planning with a higher probability. See the accompanying Microsoft Excel file "Appendix J2 sampling method production planning" for the details. For an impression of what can be expected, see below.



I Details on the cases in the experimental design

In this appendix, we explain the differences of the two cases we investigate in our experimental phase.

In short, the two cases are as follows. The first case is obviously the current situation within the current factory (see first picture). The second case is a future factory, based on Flamco's current internal layout plan and consisting of four production lines (i.e., BVL, MGV, OEM, and X) – all working 24/7, which means in our case 5 days of 3 shifts of 8 hours. Hence, in the second case, all expected growth for the coming years is taken into account, running the new factory full throttle.

The default intralogistics capacity in the first case corresponds logically with real life, i.e., three vehicles dedicated to each of the production lines and one vehicle working for all lines, but only during the day shift. The default intralogistics capacity of the second case is in line with the first case. As now the X is added, there is also a vehicle added, dedicated to the X.

Locations of P/D-areas are such that they correspond with either their current location or the expected new location. As in the current situation, raw materials are stored both on the production floor and in the incoming goods warehouse, we add 75m to the distance with other P/D-areas to correct for the extra miles that are driven in case material is stored in the incoming goods warehouse. Note that 75m is exactly halfway the incoming goods warehouse. In the second case, the Manhattan distance metric is more questionable due to the compact layout of the production lines. As there probably will not be too much options to go right through the production lines, the actual driving distance will often be larger than anticipated. To correct to some extent for this, we sustain the 75m also in the second case. Note that Flamco itself does not put great value in the validity of driving distances, as for the concept layout for the new factory it is still undecided whether or not it is the final design. As a result, travel frequencies are much more important than distances, as these also form the input of a Facility Layout Problem (FLP).

hydronic flow control

J Detailed model results

In this appendix, we display model results that have importance, yet are not discussed in the main report.

The contents list below displays in which order the detailed model results are subsequently listed; and, how much pages they take up. We start with the current situation.

Current situation

- 2 page(s) | Complete overview of the buffer sizes of the P/D-areas; clustered per production line

Future situation

- 2 page(s) | Complete overview of the buffer sizes of the P/D-areas; clustered per production line

Current situation

SupplyInAdvanceTime	48h		24h		12h		6h		1h	
PDpointName	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**
BVL_Rondellen	24.1	63	13.3	43	7.9	33	5.2	27	2.9	22
BVL_Klemringen	16.6	37	9.6	26	6.1	20	4.3	17	2.9	15
BVL_Membranen	28.8	68	16.3	48	10.1	34	7.0	28	4.5	22
BVL_Karton	19.3	46	11.2	31	7.1	24	5.0	20	3.4	16
BVL_EmptyPallets	0.7	30	0.7	30	0.8	30	0.7	30	0.7	30
BVL_FinishedGoods	0.4	15	0.4	12	0.4	10	0.4	11	0.4	12
BVL_RM_Rondellen	17.7	62	14.4	41	13.0	31	11.9	27	10.8	22
BVL_RM_Klemringen	7.1	36	7.0	24	6.1	17	5.9	16	5.8	14
BVL_RM_Membranen	13.9	67	12.6	46	10.2	30	9.2	28	9.1	22
BVL_RM_Karton	0.7	29	0.7	14	0.7	12	0.7	13	0.7	12
BVL_FG_Warehouse	0.3	1	0.3	1	0.3	1	0.3	1	0.3	1

SupplyInAdvanceTime	48h		24h		12h		6h		1h	
PDpointName	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**
MGV_Mantels	8.8	34	5.3	24	3.7	20	2.9	19	2.3	16
MGV_Membranen	13.4	46	7.4	34	4.9	26	3.6	23	2.6	20
MGV_Karton	0.3	7	0.3	7	0.2	7	0.2	7	0.2	7
MGV_EmptyPallets	0.5	30	0.5	30	0.5	30	0.5	30	0.5	30
MGV_FinishedGoods	0.2	18	0.2	9	0.2	10	0.2	11	0.2	6
MGV_RM_Rondellen	3.8	20	2.6	13	2.0	10	1.7	9	1.5	7
MGV_RM_Mantels	5.5	31	4.1	22	3.7	18	3.6	18	3.2	15
MGV_RM_Membranen	7.0	44	6.0	32	5.5	24	5.3	21	5.2	19

MGV_RM_Karton	0.4	7	0.4	7	0.4	7	0.4	7	0.4	7
MGV_FG_Warehouse	0.2	1	0.2	1	0.2	1	0.2	1	0.2	1

SupplyInAdvanceTime	**48h**		**24h**		**12h**		**6h**		**1h**	
PDpointName	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**
OEM_Platines	21.1	63	13.2	52	9.3	45	7.2	42	5.6	39
OEM_Klemringen	13.8	40	8.6	31	6.0	26	4.6	23	3.6	21
OEM_Membranen	20.2	59	12.6	46	8.8	41	6.9	38	5.4	35
OEM_Karton	1.0	28	0.8	20	0.6	14	0.4	12	0.2	9
OEM_EmptyPallets	0.7	30	0.7	30	0.7	30	0.7	30	0.7	30
OEM_FinishedGoods	0.3	7	0.3	7	0.3	7	0.3	8	0.3	6
OEM_RM_Platines	16.6	61	16.5	51	16.0	44	16.2	39	16.5	38
OEM_RM_Klemringen	11.5	38	10.5	30	9.9	24	9.6	21	9.5	20
OEM_RM_Membranen	14.9	58	14.4	46	14.2	40	14.4	37	14.3	34
OEM_RM_Karton	2.6	28	1.8	20	1.3	14	1.1	12	0.8	9
OEM_FG_Warehouse	0.3	1	0.3	1	0.3	1	0.3	1	0.3	1

Future situation

SupplyInAdvanceTime	48h		24h		12h		6h		1h	
PDpointName	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**
BVL_Rondellen	24.0	63	13.2	43	7.8	33	5.1	27	2.9	22
BVL_Klemringen	16.5	37	9.5	26	6.0	20	4.3	17	2.8	15
BVL_Membranen	28.6	69	16.1	47	9.9	34	6.9	27	4.4	22
BVL_Karton	19.1	46	11.0	31	7.0	24	5.0	20	3.3	17
BVL_EmptyPallets	0.7	30	0.7	30	0.7	30	0.7	30	0.7	30
BVL_FinishedGoods	0.4	34	0.4	19	0.4	13	0.4	15	0.4	17
BVL_RM_Rondellen	17.8	62	14.3	42	12.8	32	11.8	26	10.7	22
BVL_RM_Klemringen	7.2	36	6.9	25	6.0	18	5.9	15	5.7	14
BVL_RM_Membranen	14.3	67	12.3	46	10.1	32	9.1	26	8.9	21
BVL_RM_Karton	0.7	28	0.7	15	0.7	12	0.7	13	0.7	12
BVL_FG_Warehouse	0.3	1	0.3	1	0.3	1	0.3	1	0.3	1

SupplyInAdvanceTime	48h		24h		12h		6h		1h	
PDpointName	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**
MGV_Mantels	6.3	25	3.9	17	2.7	12	2.0	11	1.5	9
MGV_Membranen	11.2	35	7.3	26	5.2	23	4.2	19	3.4	17
MGV_Karton	17.0	50	10.0	36	6.6	27	4.9	24	3.5	20
MGV_EmptyPallets	0.4	9	0.4	9	0.4	8	0.4	8	0.4	8
MGV_FinishedGoods	0.6	30	0.6	30	0.6	30	0.6	30	0.6	30
MGV_RM_Rondellen	0.3	17	0.3	15	0.3	13	0.3	34	0.3	20

MGV_RM_Mantels	4.4	23	3.3	15	2.8	11	2.5	10	2.3	8
MGV_RM_Membranen	6.7	32	6.1	23	5.3	21	4.7	18	4.5	16
MGV_RM_Karton	8.4	48	7.9	33	7.1	25	6.9	21	6.8	19
MGV_FG_Warehouse	0.5	9	0.6	9	0.6	8	0.7	8	0.6	8

SupplyInAdvanceTime	**48h**		**24h**		**12h**		**6h**		**1h**	
PDpointName	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**
OEM_Platines	20.9	63	13.0	52	9.1	45	7.1	42	5.4	39
OEM_Klemringen	13.6	40	8.4	31	5.9	26	4.6	23	3.4	21
OEM_Membranen	19.9	59	12.3	46	8.7	40	6.8	38	5.2	35
OEM_Karton	1.1	28	0.7	20	0.6	14	0.4	11	0.2	9
OEM_EmptyPallets	0.7	30	0.7	30	0.7	30	0.7	30	0.7	30
OEM_FinishedGoods	0.4	17	0.4	10	0.4	11	0.4	12	0.4	6
OEM_RM_Platines	16.7	63	16.3	52	15.9	45	15.8	42	15.9	39
OEM_RM_Klemringen	11.1	39	10.4	31	9.8	25	9.4	23	9.3	21
OEM_RM_Membranen	14.8	59	14.2	46	14.1	41	14.0	38	14.1	35
OEM_RM_Karton	2.7	28	1.8	20	1.3	14	1.0	11	0.8	9
OEM_FG_Warehouse	0.3	1	0.3	1	0.3	1	0.3	1	0.3	1

SupplyInAdvanceTime	48h		24h		12h		6h		1h	
PDpointName	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**
X_Rondellen	24.1	63	13.3	44	7.8	33	5.2	27	2.9	22
X_Klemringen	16.6	37	9.5	26	6.0	20	4.3	17	2.8	15
X_Membranen	28.7	69	16.2	47	10.0	34	6.9	27	4.4	22
X_Karton	19.2	46	11.2	31	7.1	24	5.0	20	3.3	17
X_EmptyPallets	0.7	30	0.7	30	0.7	30	0.7	30	0.7	30
X_FinishedGoods	0.4	29	0.4	16	0.4	16	0.4	16	0.4	17
X_RM_Rondellen	17.6	60	14.8	40	12.9	30	11.8	25	10.7	22
X_RM_Klemringen	7.1	34	7.0	23	6.2	17	5.9	15	5.7	13
X_RM_Membranen	14.3	66	12.6	44	10.2	30	9.1	25	9.0	21
X_RM_Karton	0.7	29	0.7	16	0.7	12	0.7	13	0.7	12
X_FG_Warehouse	0.3	1	0.3	1	0.3	1	0.3	1	0.3	1

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