Master Thesis Industrial Engineering and Management

Provide insights and improve the Poland material flow

UNIVERSITY OF TWENTE.

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Colophon

"Provide insights and optimize the Poland material flow."

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Management Summary

VMI (Veluwse Machine Industrie) is market leader in production machinery specialized in the manufacturing of machines for: the tire, can, rubber, and care industry. VMI started in 2015 with production activities in Leszno. A new material flow has developed due to this new production site. In the past few years, the material flow towards this production location has increased rapidly to almost 5000 items per week. The performance of the associated material flow is currently unknown. The objective of this research is to provide insights into the performance of the current material flow towards Leszno. The second (main) goal includes alternatives or improvements for specific scenarios which can be recommended to the board of the VMI. We therefore composed the following main research question:

"*What are promising alternatives given the material flow towards Leszno for multiple scenarios?*"

We used the literature to select six suitable supply chain drivers with an associated framework for analyzing supply chains in general. We performed a stakeholder analysis to acquire the driver related supply chain information which was used to analyze and clarify the current material flow towards Leszno. These findings were used, besides other resources, during the KPI selection.

We selected four KPIs to measure the performance of the current material flow towards Leszno. Multiple analyses, recourses, theories, and interviews were used to select the following KPIs:

- Total CO2 footprint.
- Average total lead time.
- Transportation costs.
- Handlings costs.

We constructed a model to analyze and measure the performance of the current material flow towards Leszno. We were advised to use a so-called toy problem for our model, since the model would become too complex for the complete material flow. A toy problem is a simplified version of a more complex real-world problem. We composed our toy problem in such a way that it represents the material flow towards Leszno accurately. We analyzed the KPI outcomes to determine which supply chain aspects affect the performance of the current material flow significantly. We obviously checked whether the aspects could be influenced. This resulted in the following material flow aspects:

- The total shipment distance
- The CO2 emissions of the used trucks
- The Intercompany shipment lead time
- The supplier related lead time
- The consolidation lead time
- Total number of required handlings
- Specific handling costs

We have translated these findings into research directions and topics which were used during a literature study. This study revealed nine potential alternatives. We analyzed each alternative in more detail to select the most suitable and appropriate alternatives for this research. This resulted in the following alternatives selection:

Material flow network alternatives:

1 Direct Shipping to Single Destination
2 Milk-run
3 Direct Shipping with Milk-Run(s)
4 Cross Dock Warehouse

Additional alternatives:

5 Environmentally Friendly Trucks.
6 Additive Manufacturing (3d Printing).

We first determined the quantitative KPI outcomes of the supply chain network alternatives within our model and based on our toy problem. We used the literature to define the potential of the two additional alternatives. We then determined the performance of the alternatives for the complete material flow, given some scenarios, by extrapolating the toy problem outcomes. We used scenarios to measure the sustainability of the alternatives during market changes. The scenarios were composed during interviews. The alternative performances given the selected scenarios are provided for each KPI in the figures below.

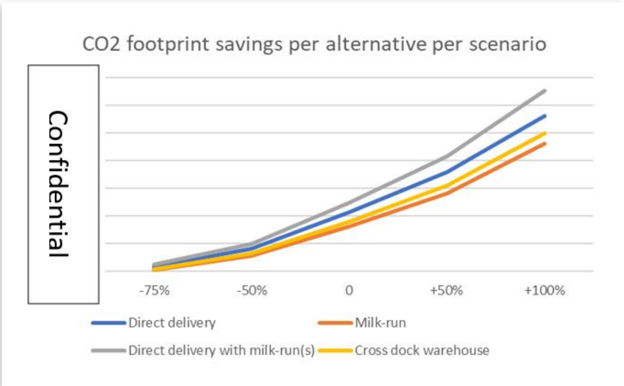

Figure 0.1 CO2 footprint savings per alternative per scenario.

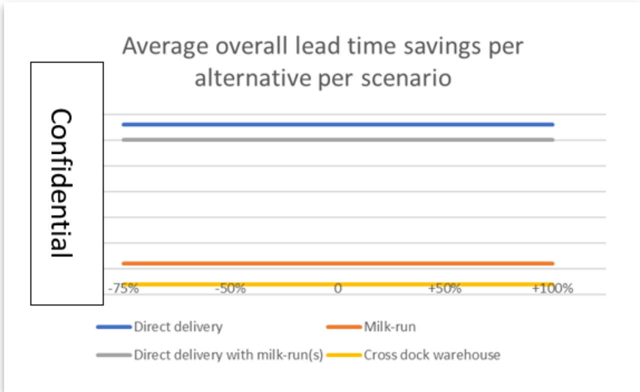

Figure 0.2 Average overall lead time savings per alternative per scenario.

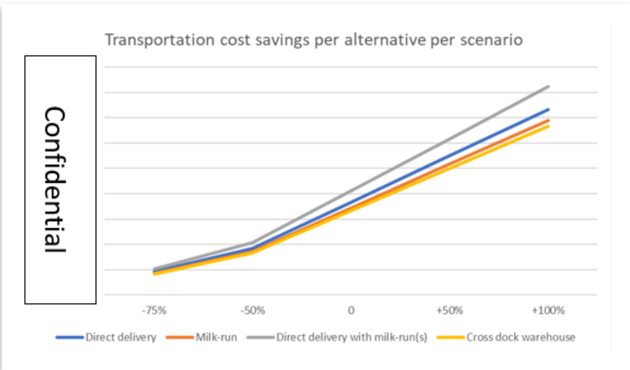

Figure 0.3 Transportation cost savings per alternative per scenario.

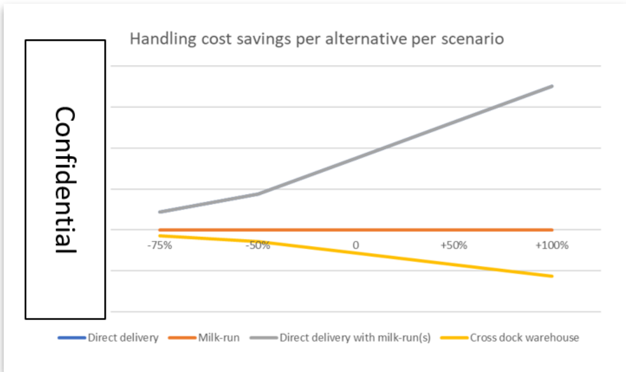

Figure 0.4 Handling cost savings per alternative per scenario.

The specific alternative outcomes have been analyzed for each KPI and scenario separately to determine which alternative should be recommended to the board of the VMI. The alternative recommendation was cost based, since the stakeholders declared that the cost related KPIs should be decisive. We divided the alternatives over two types which differ based on the required investment. So the choice for the "best" alternative depends on VMIs willingness to invest. Our recommendation regarding the best material flow alternative is therefore twofold:

"We recommend the directly delivery with milk-run(s) alternative if the VMI is willing to do a serious investment, since this alternative has the biggest potential. But we would recommend the milk-run alternative if the VMI is not willing to invest, since the milk-run alternative does not require a major investment."

We also recommend the VMI to investigate the implementation of environmentally friendly trucks, since they have the potential to reduce the total CO_2 footprint even further. The additive manufacturing technique might improve the supply chain performance as well, since it is developing rapidly and is expected to influence the global supply chains significantly. This could lead to a high applicability of the technique for the VMI in the near future.

Preface

This thesis is written in order to conclude my master Industrial Engineering and Management at the University of Twente. This thesis describes my graduation project at VMI. I look back on a pleasant time in which I learned a lot from many professionals.

I would like to thank my supervisor Peter Schuur for his guidance and support during this project. His feedback really improved the quality of this research. I would also like to thank Wieteke de Kogel – Polak for her valuable feedback at the final stage of this project.

Furthermore, I want to thank my supervisors Bob Brummelhuis and Henk Esveld for their guidance during my time at VMI. Especially, I would like to thank Bob Brummelhuis for the weekly meetings and discussions which were extremely valuable and really helped to increase the quality of this project. I also want to thank the people from the VMI for their assistance during this research.

Finally, I would thank my friends, family, and girlfriend for their support.

I hope you all enjoy reading this thesis.

Richard Pannekoek
Epe, September 2020

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Glossary

Acronym	Explanation	Introduced on Page
VMI	VMI-Group	1
TKH	Twentse Kabel Holding group N.V.	1
OC	Operation Control	2
KPI	Key Performance Indicator	3
SKU	Stock Keeping Unit	4
CODP	Customer Order Decoupling Point	8
MTS	Make-To-Stock	8
CTO	Configure-To-Order	8
MTO	Make-To-Order	8
ETO	Engineer-To-Order	8
E.G.	Exempli Gratia	10
BPMN	Business Process Modeling Notation	10
AHP	Analytical Hierarchy Process	11
CI	Consistency Index	12
CR	Consistency Ratio	12
OR-gateway	Inclusive OR-Gateway	16
SCI	Supply Chain Innovation	17
IP	Intellectual Property	19
VLM	Vertical Lift Module	20
EP	Euro Pallet	20
SP	Steel Pallet	20
ZD	Self-Supporting	20
RFQ	Request for Quotation	22
SQA	Supplier Quality Assurance	22
TCO	Total Cost of Ownership	22
OEM	Original Equipment Manufacturer	22
SUB	Sub-Assembly	24
BOM	Bill of Material	24
MMP	Multidimensional Modeling Process	25
QLTC	Quality, Logistics, Technology and Costs	26
S.M.A.R.T.	Specific, Measurable, Assignable, Realistic and Time-related	26
CO2e	Carbon Dioxide Equivalent	26
FTL	Full Truck Load	52
LTL	Less Than Truckload	52

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1. Introduction

This chapter introduces the research which is conducted and required for completing my Master Industrial Engineering and Management. The project is carried out at the VMI-Group (from now VMI) in Epe, to provide insights and optimize the current material flow towards Leszno, Poland. A short description about the VMI as well as the research characteristics are given within this chapter. These research characteristics consist of: organization, research motivation, problem description, scope, research design, deliverables, and the thesis outline.

1.1. Organization

VMI (Veluwse Machine Industrie) is market leader in production machinery specialized in the manufacturing of machines for: the tire, can, rubber, and care industry. It was founded in 1945. Since this foundation, VMI has expanded into a modern company with nine facilities on four continents, providing proven, reliable equipment, services, and solutions. VMI became part of the TKH group N.V. (Twentse Kabel Holding) in 1985. The company's common stock is 100% owned by TKH Group N.V. (from now TKH) which is an internationally operating group of companies specialized in the creation and delivery of innovative Telecom, Building and industrial Solutions. VMIs headquarter is located in Epe, the Netherlands, and employs about 900 of the 1600 employees who work for the VMI in total. The success of VMI lies in the constant effort to develop new innovative products and solutions, to meet current and future manufacturing demands. (About us, 2019) The slogan of the VMI is as follows:

"In everything we do we focus on our customers. Their success is our success." (About us, 2019)

1.2. Research motivation

The assignment request is a result of the increased material flow, towards VMIs production location in Leszno (Poland), to almost 5000 items per week. Currently these items are consolidated at the Epe and Haaksbergen warehouses and sent towards Leszno. Multiple items are supplied by companies that are located in Eastern Europe. The current material flow is expected to be inefficient in multiple ways, for example with the lead times and the (total) CO_2 footprint.

1.3. Problem description

Before 2015 VMI had only production locations in Epe and Yantai, China. VMI started in 2015 with production activities in Leszno. A new material flow has developed due to this new production site. Initially, the Leszno related parts were consolidated in Epe warehouse. This situation changed after a while. Everything bigger than a euro pallet was sent (if possible) directly towards Leszno in this new configuration. The introduction of Haaksbergen warehouse changed the material flow into the current situation. The XL-parts are currently sent towards Epe or, if possible, sent towards Leszno directly, since the warehouse in Haaksbergen is not intended for XL-parts. Almost all the remaining, Leszno related, parts are supplied by Haaksbergen warehouse due to its efficiency. Figure 1.1 visualizes the associated facilities: Epe (red), Haaksbergen (blue) and Leszno (green). In the past few years, the material flow towards this production location has increased rapidly to almost 5000 items per week. The performance of the associated supply chain is currently unknown. Analyzing the performance of this supply chain is therefore an important objective of the assignment. Examples of performance indicators could be: lead times, costs, reliability, CO_2 footprint etc. The combination of the new material flow and the associated supply chain (performance) might be a perfect opportunity to optimize the entire material flow/supply chain concerning Leszno and Eastern Europe.

Figure 1.1 Map with multiple company sites (Epe, Haaksbergen and Leszno).

1.4. Scope

The figure below shows a simplified version of the complete process from a machine request towards the end customer. See Appendix A for an expanded version of Figure 1.2 when the figure below is unreadable due to its limited size.

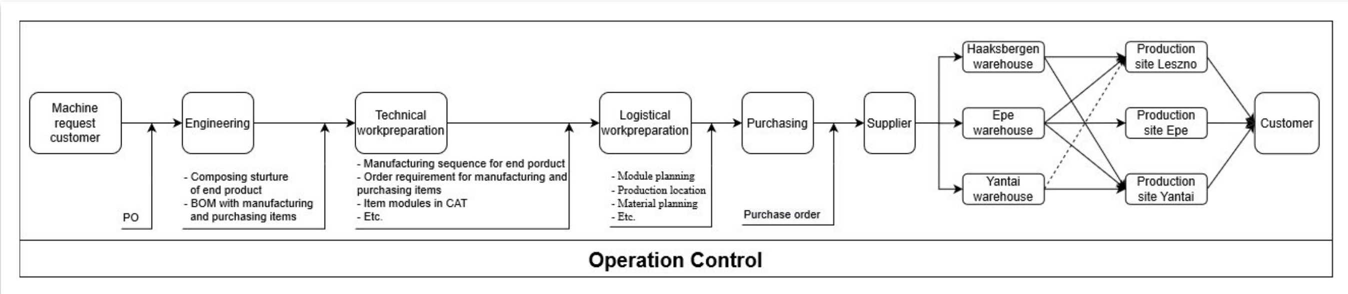

Figure 1.2 Complete process from machine request towards end customer (simplified).

Multiple actors are part of this process. Most of the elements are obvious, but Operation Control (OC) requires some additional explanation. OC monitors the complete process and determines the strategic deadlines. The text boxes below the flow represent the input and output of the associated process elements. We restricted the scope of this assignment to a specific part of the supply chain. A simplified version of the complete supply chain is visualized in Figure 1.3. Only the material flows towards the production sites are visualized in the supply chain, since the outgoing flows are not part of the scope. The highlighted parts of the supply chain in Figure 1.3 belong to the scope of this assignment. So each flow, with its associated supply chain elements, towards the production side in Leszno is included into the scope. This means that the complete route of the items, which reached the production side in Leszno, is considered. So the outbound logistics of the production site in Leszno are not part of the scope. Air and marine transportation are also out of scope. The items from Eastern European suppliers are included specifically as well, due to potential optimization possibilities.

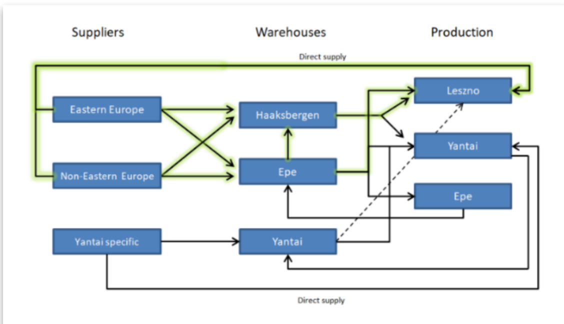

Figure 1.3 Complete supply chain simplified (dotted line is being introduced currently).

1.5. Research design

This section addresses the goal and the strategy of the research. First, we describe the research goals and the associated core problems. Secondly, we motivate the required research questions which are constructed for solving the core problem. Finally, we outline the problem approach which is used for answering the research questions.

1.5.1 Goal(s) of the research

This research includes two main goals which are related to each other. The first goal of the assignment is to get better insights into the performance of the current supply chain corresponding to the material flow towards Leszno. This performance should be measured based on some key performance indicators (KPIs). Examples of such indicators are: lead times, costs, reliability, CO_2 footprint etc. A clear and structured visualization of "new" performance insights is obviously an additional objective. The second (main) goal includes alternatives or improvements for specific scenarios which can be recommended to the board of the VMI.

1.5.2 Core problem(s)

Constructing a problem cluster is a useful method to get a clear and structured view of the problem context. A problem cluster is based on a quick scan where the already known information about the context is identified and put together. The red box on the right side of the cluster represents the observed "problems" related to the assignment. All the causes of the problems are at the left side of the boxes. The boxes continue towards the left, until there are no more causes for the (side) problems. The numbered boxes on the left, which have no cause(s), are potential core problems.

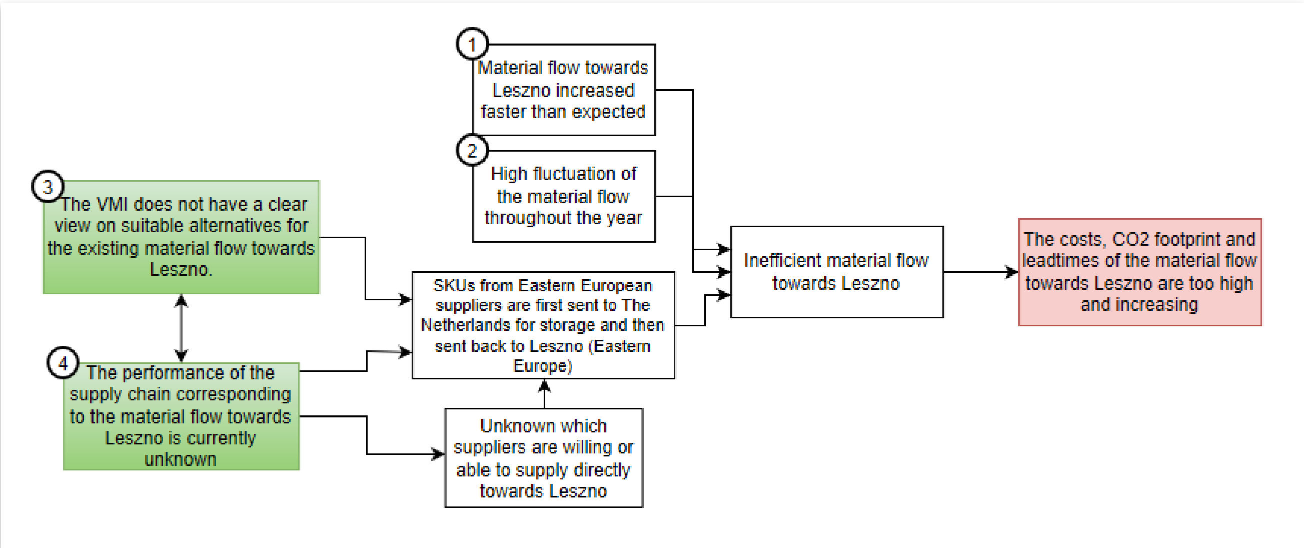

Figure 1.4 Problem cluster.

It is important that core problems can be affected, otherwise they are not real core problems (Heerkens & Van Winden, 2012). Based on this characteristic, problem 1 and 2 cannot be core problems. Problem 1 cannot be affected since it already happened. Problem 2 still occurs, but the (high) fluctuation is depending on the required production which cannot be affected directly.

The remaining potential core problems (3 & 4) do meet the requirements of a core problem. The choice between the remaining problems can be based on a cost-benefit analysis. However, in this case both problems are related to each other and both affect the same problem. Namely: *Stock keeping units (SKUs) from Eastern European suppliers are first sent to The Netherlands for storage and then sent back to Leszno (Eastern Europe).* The relation between both, and therefore the reason why both are core problems, is clear since it is hard to configure promising improvement alternatives when the current performance of the corresponding supply chain is unknown. Thus, the supply chain performance, corresponding to the complete material flow towards Leszno, should be analyzed and visualized first. The fourth problem should be investigated or solved afterwards. This is also the reason why we selected the third problem as core problem for now.

Operationalization

A core problem should be measurable, otherwise it is hard to verify whether the performed research solved the problem. So the next step of the problem identification is determining the discrepancy between the standard and the reality for the core problem. The discrepancy for this core problem is as follows:

The standard would be a clear overview of all the related data, flows and characteristics of the current material flow (supply chain) towards Leszno.

But in reality, the performance of the current material flow (supply chain) towards Leszno is unknown.

1.5.3 Research questions

We composed the following main research question, which is based on the already determined core problems.

"*What are promising alternatives given the material flow towards Leszno for multiple scenarios?"*

The goal of the main research question is solving the core problem. It contains multiple aspects which cannot be solved at once. That is why the main question is divided over multiple sub-questions, which are mentioned and motivated below. These sub-questions form the phases of the problem approach. Each phase answers one sub-question.

1. *"What does the current material flow look like?"*
2. *"What is the performance of the current situation?"*
3. *"What are promising alternatives or improvements?"*
4. *"What is the best alternative or improvement for a specific scenario?"*

The sub question specific strategies are given for each phase separately in the next section.

1.5.4 Problem approach

This section provides an overview of the used approach during the executed research. We translated the required and missing information into knowledge problems, which are also given and motivated below. An overview of the used methods for solving the knowledge problems is given in Section 1.5.5.

Phase 1) What does the current material flow look like?

The starting point of this phase is an analysis of the current supply chain. The goal of this analysis is to get a better understanding of the current situation. To do so, we will describe and visualize the complete material flow. We first need to select the supply chain aspects which will be analyzed. We therefore composed the following knowledge problem.

1.1 What are important aspects (qualitative and quantitative) of a supply chain in general?

We will conduct a literature study to solve the first knowledge problem. The list of important aspects, resulting from the literature study, is expected to be theoretical. The second knowledge problem is therefore:

1.2 How do the supply chain aspects relate to VMIs current material flow?

Only the qualitative supply chain aspects are used within this phase to describe the current material flow. The so-called quantitative supply chain aspects are used to measure the performance of the current material flow in Phase 2. We will use a stakeholder analysis to acquire insights regarding the qualitative supply chain aspects with respect to VMIs current material flow. The stakeholders will be selected in such a way that multiple supply chain aspects are represented. The outcomes of the stakeholder analysis are used to describe VMIs current material flow. We will also visualize the current material flow. We should therefore acquire some visualization method(s) which are suitable for visualizing “general” supply chain aspects. So the next knowledge problem is:

1.3 What are suitable methods for analyzing and visualizing the current situation?

A literature study will be conducted to acquire these suitable visualization methods. A toy problem is used to analyze the current material in more detail at the end of this phase. We use a toy problem to ensure that we do not get overwhelmed by the complexity and size of the complete material flow. A toy problem is a simplified, but still a representative, version of the actual problem. This makes it useful to provide key values and additional insights about the current material flow towards Leszno.

The defined approach should provide a clear visualization and understanding of the current supply chain towards Leszno.

Phase 2) What is the performance of the current situation?

We will use the acquired quantitative supply chain aspects (KPIs) from Phase 1 to measure the performance of the current material flow. An assessment on the identified quantitative aspects is desirable to determine whether all (or just a selection) of the (available) aspects should be used as KPIs for the performance analysis. So we compiled the following knowledge problem:

2.1 Which quantitative supply chain aspects (KPIs) should determine the performance of the current situation?

We use a stakeholder analysis to select some KPIs which will be used to measure the performance of the current situation. We will not execute an additional stakeholder analysis, since the stakeholders will be asked about their opinion regarding the KPIs during the stakeholder analysis from Phase 1. The toy problem outcomes as well as some analyses are used in addition to the stakeholder analysis outcomes to define the final KPI selection.

The material flow will be measured once the final KPIs are selected. We decided to use the already introduced toy problem to measure the performance of the current material flow. The quantitative performance values are measured within a model, which will be constructed during Phase 2. These KPI values should be visualized to provide a clear overview of the current material flow. We should therefore select a suitable method for visualizing the performance of the current situation. This leads to the following knowledge problem:

> 2.2 *What are suitable methods for visualizing the performance of the current situation?*

A literature study will be executed to acquire suitable methods for visualizing the performance of the current material flow. Executing the above-mentioned approach should provide a correct indication regarding the performance of the current situation. This indication is the conclusion of this phase.

Phase 3) What are promising alternatives or improvements?

The goal of this phase is a selection of suitable alternatives or improvements for the current material flow. It is important to take the outcomes of the current performance into account, so we compiled the following knowledge problem:

> 3.1 *Are there specific outcomes from the previous analyses that should be considered during the alternative acquisition?*

We will analyze the outcomes of the current performance with the problem owners in order to determine some research directions and topics. The associated knowledge problem is:

> 3.2 *What are suitable research directions and topics for potential alternatives?*

The next step is obviously the alternatives acquisition. We composed the following associated knowledge question:

> 3.3 *What are interesting and promising material flow alternatives or improvements?*

A literature study is used to acquire promising material flow alternatives or improvements. The defined research topics (knowledge problem 3.2) form the base of this literature study. A first check on suitability would be useful to eliminate inappropriate alternatives in advance which leads to time saving. The related knowledge problem is specified below.

> 3.4 *Which alternatives can be neglected based on some specific characteristics and without an extensive research?*

We use an effort/impact analysis to check whether there are some alternatives which can be neglected upfront. The opinion of the problem owners will be taken into account during the effort/impact analysis. The remaining (suitable) alternatives or improvements form the outcome of this phase.

Phase 4) What is the best alternative or improvement for a specific scenario?

We will compare the alternatives/improvements for specific scenarios in order to find the "best" alternative per scenario during this phase. We first measure and analyze the outcomes of the supply chain network alternatives related to the toy problem. We then analyze the alternatives for the (current) complete material flow by extrapolating the toy problem outcomes. We then determine the alternative performances for some scenarios. The scenarios are used to determine the sustainability of the alternatives during potential market changes. This leads to the following knowledge problem:

4.1 What are suitable and interesting scenarios?

Discussions with the problem owners are used to define some suitable and interesting scenarios. We then determine the alternative performances given the defined scenarios. These outcomes are analyzed in order to find the best alternative given the scenarios. The best alternative(s) will be recommended to the board of the VMI. This recommendation is the outcome of this research.

1.5.5 Methodology and data collection

Table 1.1 Used method for each knowledge problem.

Knowledge problem (per phase)	Used method
1.1 What are important aspects (qualitative and quantitative) of a supply chain in general?	Literature study.
1.2 How do the supply chain aspects relate to VMIs current material flow	Stakeholder analysis.
1.3 What are suitable methods for analyzing and visualizing the current situation?	Literature study.
2.1 Which quantitative supply chain aspects (KPIs) should determine the performance of the current situation?	Stakeholders analysis and toy problem analysis.
2.2 What are suitable methods for visualizing the performance of the current situation?	Literature study.
3.1 Are there specific outcomes from the previous analyses that should be considered during the alternative acquisition?	Data analysis and interviews.
3.2 What are suitable research directions and topics for potential alternatives?	Data analysis and interviews.
3.3 What are interesting and promising material flow alternatives or improvements?	Literature study.
3.4 Which alternatives can be neglected based on some specific characteristics and without an extensive research?	Interviews and impact/effort analysis.
4.1 What are suitable and interesting scenarios?	Interviews.

1.6 Deliverables

The deliverables of this research are:

- Insights in the performance of current material flow towards Leszno.
- A model that determines the performance of the current material flow.
- A selection of appropriate alternatives and scenarios.
- A clear recommendation about the most suitable alternative(s) given the selected scenarios.
- An overview of topics and assumptions which should be investigated further.

1.7 Thesis outline

We will provide an overview of the (research) related literature within a theoretical framework in Chapter 2. This report is divided into two parts, since there are two core problems (See section 1.5.2). Part one is related to the first core problem and part 2 is related to the second core problem, see Figure 1.5. Part one contains the Chapters 3 and 4, the remaining chapters are devoted to the second part. Chapter 3 defines and visualizes the current material flow. We define and quantify the KPIs which are used for determining the performance of the current material flow in Chapter 4. The performance of the current material flow will be provided as well in Chapter 4. Chapter 5 addresses and motivates the selected alternatives. We measure and describe the performance of the potential alternatives, given multiple scenarios, in chapter 6. The conclusions as well as the recommendations for further research are given in chapter 7.

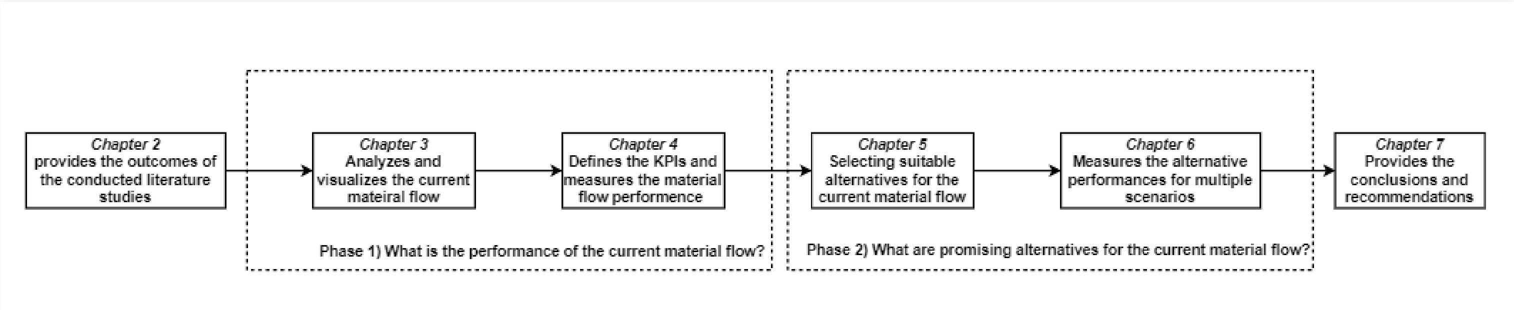

Figure 1.5 Thesis outline visualization.

2. Theoretical framework

This chapter provides an overview of the acquired literature which is vital for solving the knowledge problems (see Section 1.5.5). We conducted multiple literature studies to acquire the required literature. We only used reliable literature sources such as: Scopus, Science direct, Web of Science and multiple study books. Section 2.1 provides an overview of important aspects (qualitative and quantitative) of a supply chain in general. Section 2.2 focusses on an appropriate method or framework for analyzing the current situation. We provide suitable visualization methods in Section 2.3. Multiple material flow alternatives or improvements are given in Section 2.4. The conclusions regarding this theoretical framework are given in Section 2.5.

2.1. Important aspects (qualitative and quantitative) of a supply chain in general

This section provides both qualitative and quantitative aspects which are required for solving the first knowledge problem. First, we define the main drivers of a supply chain. These drivers are divided over 6 divisions. Each division contains multiple metrics. Secondly, we introduce the customer order decoupling point, which is defined by the product type(s) in combination with the postponement strategy.

2.1.1. The main supply chain drivers

Chopra and Meindl introduced three logistical drivers (Facility, Inventory and Transportation) and three cross-functional drivers (Information, Sourcing and Pricing). These drivers determine the performance of any supply chain. A company should balance between responsiveness and efficiency, which supports the company’s competitive strategy, to insure the strategic fit. We must examine the logistical and cross-functional drivers of a supply chain performance to understand how a company can improve its supply chain performance in terms of responsiveness and efficiency. The desired level of responsiveness at the lowest possible costs can be achieved by structuring the drivers. The goal is to structure the drivers to achieve the desired level op responsiveness at the lowest possible costs, thus improving the supply chain surplus and the firm’s financial performance. The supply chain surplus is determined by the following formula: *Revenue generated from a customer – total cost incurred to produce and deliver the product.* Cross-functional drivers have become increasingly important in raising the supply chain surplus in the recent years. While logistics remains a major part, supply chain management is focusing more on the three cross-functional drivers. It is important that the drivers do not act independently but interact to determine the overall supply chain performance. The following drivers interact with each other to determine the supply chain’s performance in terms of responsiveness and efficiency (Chopra & Meindl, 2013):

1. Facilities
2. Inventory
3. Transportation
4. Information
5. Sourcing
6. Pricing

Facilities: the facilities are the actual (physical) locations in a supply chain which are used to store, assemble or fabricate products. The main facility types are the production and storage sites. Decisions about the role, location, capacity, and felicity of the facilities have a significant effect on the supply chain’s performance.

Inventory: inventories contain all raw materials, work in process, and finished goods within a supply chain. Inventory exists due to a mismatch between supply and demand. This mismatch is often intended, e.g.: economies of scale or to anticipate on future demand. Changing the inventory policy can radically alter the supply chain's efficiency and responsiveness.

Transportation: transportation includes the moving inventory from point to point in the supply chain. There are multiple transportation modes and routes with their own performance characteristics. Combinations of transportation modes and routes are also optional. Faster transportation increases the responsiveness but reduces the efficiency. The type of transportation also affects the inventory and facility locations in the supply chain.

Information: information embraces the data and analysis concerning the facilities, inventory, transportation, costs, prices, and customers throughout the entire supply chain. This driver is potentially the biggest driver of performance in the supply chain, since it affects all the other drivers. Information can show the opportunities for making the supply chain more efficient and responsive.

Sourcing: sourcing decides who will perform a particular supply chain activity, e.g.: production, storage, transportation, and the management of information. Sourcing decisions affect both the efficiency and the responsiveness of a supply chain. Sourcing includes the business processes required to purchase goods and services.

Pricing: pricing determines how much a firm will charge for the products and services which it makes available. Pricing affects the behavior of the buyers, thus it also affects the supply chain.

Each of the above-mentioned drivers contain a set of quantitative metrics which can be used as indicators during the supply chain analysis. The metrics are given in appendix B, since it is an extensive list.

2.1.2. Customer order decoupling point

Another important aspect of a supply chain is the customer order decoupling point (CODP). "*At a production site, the CODP is the separating point between production for stock, which is based upon forecast and production due to certain customer demand. Activities before the CODP are driven by forecasts and are uncertain processes. On the order hand, activities after the CODP are driven by real customer order demands and are certain processes.*" (Ghalehkhondabi, Ardjmand, & Weckman, 2017). The type of products (components, sub-assembly, assembly etc.) in combination with the strategy determines where the customer order decoupling point lies. The CODP defines whether the strategy is to have a high variety of products, or a quick response time. The need to have a high variety of products and quick response time are two conflicting goals in a production system. Materials upstream the CODP are pushed downstream. Optimization should be realized by balancing inventory and capacity. Materials downstream the CODP are pulled by orders. Optimization should be realized by balancing capacity and lead-times. Traditionally, there are four types of classifications depending on the position of the CODP point: 1) Make-to-stock 2) Assemble-to-order 3) Make-to-order 4) Engineer-to-order. (Sjøbakk, Bakas, Bondarenko, & Kamran, 2015) The types with the associated CODP positions are visualized in Figure 2.1.

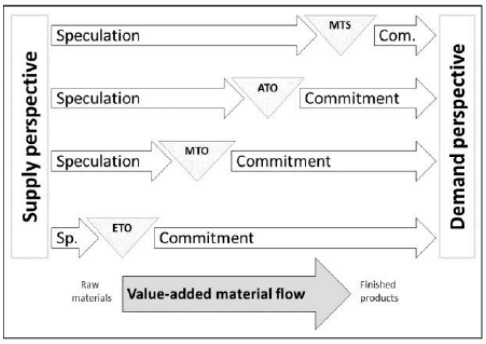

Figure 2.1 Customer Order Decoupling point **(Powell, Strandhagen, Tommelein, Ballard, & Rossi, 2014)**.

2.2. Material flow analysis

This section describes a convenient framework for analyzing the current situation. The output of the analyses will be the input for the performance section. The supply chain drivers which are introduced above (see Section 2.1.1) form the base of the framework.

2.2.1. Framework for structuring drivers

The used framework builds upon the above-mentioned supply chain drivers. This framework is preferred since it uses the output of the first knowledge problems as input, which makes it efficient. The framework helps to clarify the role of each driver in improving the supply chain performance. Although this framework (see Figure 2.2) is generally viewed from top down, in many instances, a study of the six drivers may already indicate the need to change the supply chain strategy. The supply chain strategy determines how the supply chain should perform with respect to efficiency and responsiveness. A company should structure the right combination of the three logistical and the three cross-functional drivers to reach the desired performance level, which is dictated by the supply chain strategy, and to maximize the supply chain profits. Choices regarding the supply chain drivers influence the responsiveness and the efficiency of a supply chain. They influence the entire supply chain. E.G., more facilities cause a (generally) more responsive supply chain. So there is a clear tradeoff between efficiency and responsiveness. (Chopra & Meindl, 2013). An overview of these impact relations is given in appendix C. Table 2.1 shows the different functional strategies for both, efficient and responsive supply chains.

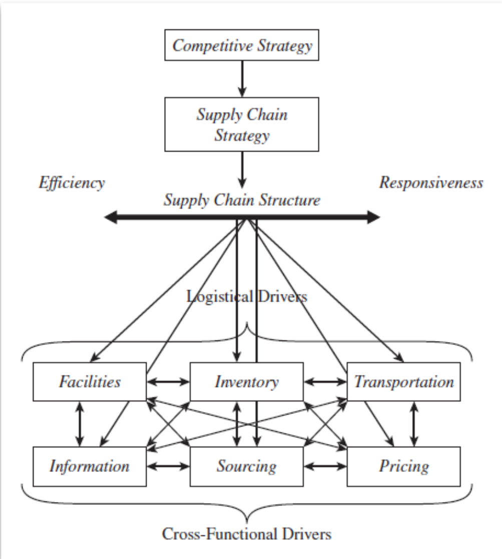

Figure 2.2 Supply chain analysis framework (Chopra & Meindl, 2013).

Table 2.1 Functional strategy differences for efficient and responsive supply chains. (Chopra & Meindl, 2013).

	Efficient Supply Chains	**Responsive Supply Chains**
Primary goal	Supply demand at the lowest cost	Respond quickly to demand
Product design strategy	Maximize performance at a minimum product cost	Create modularity to allow postponement of product differentiation
Pricing strategy	Lower margins because price is a prime customer driver	Higher margins because price is not a prime customer driver
Manufacturing strategy	Lower costs through high utilization	Maintain capacity flexibility to buffer against demand/supply uncertainty
Inventory strategy	Minimize inventory to lower cost	Maintain buffer inventory to deal with demand/supply uncertainty
Lead-time strategy	Reduce, but not at the expense of costs	Reduce aggressively, even if the costs are significant
Supplier strategy	Select based on cost and quality	Select based on speed, flexibility, reliability, and quality

2.3. Material flow visualization

Three appropriate visualization methods are given below. Each method will visualize specific characteristics of the supply chain. The methods are discussed separately. The three visualization methods below complement each other in such a way that they give a good representation of the current situation.

2.3.1. Business process modeling notation

An important aspect of the supply chain analysis is mapping the material flow. Various tools and languages have been developed for mapping processes. An example of such languages is the Business Process Modeling Notation (BPMN). BPMN is developed under de coordination of the Object Megamenu Group with the intention to identify the best practices of existing approaches and to combine them into a new and generally accepted language. The primary goal of BPMN is to provide a notation that is readily understandable by all business users.

Flow objects are the building blocks of business processes, they include: events, activities, and gateways. Events represent occurrences of states in the real world. Activities represent work performed during business processes. The gateways are used for the representation of the split and join behavior of the flow between activities, events, and gateways. Swim lanes represent organizational aspects. They are restricted to a two-level hierarchy: pools and lanes. Pools represent organizations and lanes represent organizational entities such as departments within a participating organization. Artefacts are used to show additional information. An example of a BPMN diagram is given in Figure 2.3. The visualization of the notation is given in Figure 2.4 on the next page (Weske, 2007). BPMN will be used to visualize the supply chain.

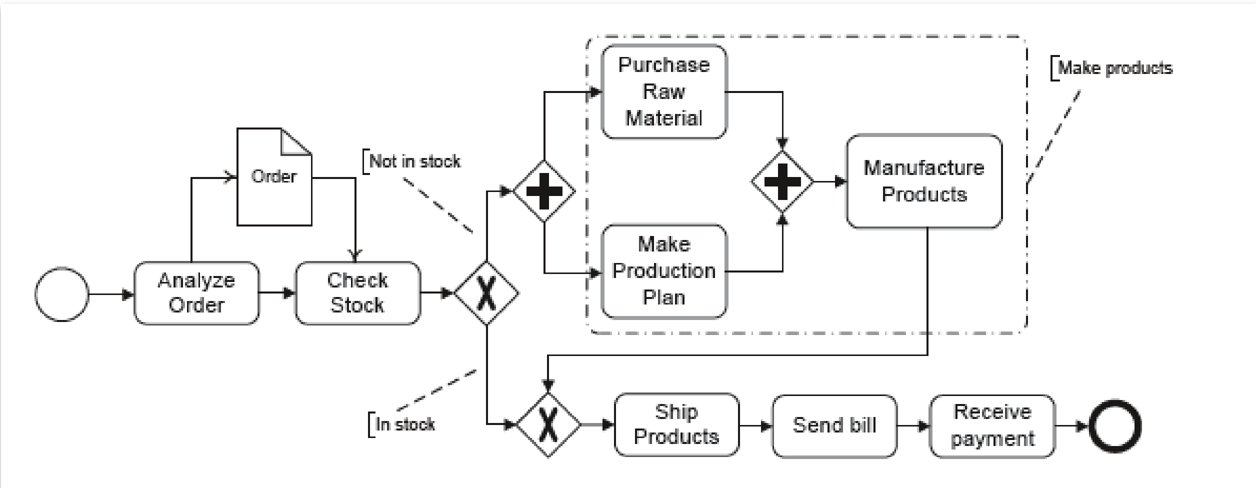

Figure 2.3 BPMN diagram example.

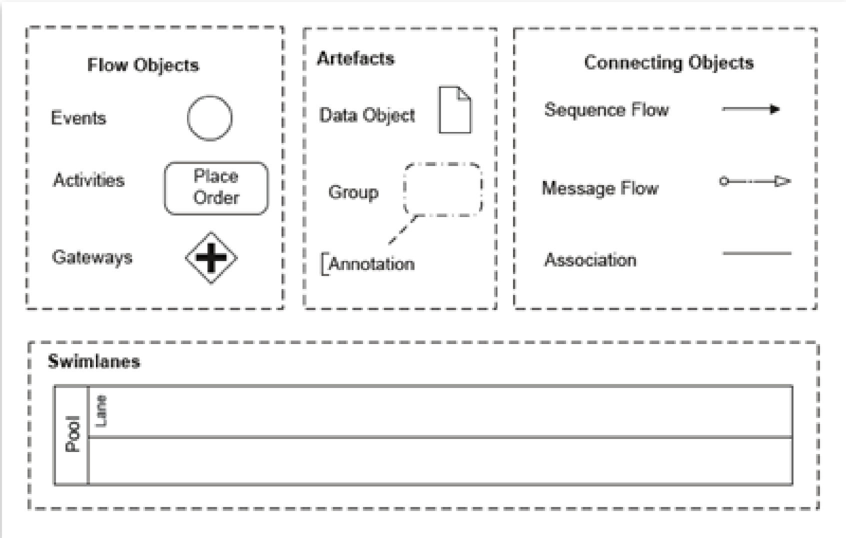

Figure 2.4 BPMN notation overview.

2.3.2. Geographic mapping

Geographic charts use a portion of the world's map, in pictorial form, to show variations in regional data. They can be used for product sales, distribution status, supply chains, or any of several other geographically specific variables. Variables of interest can be aligned on a common geographic referent. The resulting pictorial display allows the user to "drill" through the layers and visualize the relationships (Cooper & Schindler, 2011). This method seems to be suitable since it gives a clear overview of the complete (geographic) supply chain. Figure 2.5 shows a geographic mapping example for a supply chain.

Figure 2.5 Geographic visualization example for a supply chain **(Kovács, 2017)**.

2.3.3. Graphical charts

Graphs show (compared to tables) less information and often only approximate values. However, they are more often read and remembered than tables. Their great advantage is that they convey quantitative values and comparisons more readily than tables. With charting programs, a dataset can easily be turned into a chart or graph (Cooper & Schindler, 2011). The choice between the graph/chart types is data and purpose specific. Cooper & Schindler (2011) provided a clear guide for selecting the correct charts for written reports. The list with suitable charts for comparisons is too extensive for this section, an overview is therefore given in Appendix D. The choice for a given chart is data specific, so this decision cannot be made yet. The used indicators (driver metrics) are after all unknown. Graphical charts are, besides visualizing the current situation, also suitable for constructing a dashboard. A dashboard with tables and graphical charts would be valuable since graphical charts have the great advantage that they can convey quantitative values and comparisons more readily than tables. See Figure 2.6 for a dashboard example.

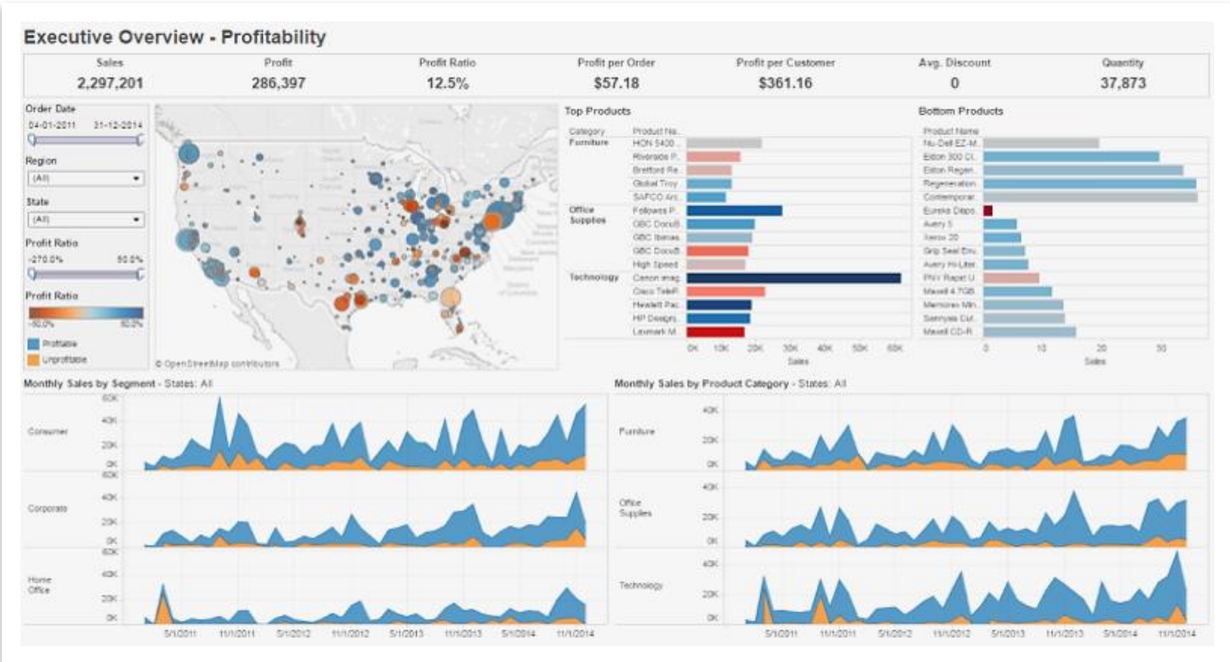

Figure 2.6 Dashboard example.

2.4. Material flow improvements

We conducted a literature study to acquire multiple material flow alternatives or improvements. This literature study was based on three research topics, see Figure 2.7. The performance outcomes of the current material flow formed the basis of these research topics, since we translated the outcomes into several research directions. These research directions were initially too specific for a literature study. We therefore identified the associated research topics, which are more general and therefore more suitable for a literature study. The specific argumentation regarding the research direction and literature topics will be provided in Section 5.1. The provided material flow alternatives will be used in Chapter 5 during the alternative selection.

Figure 2.7 Literature topics.

We acquired multiple alternatives during the executed literature study. We also included some "out of the box" alternatives, to protect ourselves against a tunnel vision during the literature research. The following nine alternatives were acquired during the literature study:

1. Direct Shipping to Single Destination
2. Milk-Run
3. Direct Shipping with Milk-Run(s)
4. Cross Dock Warehouse
5. Environmentally Friendly Trucks
6. Intermodal Transportation
7. Vendor Managed Inventory
8. Additive Manufacturing (3d printing)
9. DC Bypass Strategy

Each of the nine alternatives contains aspects of at least one literature topic. E.G. alternative five, environmentally friendly trucks, is an example of an alternative which is related to a green supply chain. We have divided the alternatives over two types, the material flow network alternatives and the additional alternatives. The associated descriptions, advantages and disadvantages are provided below. We first describe the material flow network alternatives in Section 4.2.1. The descriptions associated to the additional alternatives are provided in Section 4.2.2.

2.4.1. Material flow network alternatives

The alternatives provided within this section require a new supply chain network configuration. This means that the alternatives require network modifications.

Direct Shipping to Single Destination

With the direct shipment configuration towards a single destination, the destination structures the transportation network in such way that all the shipments are shipped directly from each supplier to the destination (facility), as shown in Figure 2.8. The routing of each associated shipment is specified and only the quantities, shipment modes and the shipment days needs to be configured by the supply chain manager(s).

Advantages:

The major advantage of the direct shipping configuration is the elimination of intermediate warehouses and its simplicity in terms of operation and coordination. The shipment decisisions are local and the decisions made for one shipment do not influence other supplier shipments. The transportation time will also be reduced because the shipments are delivered, without intermediate warehouses. A destination facility close to the suppliers will reduce the transportation times significantly. The handling costs might reduce as well since there are no intermediate warehouses and there is only one warehouse required at the destination location.

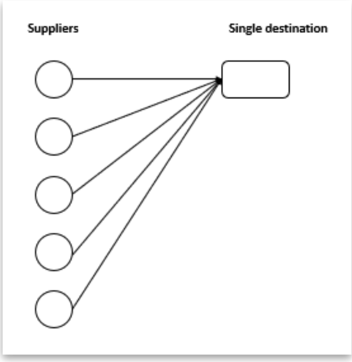

Figure 2.8 Direct Shipping to Single Destination visualization.

Disadvantages:

The direct delivery configuration is only justified when the demand at the single destinations are large enough and are close to a full truckload. The high implementation costs of the required warehouse (if needed) at the single destination might be a disadvantage as well, since such a warehouse is only justified when the savings on transportation and handling costs outweigh the costs of such a new warehouse. Finally, the suppliers should (at least) be willing to deliver under the same conditions to the "new" destination facility. (Chopra & Meindl, 2013)

Milk-Run

A milk-run is a route where a truck either delivers a product from a single supplier towards multiple warehouses or goes from multiple suppliers towards a single warehouse. With the second option the truck picks up deliveries from multiple suppliers destined for the same warehouse. This option is visualized in Figure 2.9. A milk-run configuration forces a supply chain manager to determine the routing of each milk-run.

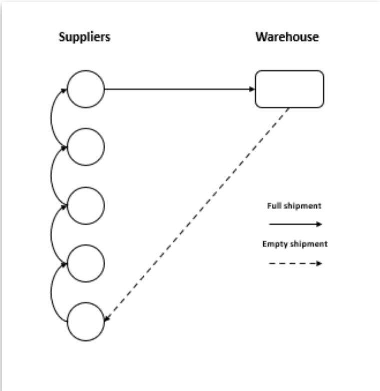

Figure 2.9 Milk-Run visualization.

Advantages

Milk-run routing lowers transportation costs and distance by consolidating shipments from multiple suppliers towards a single warehouse on a single truck. The total distance reduction has obviously a positive effect on the total CO2 footprint. The costs savings, as a result of the milk-run(s), might be significant as well, since frequent small deliveries can be transported efficient and consolidated with a milk-run. This can also result in lead time reduction, since the suppliers can deliver more frequently because "milk-run trucks" come along anyway. More frequent deliveries lead in general to lead time reduction.

Disadvantages

Milk-runs are only optional when the supplier's shipments are Less Than Truckload (LTL), since it is hard to combine multiple Full Truck Load shipments into one shipment. It is also important that the suppliers are located close enough to each other. Milk-runs lead to increased coordination complexity, since the associated suppliers must be "linked" correctly within the route. (Chopra & Meindl, 2013)

Direct Shipping with Milk-Runs

This supply chain configuration combines the advantages (and disadvantages) of the Direct Shipping to Single Destination and the Milk-Run configurations. Figure 2.10 provides a visualization of the Direct Shipping with a Milk-Runs configuration. The direct shipping "part" provides the benefits of eliminating intermediate warehouses, whereas milk-runs reduce the transportation and handling costs by consolidating shipments from multiple suppliers into a single truck. The coordination complexity does increase, even though this configuration contains direct shipping aspects. This is a consequence of the used milk-run(s).

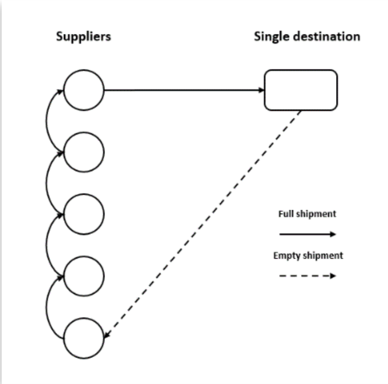

Figure 2.10 Direct Shipping with Milk-Runs visualization.

Cross dock Warehouse

Suppliers ship their shipments to a DC where the shipments are cross-docked and sent to the warehouse(s) without storing them. Each inbound truck contains items from a supplier which are intended for several warehouse locations, whereas the outbound trucks contain items that are intended for one warehouse from several suppliers. In short; items from several inbound trucks that belong to the same warehouse are consolidated into the same outbound truck(s). Figure 2.11 visualizes the cross-dock warehouse configuration. It is also optional that suppliers only ship products intended for the same warehouse. The items from several inbound (LTL) shipments will in such a situation be consolidated into outbound (FTL) trucks.

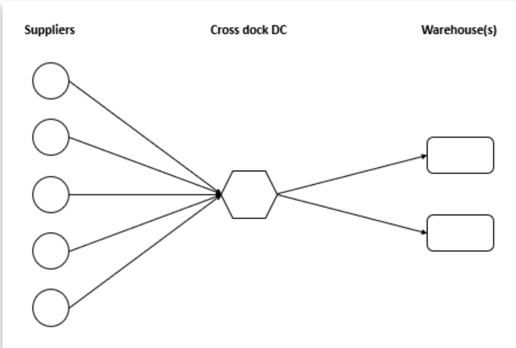

Figure 2.11 Cross dock warehouse visualization.

Advantages

Many of the advantages are equal to the milk-run advantages, this is a logical result of the consolidated (FTL) trucks which is a shared consequence of the alternative types. First of all the distance reduction, and therefore CO2 footprint reduction, which is caused by less FTL trucks instead several LTL trucks. It is therefore likely that this supply chain configuration will reduce the transportation costs, since the total shipment distance will be reduced for the associated suppliers.

Disadvantages

The additional DC costs, fixed and variable, are logically a disadvantage, the saved costs should therefore outweigh the additional DC costs. The inbound shipments which are intended for only one warehouse should be LTL. Cross docking would logically be useless when those shipments are FTL. The increased coordination complexity is also an obvious disadvantage. The suppliers should also reduce their transportation costs as a result of the reduced distance, otherwise becomes cross docking useless as well (Chopra & Meindl, 2013).

Intermodal transportation

Intermodal transportation is the use of multiple (more than one) transportation modes to move a shipment to its destination. Multiple intermodal combinations are possible. However, the most common combination is the truck/rail combination. Containerized freight simplifies the intermodal transportation implementation, since containers are easy to transfer from one mode to another. The information exchange should be correct to prevent delays.

Advantages

By using intermodal transportation, the company can take advantage of the benefits associated to the multiple transportation modes. E.G. rail transportation is often more energy efficient. Another advantage are the associated transportation costs, since rail and barge transportation are relatively cheaper compared to road transportation.

Disadvantages

The shipment times are often longer for intermodal transportation, so the overall lead time will increase. Quality issues might arise due to damage risks, since transferring the freight from one to another transportation mode increases the risk of damage. The required transfer of the freight from one to another transportation mode results in additional handling costs as well. The optional delay due to incorrect information exchange is, as already mentioned, an associated disadvantage of intermodal transportation.

DC bypass strategy

The first “out of the box” alternative is the DC bypass strategy. The idea behind the strategy is to take out one link of the supply chain. The products are transported consolidated towards the harbor or gateway where the freight is broken down (deconsolidated) into individual shipments with different receipt facilities. Figure 2.12 shows that multiple transportation modes (vessels, trucks, and airplanes) can be used in combination with DC bypass strategy. The strategy is especially interesting when the DC’s and warehouse(s) are located far inland.

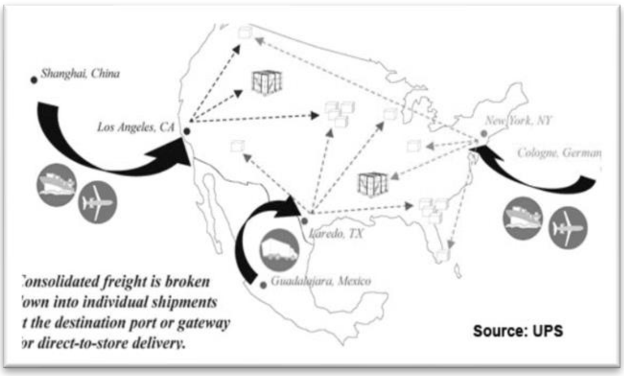

Figure 2.12 DC bypass strategy visualization.

Advantages

The biggest advantages of the DC bypass strategy are the (lead) time and cost savings due to fewer touch points and handling shipments. The costs savings are twofold, since both the handling and transportation costs will drop once the strategy is implemented correctly. The reduced touchpoints also lead to less damage risks throughout the entire transportation process.

Disadvantages

The coordination complexity is one of the main disadvantages, since tracking and tracing tools are necessary to provide the required supply chain visibility. If the process is not managed correctly, the receipt facility can be flooded with either too many shipments or deal with out of stock situations (Singh & Ganapathiraman, 2013). The strategy might also result in less efficient shipping, because the direct shipments form the bypass facility are often smaller than the shipments from a regular DC. This might mean that the receipt facility does not receive its complete order on a single shipment (SCDIgest Editor Staff, 2008).

2.4.2. Additional alternatives

The alternatives provided within this section do not require any new supply chain network configurations. So alternatives can be implemented directly without any considerable network modifications.

Environmentally friendly trucks

Environmentally friendly trucks have the ability to reduce the total CO2 footprint. This alternative does not require any supply chain network adjustments and can be introduced directly once the environmentally friendly trucks are available.

Advantages

The environmentally friendly trucks can reduce the CO2 emission significantly. Electric trucks reduce the CO2 emission even up to zero.

Disadvantages

The main disadvantage of this alternative might be the (implementation) willingness of the suppliers when they are responsible for the used trucks. A company can prevent this by securing the shipment responsibilities. The costs of the expensive and new trucks might remain a disadvantage. The transportation range of electric trucks might be a disadvantage as well when it results in longer shipment times.

Vendor managed inventory

With vendor managed inventory is the vendor responsible for inventory management. The manufacturer shares its demand with the vendor and the vendor ensures that the items are on time at the manufacturer. So the manufacturer has no influence on its own inventory.

Advantages

The vendor can anticipate optimally on the manufactures demand, since the production can be scheduled properly and in advance. It is therefore of great importance that the manufacturer shares correct and recent information regarding the demand forecasts. The manufacturer benefits from the high product availability (when the vendor manages the inventory correctly). The inventory and handling costs will decrease due to just in time delivery by the vendors.

Disadvantage

The vendors should be willing and able the implement the concept as well. As mentioned before, has the manufacturer no longer influence on its own inventory. The manufacturer becomes completely dependent on the vendor. It is also important that each supplier introduces the vendor managed inventory concept, otherwise it is useless. (Luo, 2019)

Additive manufacturing (3d printing)

The second “out of the box” alternative is additive manufacturing, also called 3d printing. Many supply chain professionals predict that additive manufacturing will eventually rival the impact of Henry Ford’s assembly line. Additive manufacturing is a process which uses a three-dimensional (digital) model to create physical objects by adding many thin layers on top of each other. This new production method reduces material waste radically, since it is an additive instead of subtractive technique. The technology is developing rapidly and it is expected to influence the global supply chains significantly. The additive manufacturing technique is already applied in multiple industries like, the aerospace industry, the medical industry, and the automotive industry.

Advantages

Additive manufacturing provides many design advantages like: weight reduction, waste reduction and customization. All these advantages are a result of the technique itself which provides more design freedom and less production limitations. The lead time reduction is also one of the many advantages since transportation and warehouse activities are no longer required when the items are printed at the production facilities.

Disadvantages

Additive manufacturing has (currently) multiple disadvantages as well, but it must be said that these disadvantages might disappear once the technology is developed even further. One of the main disadvantages is the limited material selection, since the technique is (currently) not able to print every material. The limited item size is also a major drawback, since the manufacturing (printing) time increases rapidly with the item size. The high investment costs associated with the high variable manufacturing costs are also a significant disadvantage. (Janssen, Blankers, Moolenburg, & Posthumus, 2014)

2.5. Conclusion

We provided the theoretical framework of the research within this chapter. The framework contains multiple methods and theories which can be used for solving the knowledge problems from Section 1.5.5. We first identified six suitable supply chain drivers with an associated framework for analyzing supply chains in general. Each driver contains a set of metrics which can be used as KPIs for measuring the supply chain performance.

Secondly, we provided multiple visualization methods for visualizing the current material flow. We first identified a notation method for mapping business processes and flows. The second visualization method is intended for visualizing supply chains geographically. Various graphical charts have been identified as well. These charts can be used for constructing a complete dashboard.

Finally, we identified and clarified nine potential material flow alternatives which might improve the current situation. These alternatives are divided over two types, the so-called material flow network and additional alternatives.

Part 1

3. What does the current material flow look like?

This chapter analyzes and visualizes the current material flow to solve the first research question. The structure of this chapter is based on the sequence of the different knowledge problems related to Phase 1. We start with the important aspects of a supply chain in general, which were acquired during the conducted literature study, see Chapter 2. A summary of the important supply chain aspects is provided in Section 3.1. The driver (metrics) selection which will be used for analyzing and visualizing the current situation is given in Section 3.2. The subsequent sections analyze and visualize the current material flow. We discuss a toy problem at the end of this chapter which is used to acquire some insights regarding the current material flow. We will use these insights when we start with analyzing the real material flow. Finally, we provide some conclusions and findings related to provided information within this chapter.

3.1. Summary of the important supply chain aspects

This section provides a short overview of the identified literature regarding the important quantitative and qualitative supply chain aspects. See Section 2.1.1 ford the specific details.

Main supply chain drivers

We have selected six main supply chain drives for analyzing the current material flow towards Leszno. The drivers are given below:

1. Facilities
2. Inventory
3. Transportation
4. Information
5. Sourcing
6. Pricing

CODP

We will use the customer order decoupling point, in addition to the above-mentioned drivers, to analyze the current supply chain. The CODP determines whether the supply chain is forecast or demand driven.

3.2. Selection of important aspects

The general supply chain aspects (drivers) will be used for analyzing the current material flow. We performed a stakeholder analysis to acquire the driver related supply chain information. Only the qualitative driver aspects are used within the next section to describe the current material flow. The so-called quantitative supply chain aspects are used in Chapter 4 to measure the performance of the current material flow. We decided, due to efficiency, to perform only one stakeholder analysis instead of two. The stakeholders where therefore asked to give their opinion about both, the qualitative and quantitative supply chain aspects. The information about the qualitative (driver) aspects will be provided in next section. This section provides a short overview about the quantitative driver (metrics) selection which will be used in Chapter 4. The driver metrics (see Appendix B) are the quantitative aspects which we acquired during our literature study.

Stakeholders are the people which will be affected by this research, so it is important that they will support the research (outcomes). We will therefore ask them about their opinion. We first identified and selected six departments which would be included in the stakeholder analysis. Stakeholders were chosen in such a way that each driver (aspect) was represented. The specific managers and representatives of each department were selected during meetings with the supervisors. We selected the following departments:

- Supply Chain Innovation
- Warehouse
- Production
- Transportation
- Sourcing
- Supply

Interviews were held with all stakeholders to find out which quantitative aspects are important in their opinions. We also asked them about their opinion regarding the qualitative aspects. We used one general outline for the interviews (see Appendix E), since multiple metrics are quite general and can be related to multiple departments. Table 3.1 shows how many times a specific percentage of the total number of metrics (50) were mentioned. The intensities were leading for the ultimate metric selection. We selected the following metrics based on the interview outcomes (see Appendix F):

Table 3.1 Metric intensity (based on interviews).

Total amount of metrics:	**50**
Metrics mentioned during the interviews	44%
Metrics mentioned more than 1 time	32%
Metrics mentioned more than 2 times	20%
Metrics mentioned more than 3 times	8%
Metrics mentioned more than 4 times	4%
Metrics mentioned more than 5 times	2%

1. Average inbound and outbound (between facilities) transportation cost.
2. Supply lead time.
3. Total CO2 footprint.
4. Supplier reliability.
5. Incremental variable & fixed ordering costs.
6. Average incoming shipment size.
7. Warehouse capacity (utilized).
8. Volume contribution of top 20% suppliers.
9. Handling costs.
10. Fraction transported by transportation mode.

The selected driver metrics will be used as KPIs in the next chapter. The intensities for all metrics are given in Appendix G. The stakeholders output regarding the qualitative aspects is used in the next section to analyze the current material flow.

3.3. The current material flow towards Leszno

This section provides insights regarding the current material flow based on the selected supply chain aspects (qualitative and quantitative). We start with visualizing the material flow towards Leszno by using the BPMN to provide a better it. Secondly, we define for each supply chain driver (characteristic) how it relates to VMIs current context. The theory of the supply chain drivers and the associated framework (see Sections 2.1.1 and 2.2.1) is considered as well. We analyze the customer order decoupling in Section 3.3.3. The used Toy Problem is illustrated and defined in the last section.

3.3.1. BPMN visualization of the current material flow towards Leszno

We introduced the basic principles of the BPMN in Section 2.3.1. Nevertheless, we start with explaining the specific BPMN flow objects of our visualization to guarantee readability. The required knowledge is gathered through guided tours and supervisor meetings. Afterwards, we discuss the multiple supply chain components (lanes) one by one.

The BPMN visualization of the current material flow contains one pool (Material flow towards Leszno) and four lanes: Suppliers, Epe Warehouse, Haaksbergen Warehouse and the Leszno production site (see Figure 3.1). The specific sourcing interactions as well as the specific supplier activities are not taken into account, since we are only interested in the material flow towards Leszno for now (see Section 1.4). There is only one pool, because each lane is related to the material flow towards Leszno. The lanes are based on the supply chain elements which have been defined in the scope. The flow sequence for each supply chain element is visualized by arrows. The dotted arrows visualize the physical product flows. Each flow sequence starts and ends with a start and an end event. The multiple rounded boxes are related to the activities. The Inclusive OR Gateways (OR-gateway(s)) are used when there are multiple activity options. These options will be defined later. The message events visualize the product requests. See Appendix H for an expanded version of Figure 3.1, when it is unreadable due to its limited size. We describe all the elements of each lane below.

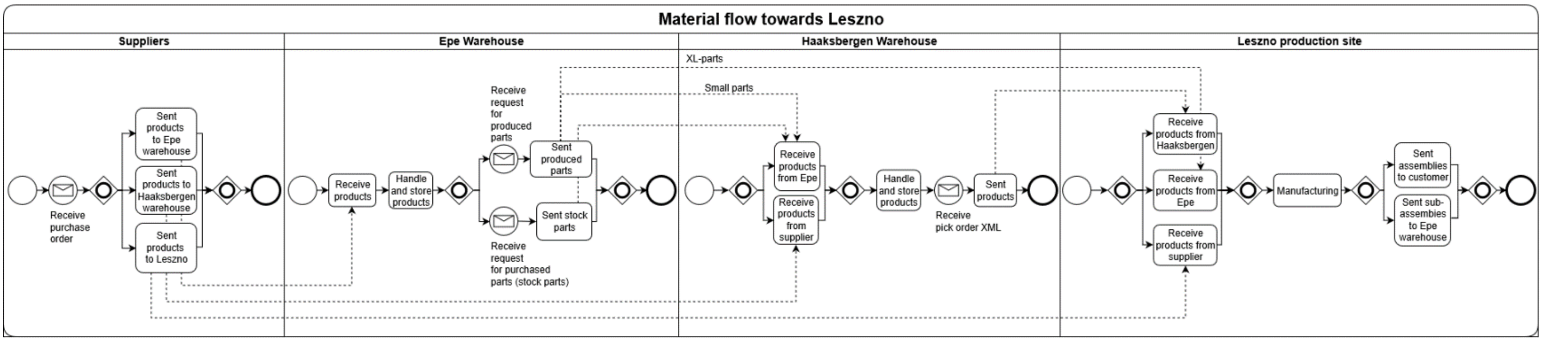

Figure 3.1 BPMN visualization of the current material flow towards Leszno.

Suppliers

The material flow towards Leszno starts with the suppliers which produce "Leszno related" parts. Figure 3.2 shows the suppliers' lane. The first event (besides the start event) is a message event, which represents a purchase order from the VMI. The OR-gateway, after the message event, is required since there are three sending options, see Section 1.4. The options differ from each other based on the recipients. The product type and supplier combination define the associated recipient. There are three options:

1. Products that should be sent towards Epe warehouse.
2. Products that should be sent towards Haaksbergen warehouse
3. Products that are sent directly towards the production site in Leszno

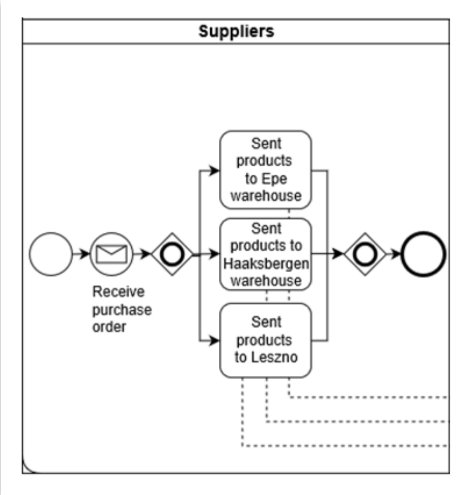

Figure 3.2 Suppliers lane.

The first option is related to XL-parts which are supplied towards Epe by suppliers which do not supply XL-parts directly towards Leszno (under the same conditions). The second option is related to parts (except the XL-parts) which are intended for Leszno and are supplied by Haaksbergen. The third option is related to the XL-parts which are supplied directly towards Leszno.

Another OR-gateway is added to merge the flows. An end event is placed to terminate the supplier related activities and events.

Epe warehouse

The first activity of the flow sequence is receiving the products which are supplied by the supplier. We merged the handling and storage related activities into one activity, since warehouse activities are not part of this research project. There are (based on the scope) two sending options for Epe warehouse, so an OR-gateway is used to split the flow sequence. There are also two message events which precede the two sending options. The two options are:

1. Receive a request for produced parts which are required at the production site in Leszno.
2. Receive a request for purchased parts (stock parts) which are intended for Leszno.

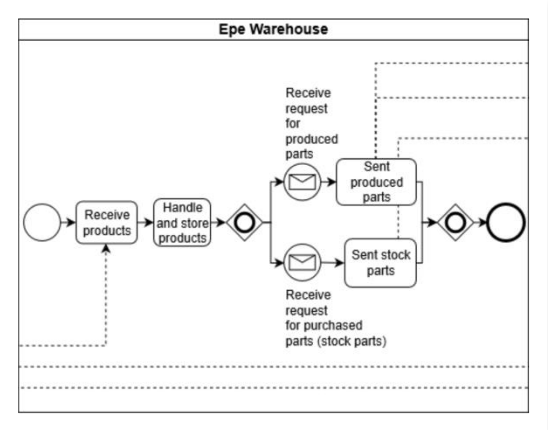

Figure 3.3 Epe warehouse lane.

The produced XL-parts are sent towards Leszno directly, while the other produced parts are first sent towards Haaksbergen warehouse. The purchased (stock) parts which are intended for Leszno are first sent to Haaksbergen warehouse due to its efficiency.

Stock parts are frequently used in Epe and rarely in Leszno, so they are consolidated in Epe.

Another OR-gateway is added to merge the flows back together. An end event is placed to terminate the Epe warehouse related activities and events. See Figure 3.3 for the visualization.

Haaksbergen warehouse

An OR-gateway is required, since there are 3 types of incoming products (with two combined flows from Epe). Namely:

1. The produced small parts intended for Leszno and supplied by Epe warehouse.
2. The purchased (stock) parts intended for Leszno and supplied by Epe warehouse.
3. The “regular” products intended for Leszno and supplied by a supplier.

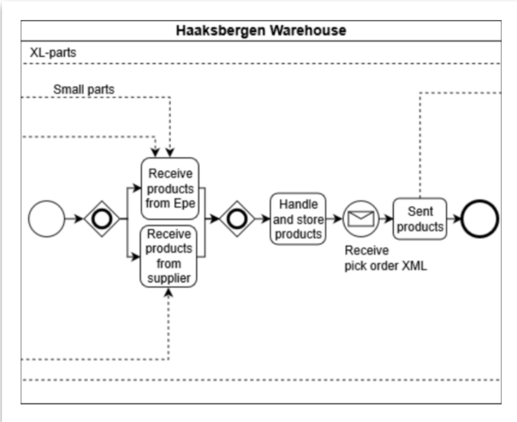

Figure 3.4 Haaksbergen warehouse lane.

A second OR-gateway is required for merging both flows back together once the parts are received. The next activity is (again) a combination of the required handling and storage related activities. The message event represents a pick order XML. The successive activity is sending the products towards Leszno. This is the last activity, because it is followed by an end event.

Leszno production site

The lane which is related to the production site in Leszno contains two sets of OR-gateways. The first set is required due to different types of incoming parts. The three product types which are received at Leszno are:

1. Parts from Haaksbergen warehouse.
2. XL-parts from Epe warehouse.
3. XL-parts which are delivered by the suppliers directly.

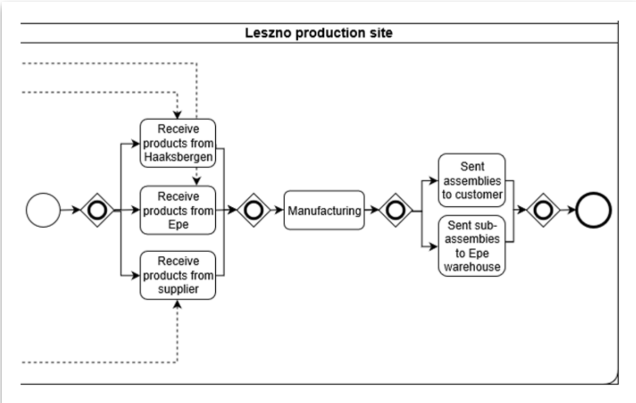

Figure 3.5 Leszno production site lane.

The next activity is manufacturing the assemblies or sub-assemblies. An OR-gateway is required, since the assemblies have another destination than the sub-assemblies. The (complete) assemblies are sent towards the customers, while the sub-assemblies are sent back to Epe for further manufacturing at the production site in Epe. The flows of the assemblies and subassemblies are not visualized due to readability issues. It is also unnecessary, since the outbound logistics of the production site in Leszno are not part of the scope. Another OR-gateway and an end event complete the flow.

3.3.2. Supply chain drivers

We provide the current context for each driver (characteristic), based on the scope, within this section. The given information is based on interviews held with some stakeholders (see Section 3.2). The qualitative interview outcomes are given in Appendix I. The stakeholders were asked about their opinion regarding the current context of the supply chain drivers. The drivers are discussed separately.

Facilities

The given scope (see Section 1.4) contains the following three facilities: a warehouse in Epe, a warehouse in Haaksbergen and a production site in Leszno. The warehouse facilities within the scope are centralized. The warehouse in Epe is a logical consequence of the headquarters being located in Epe. The location of the second warehouse in Haaksbergen (close to Epe) is argumentative as well since this warehouse is part of TKH. The production site in Poland on the other hand is decentralized due to cost and lead time reduction. The production facility in Leszno is in general flexible, since the facility has, or should be able to gather, the required knowledge and tools to produce each machine type. But the Intellectual Property (IP) related information restricts the production facility since the facility is not allowed to produce all the machines. The production site is also product focused, since all the product related functions can be performed in Leszno. But again, the IP related information determines which parts may or may not be produced in Leszno. VMIs warehousing facilities are storage warehouses which store and consolidate items for a longer period of time.

Figure 3.6 Haaksbergen warehouse (THK, 2019).

Inventory

VMI has two main inventory types: anonymous and project inventory. Anonymous inventory serves as a bulk/reserve area and project inventory serves as a picking area. The anonymous items are transferred towards the project inventory by replenishments between both areas. Both warehouses use multiple storage options. The storage options related to Epe warehouse are:

Anonymous inventory

- Vertical Lift Module (VLM).
- Bin (40 cm*30 cm*12 cm) Rack.
- Euro pallet (EP) Storage Rack, with:
  - 1 EP, 1/2 EP and 1/4 EP.
- Floor Stock.

Project inventory

- Bin (40 cm*30 cm*12 cm) Rack, with
  - 1 Bin, 1/2 Bin and 1/4 Bin.
- EP Storage Rack, with:
  - 1 EP, 1/2 EP and 1/4 EP.
- Steel Pallet (SP) storage.
- Self-supporting (ZD) parts stored on long SPs.
- ZD XL parts stored on the ground.
- Bar and Tube Storage Rack.
- Cantilever Rack.

Haaksbergen warehouse stores only project related parts. The related storage options are:

Project inventory

- Miniload(s), bin dimensions: (60 cm*40 cm*18 cm)
- EP Storage Racks
- Bar and Tube Storage Rack
- Cantilever Racks
- Limited amount of floor locations
- Steel Wire Pallet Racks

Figure 3.7 Miniloads at Haaksbergen warehouse.

The bins can be subdivided by placing partitions within the bins. Product characteristics, weight and dimensions determine the most suitable storage option. The product type determines whether a high or low inventory level is preferred. Anonymous inventory has on average high inventory levels. The inventory levels of project related parts are generally low.
Inventories and safety stocks are used for the following items:

- Items with high minimum order quantities.
- Items that should be forecasted and ordered upfront due to their long lead times.
- Forecasted items for which it is economically attractive to order multiple items at once.

The storage options confirm the statement from Section 1.3, since the storage options related to the warehouse in Haaksbergen are more appropriate and efficient for relatively small items. The warehouse in Epe on the other hand is able to handle the big items as well.

See Appendix J for the pictures of the multiple storage options related to both warehouses.

Transportation

VMIs suppliers use multiple transportation modes to supply their goods towards the warehouses. We will not describe each transportation mode in detail, since our research focusses on road transportation only (see Section 1.4). Multiple road transportation modes are used; vans, small truck, medium trucks etc. The specific truck type is determined based on multiple item characteristics: the volume, item dimension, item weight etc. VMI uses only external transportation modes. The shipments from the suppliers towards the warehouses are not combined, since each supplier is responsible for their own shipments. The suppliers are only allowed to delivery their goods on their own fixed delivery day at the warehouses.

Information

VMI uses an MRP system called INFOR. INFOR uses backwards planning to make sure that the required resources are managed in such a way that the resources are Just in Time at the corresponding facility. Almost all departments/employees have access to INFOR. The employee's task or function determines which information can be retrieved from INFOR. The MRP system is not company-wide, since Haaksbergen warehouse is not directly linked to INFOR. This warehouse uses only a Warehouse Management System (WMS), since multiple companies use this warehouse. The required WMS input is generated by INFOR and updated every night. The WMS output is loaded into INFOR again once the order picking activities are finished. Other side programs for generating input, reports, etc. are also not company-wide integrated. Those programs are used and maintained by a group of people who are responsible for it.

Sourcing

VMI uses an extensive selection procedure. There is only one sourcing department in Epe which is responsible for the suppliers which supply Epe and Leszno. A flowchart of the complete process is given in Appendix K. The sequence of the main steps is as follow:

1. Request for new supplier
2. Composing a supplier longlist
3. Generating a short list based on a supplier assessment list
4. Performing multiple checks
5. On site supplier audit
6. Sending a Request for Quotation (RFQ) towards supplier
7. Ordering and inspecting an order sample
8. Meeting between Sourcing, Supply and Supplier Quality about the supplier selection
9. Multiple shipment inspections
10. Final approval

The selection procedure can be terminated at any moment in time when a supplier does not comply with the expectations. VMI prefers, in most cases, efficient suppliers with: low technical and logistical rejection rates, high quality of the deliveries themselves and low Total Cost of Ownership (TCO). But for some parts responsive suppliers are preferred. These parts relate to the 10-30% of a machine which is engineered and designed based on the wishes and characteristics of a customer, see Section 3.3.3. Almost all the required parts are currently outsourced. The specific product characteristics determine whether they are purchased based on; forecasts, actual demand or a two-bin system. VMI uses only first tiers suppliers, since the VMI is an Original Equipment Manufacturer (OEM). VMI prefers two or three suppliers due to risk pooling. But that is not always possible due to the technical characteristics. There are also some products which are standardized for specific suppliers. The selection procedure reveals that the supplier selection is costs and quality driven, since aspects like the geographic location and lead times are not critical.

Pricing

Pricing affects the behavior of the buyers (Chopra & Meindl, 2013). VMIs machine prices are not fixed, because the prices depend on the machine configurations. Those configurations are unique due to the (customer specific) engineered part of each machine (see Section 3.3.3). The prices are based on the associated; purchase prices, handlings, transportation, inventory costs etc.

3.3.3. Customer order decoupling point

The CODP determination is based on the earlier mentioned interviews as well as meetings with the supervisors. The CODP analysis is executed for the majority of the machines produced by the VMI and the "main" production strategy. We ignore the specific production strategies used for some exceptions.

VMI is market leader in production machinery specialized in the manufacturing of machines for: the tire, can, rubber, and care industry (see Section 1.1). The characteristics of the associated machines are not suitable for push strategies, since the machines are so expensive that keeping high inventory levels is not desirable. The dimensions of the machines are also not ideal for high inventory levels. Both push strategies, MTS and ATO, are therefore inappropriate. The two remaining strategies are MTO (also referred to as build to order) and ETO. MTO is a pull strategy where manufacturing starts only after a customer's order is received. Customizable changes are allowed. ETO is also a pull strategy, where the products are designed, engineered, and finished after an order has been received. The MTO strategy fits best with the machines, since the VMI engineers and designs most of the machine parts by itself upfront. But not everything (10-30%) can be engineered and designed in advance, since the machines are engineered and designed for the specific customer and company wishes and characteristics. So the actual applied strategy is in reality a combination of both, MTO and ETO. However, the main strategy is nevertheless MTO. Even though MTO leads to longer lead times is it, based on the machine characteristics, the most suitable strategy. The MTO policy is pulled by orders, so optimization should be realized by balancing the capacity and lead times. The MTO policy has, due to its characteristics, some advantages, and disadvantages.

Advantages

The MTO strategy minimizes waste, since it starts manufacturing once an order comes in. So resources are only spent for a product if it adds value to the customer, this eliminates unnecessary inventory and costs. It reduces the risk of inefficiency as well since the operations are focused on manufacturing the required products efficiently. Customizable changes are sometimes allowed. The products are therefore unique compared to the products which are made to stock.

Disadvantages

The long lead times are the main disadvantage of the MTO strategy. Long lead times are an obvious consequence of the method's nature. This is also the reason why the lead times should be optimized. Another disadvantage is low supply. The order production starts once the orders are received. So the required production material is not directly available.

3.3.4. Toy problem

We will not analyze the complete material flow towards Leszno directly since we first design and analyze a so called "toy problem". We use a toy problem to ensure that we do not get overwhelmed by the complexity and size of the complete material flow. Analyzing a toy problem upfront should provide some insights and remarks which will be used for the actual research. A toy problem can be defined as:

"A toy problem is a problem that doesn't have all the complexity of a real-world engineering problem. It could be a simplified or shallow version of a more difficult and intricate problem or class of problems." (Van Beek, 2018)

This chapter will discuss the following: the general toy problem aspects, the characteristics of the used toy problem, some key values, and the observations regarding the toy problem characteristics.

It is important that the used toy problem represents VMIs actual material flow towards Leszno accurately. We already visualized the current material flow towards Leszno in Section 3.3.1, but it is important that our toy problem represents the actual material flow correctly. The main characteristics of the actual material flow towards Leszno, which should be represented in our toy, are therefore given in Figure 3.8. Remark: the flow chart does not meet the specific BPMN guidelines, but it does provide the required information regarding the main characteristics of the material flow precisely.

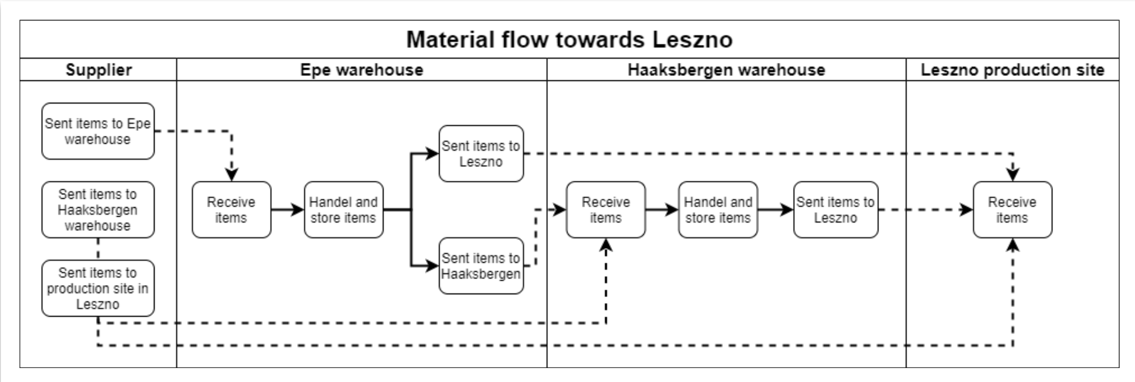

Figure 3.8 simplified material flow visualization.

We decided to use real data instead of fictitious data to ensure a good representation of the material flow. The used data has the original structure and complexity, which makes the transition towards the complete material flow easier. It is important to select an appropriate machine, module, assembly, or sub-assembly which contains sufficient and appropriate components. These items should represent the main characteristics of the material flow correctly. We have used the supervisor's advice and selected a sub-assembly (sub), the so called: *GTRU to front and rear servo A*. This sub contains a sufficient number of components which ensures both a representative and limited material flow.

We now analyze the toy problem and the chosen sub in more detail. First, we decompose the sub itself to get a better understanding of it. We then visualize and analyze the associated material flow, which is the actual toy problem, to acquire some interesting insights regarding the material flow.

The decomposition and the sub itself are given in Figure 3.9. The sub itself belongs (in this case) to the highest level of the multi-level bill of material (BOM). The manufactured components (M) of the sub belong to the remaining hierarchy levels 2, 3 and 4. The manufactured parts associated to level three and four are indicated by numbers to increase the readability of the figure. The blue boxes provide information regarding the manufactured components. The manufactured components are composed of several purchased parts (P). There are two types of purchased parts, the anonymous (a) and project related parts (p) (see Section 3.3.2). The denotation of each letter is given in Table 3.2.

Table 3.2 Letter denotations used in Figure 3.9.

Letter	Denotation
M	Manufactured part
P	Purchased part
p	Project related purchased part
a	Anonymous purchased part

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Figure 3.9 Sub-Assembly decomposition.

We have visualized the associated material flow geographically (see section 2.3.2) on the next page to provide additional insights regarding the toy problem. The geographic map of the material flow clearly shows that most suppliers are located in the Netherlands. However, a significant part of the Eastern European orders is first sent to the associated warehouses in The Netherlands (see Section 3.3.2) and then sent back to Leszno (Eastern Europe). It also shows that a considerable percentage of the suppliers are located in Southeastern Europe. The facilities in Figure 3.10 are indicated as follows:

- The red circle indicates the production site in Leszno.
- The purple square indicates the warehouse in Haaksbergen.
- The blue square indicates the warehouse in Epe.
- The black arrow is pointed at the intercompany shipments between the warehouses and the production site in Leszno.

Remark: the blue line at the bottom is visualized partly due to readability. Visualizing this material flow (associated to a Turkish supplier) completely would make all the remaining material flows less readable due to overlap.

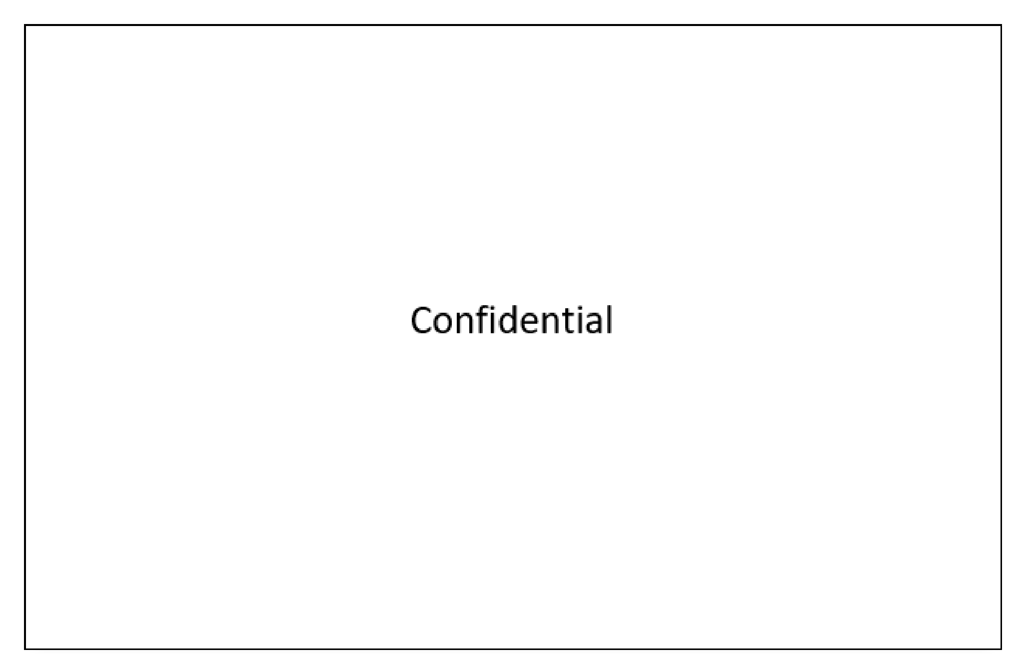

Figure 3.10 Toy problem visualization.

Key values

We now analyze the quantitative characteristics of our toy problem in more detail to provide additional insights. These quantitative characteristics are given within several tables. The key values are divided over the following three general material flow aspects to describe the toy problem characteristics: item types, supplier characteristics and the specific flow characteristics.

Associated item types

Table 3.3 General item types.

Item type	Value	Percentage
Total number of items	144	100%
Manufactured items	13	9%
Purchased items	131	91%
Anonymous items	49	37%
Project related items	82	63%

Table 3.4 Unique item types.

Item type	Value	Percentage
Total number of unique items	134	100%
Unique manufacturer items	13	10%
Unique purchased items	121	90%

Almost all items of the sub are purchased. This observation verifies the information acquired during the interviews (see Section 3.3.2). 37% of the purchased items are the so-called anonymous items, which is a much lower percentage than the project related items (63%). So about a third of the items have high inventory levels and about two-third of the sub’s items are only purchased once they are needed for a specific project, which leads to generally low inventory levels (see Section 3.3.2). Low inventory levels usually lead to lower holding costs but increase the shipment costs, since the items are ordered more frequently. The sub contains 121 unique purchased items and 13 unique manufactured items, which equals ten and nineteen percent of the total number of unique items.

Supplier characteristics

Several suppliers are responsible for the purchased items mentioned above. We now look in more detail to the suppliers and the associated geographic locations. The corresponding information is given in the table below.

Table 3.5 Supplier countries.

Country	Number of suppliers	Percentage	Distance Epe (km)	Distance Haaksbergen(km)	Distance Leszno(km)
Czech Republic	7	18.9%	791.75	737.92	262.18
Germany	1	2.7%	168.05	137.83	675.68
Poland	1	2.7%	830.25	790.10	320.69
Slovakia	3	8.1%	952.81	898.80	350.73
The Netherlands	24	64.8%	83.78	118.06	780.91
Turkey	1	2.7%	2,181.24	2,127.77	1,561.88
Total	**37**	**100%**	**5,007.88**	**4,810.48**	**3,952.07**

We determined the average linear distances towards the different facilities per country. We used the distances of the associated suppliers to determine the average distances. The distances values of Germany are biased, since there is only one German supplier which is located in West Germany. The distances towards the Dutch warehouses are therefore significantly less than the distance towards the production site in Leszno. Most of the suppliers (nearly two thirds) are located in The Netherlands. The current warehouses in Epe and Haaksbergen are therefore close to the majority of the suppliers, see table values. However, a significant number of suppliers, around 36%, are located in Southeastern Europe. This observation confirms the expectation given in Section 1.2, since these items are first sent to the associated warehouses in The Netherlands and then sent back to Eastern Europa (Poland) for production. This seems to be inefficient in terms of transport costs, lead time and the total CO2 footprint. The expectation regarding the distances is confirmed by the table values. We therefore investigate what the potential distance reduction would be when the foreign suppliers delivery directly towards Leszno instead of sending the orders first towards Epe or Haaksbergen. It must be said that this comparison provides only an indication of a potential improvement, since it is a very simplified illustration. The average distances from the table are used for this example. The total distance associated to the current material flow towards Leszno, for the foreign suppliers, equals 11427 km. The total distance for direct deliveries by the foreign suppliers equals 5446 km. This is a reduction of nearly 53%. As mentioned before, provides this example only indication. But it does provide some insights regarding a potential improvement. The example is visualized below. Remark: the symbols from above are used in the visualization.

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Figure 3.11 Example visualization.

Flow characteristics

We now provide the quantitative characteristics of the current material flow which is visualized and clarified in Section 3.3.1. The quantitative information is divided over two main material flow characteristics. Namely, the order characteristics and the specific item routes (material flow). Both the associated tables as well as the clarifications are provided below.

Table 3.6 Order characteristic.

Order(s) characteristic	value
Number of unique orders	111
Number of delivery days	10

Table 3.6 provides the quantitative values for two general order characteristics. First the number of unique orders. The total number of unique orders (111) is quite high compared to the total number of unique item (134). This indicates that most of the sub's items are ordered individually, which verifies the statement about the project related items from above. The second observation is the relatively small timespan of the deliveries, since only ten days were required to receive all orders.

Table 3.7 Incoming material flow per facility.

Facility	Number of incoming items	Percentage
Warehouse at Epe	3	2%
Warehouse at Haaksbergen	125	87%
Production facility at Leszno	16 (3)	11%

The table above provides the key values for the three optional (inbound) material flows which were defined and visualized in Section 3.3.1. These values endorse the fact, which was already given in Section 1.3, that most of the items are first sent to Haaksbergen warehouse. The direct deliveries appear to be high, however the three within the brackets indicates the purchased parts which are delivered directly. So the actual percentage is considerably lower, since the manufactured parts (13) are included in the given percentage. We can conclude that most items from Eastern European suppliers are first sent towards The Netherlands. The table below confirms this observation, since almost 40 percent of the items are supplied by Eastern European suppliers.

Table 3.8 Incoming material flow per geographic location.

Geographic location	Number of items	percentage
Eastern Europe	56	39%
Western Europe	88	61%

The table below shows the percentage of items which visit one or two facilities during their route towards Leszno. The items that visit only one facility, are the direct supplied items and the manufactured items. The items that visit two facilities, are the items which are first sent to Epe or Haaksbergen for consolidated. These numbers confirm the fact that almost all items are first sent towards Haaksbergen and that only a small percentage is supplied directly towards Leszno.

Table 3.9 Item routes.

Number of facilities visited	Number of items	Percentage
1	16	11%
2	128	89%

3.4. Conclusions

In this chapter, we analyzed and clarified the material flow towards Leszno. We used a toy problem in addition to the general supply chain aspects in order to provide addition insights. The driver analyses revealed multiple characteristics which influence the material flow strongly. First of all, the differences between both warehouses. The storage options confirm the statement from Section 1.3, since the storage options related to the warehouse in Haaksbergen are more appropriate and efficient for relatively small items. The warehouse in Epe on the other hand is able to handle the big items properly as well. The supplier related shipments also affect the material flow, since each supplier is responsible for its own shipment. That is also the reason why the shipments are not combined. The supplier selection affects the material flow as well, since the selection is cost and quality driven. The geographic location and lead times are therefore less critical. We assume that this does affect the transportation and lead times significantly. The customer order decoupling point affects the lead times as well, since the MTO characteristics lead to longer lead times. But it does eliminate unnecessary inventory and costs. Multiple conclusions regarding the toy problem can been drawn as well. The toy problem related findings and insights will obviously be used for the actual research. E.G. the KPI and improvements selection are partly based on these findings. We only provide those findings which are relevant for the actual research.

1. The majority of the suppliers are located in the Netherlands.
2. A significant part of the suppliers is located in Southeastern Europe.
3. The linear distances towards Leszno are significant lower for the Eastern Europe suppliers.
4. Nearly all items are first sent towards Haaksbergen for consolidation before being sent towards the production site at Leszno, which leads to longer lead times.
5. Direct deliveries by the foreign suppliers leads to a significant (total) distance reduction.
6. Almost all items are ordered separately which results in higher transportation costs.

We can conclude, based on the observations and the given example, that the current material flow is presumably inefficient in multiple ways. For example with the lead times, the total distance and the (total) CO_2 footprint. It is therefore important that the lead time, transportations costs and the CO_2 footprint are measured anyway. We will therefore select associated KPIs. Additionally, the improvements should improve at least on one of those material flow aspects. So both the KPIs and the improvements are driven by the lead time, transportation costs and the CO_2 footprint.

4. What is the performance of the current situation?

We analyze the performance of the current material flow, with multiple key performance indicators, within this chapter. The observations from the toy problem are used as input for the performance analysis. Some material flow aspects which should be measured, are already introduced in the toy problem section. We will use the metrics associated to the drivers mentioned in Section 3.3.2, in addition to the toy problem observations, to come up with the right performance indicators. The performance indicators should be appropriate for measuring; the current situation, the improvements, and the comparisons between both. We first select metrics which will be used for defining the right KPIs in Section 4.1. The selected KPIs and the associated measurement methods are specified in more detail in Section 4.2. The subsequent section defines how the required data related to the KPIs should be generated or acquired. The visualization methods from Sections 2.3.2 and 2.3.3 are, amongst others, used for the analysis in Section 4.4. Conclusions regarding the performance of the current situation are given at the end of this chapter.

4.1 KPIs

Figure 4.1 visualizes the used process steps towards the final KPI selection. We first selected specific metrics based on the literature and the stakeholder analysis in Section 3.2. We then used the Toy problem to acquire additional information. We now reduce this selection even further. This reduction is required since not all metrics are appropriate indicators. Remark, the material flow aspects from the toy problem are already included in the metric selection. We define and describe the KPIs one by one. The QLTC (Quality, Logistics, Technology and Costs) approach is used to group the KPIs, since the VMI uses the QLTC methodology to measure their supply chain as well. By doing so, we combine the found literature with the methodology used by the VMI. The used structure for introducing and defining the KPI(s) contains the following elements: KPI description, used formula and the measurement method. We first select which metrics will be used as KPIs. The so called S.M.A.R.T. criteria are used for the metric selection. Each metric should at least meet the following S.M.A.R.T. criteria:

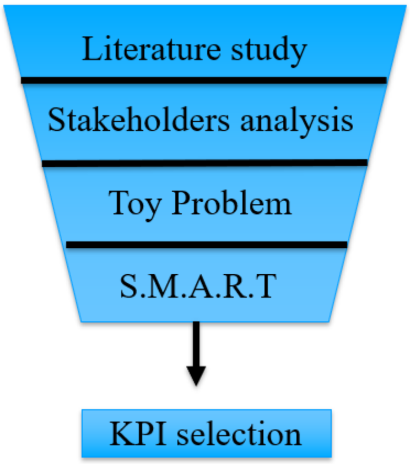

Figure 4.1 KPI selection process.

- **S**pecific – the metric should target a specific area for measurement.
- **M**easurable – there should be a clear method or procedure to measure the metric.
- **A**ssignable – it should be within the person's ability and resources to achieve the goal.
- **R**ealistic – the metric should be a relevant and valid measure.
- **T**ime-related – the researcher should be able to measure the metric within the available timeframe. (Doran, 1981)

It is important that the metrics do not only meet the S.M.A.R.T. criteria for the current situation, since they should also meet the criteria for potential scenarios and improvements. The specific scenarios and improvements are obviously unknown at this moment in time, but we will estimate which characteristics should be known for some potential improvements and whether they can be generated for such prospective improvements. The metric selection from Section 3.2 is as follows:

1. Average inbound and outbound (between facilities) transportation cost
2. Supply lead time
3. Total CO2 footprint
4. Supplier reliability
5. Incremental variable & fixed ordering costs
6. Average incoming shipment size
7. Warehouse capacity (utilized)
8. Volume contribution of top 20% suppliers
9. Handling costs
10. Fraction transported by transportation mode

We have analyzed each metric based on the S.M.A.R.T. criteria to acquire a suitable metric selection which will form the base for the KPIs. Some metrics are not selected since they serve as input for the selected KPIs. The following KPIs have been selected based on the S.M.A.R.T. criteria:

- Transportation costs
- Average total lead time
- Total CO2 footprint.
- Handlings costs

The extended analysis regarding the S.M.A.R.T criteria is given (for each metric) in Appendix L.

4.2 KPI specification

Specific insights regarding the KPI descriptions and the measurement methods are provided in the following sections. The KPIs are grouped based on the QLTC parameters. But not all parameters are taken into account, because we did not select any technology related KPIs. We explain for each parameter the characteristics and the associated KPIs. The metrics which serve as input for the KPIs are obviously defined and clarified as well.

4.2.1 Quality related KPIs

Quality related KPIs describe the quality aspects of a product, service, organization, etc. So not all the quality indicators are product or material related. E.G. one of the main quality indicators used by ASML, which invented and integrated the QLTC approach, is:

- Environmental performance.

This illustrative indicator clearly shows the link between the total CO2 footprint KPI and the quality parameter, since the total CO2 footprint measures the environmental performance of the supply chain. Our KPI selection contains only one quality related KPI. The associated measurement characteristics are given below. (Scheepers, 2019)

CO2 footprint

Description

This KPI is an important indicator due to the increasing climate change awareness. In our opinion should every company take their responsibility regarding the climate in order to become a green company. A CO2 footprint reduction might also attract (new) customers which prefer green businesses. VMI might also anticipate on optional governmental regulations, regarding CO2 emissions, by reducing their CO2 footprint. We investigate the total CO2 footprint concerning the material flow towards Leszno. We only include the emissions related to road transportation, because we assume that the potential improvements will affect those emissions the most. The following input (variables) are used for determining the total CO2 footprint.

1. Shipment distance(s) (in kilometers).
2. CO2 emission factor (kg CO2/km).

The first variable is determined for the supplier shipments and the intercompany shipments separately.

$$Total\ CO2\ footprint = \sum_{t=1}^{T} (D * C)_t \qquad \textit{Formula (4.1)}$$

With

t = unique trip number, with T is total number of trips.
D = shipment distance (km)
C = CO2 emission factor (kg CO2/km)

We determine the total shipment distance for both, the supplier related shipments and the intercompany shipments, so both shipment types have an unique trip number within the formula. We use two CO2 emission factors, since an empty truck has reasonably less CO2 emission than a full truck. The used CO2 emission factors are therefore dependent on the specific trip numbers t.

Measurement method

Shipment distances:

We determine the (linear) distances based on the latitudes and longitudes of the suppliers, warehouses and the production site at Leszno. The used formula for the Euclidean distance between two points is the so-called Great Circle formula:

$$d(\delta 1, \varphi 1, \delta 2, \varphi 2) = r * \arccos(\sin \delta 1 \sin \delta 2 + \cos \delta 1 \cos \delta 2 \cos(\varphi 1 - \varphi 2))$$

With

- r: the earth radius (6371 km)
- δi: latitude of point i.
- φi: longitude of point i.

(Longley, Goodchild, Maguire, & Rhind, 2001)

Some suppliers might combine the orders for several VMI facilities into one complete route to optimize the total distance. For example, a supplier might use a route which combines multiple facilities. It would therefore be incorrect to use the individual distances between the supplier and the recipients. An example of such a situation is given in Figure 4.2. We have used the same symbols as before (see figure 3.10) to indicate the multiple facilities within Figure 4.2.

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Figure 4.2 Optional route combinations for a Polish supplier (example).

We assume for the clarity of this example that a Polish supplier supplies each facility. It is also assumed that the associated combined route has the following sequence, Leszno → Haaksbergen → Epe. So Haaksbergen will never be supplied before Leszno in a combined route. And Epe will never be supplied before Haaksbergen in a combined route. This is justified due to cost and distance minimization which is beneficial for a supplier. The supplier has the following supply options:

1. Individual deliveries towards each facility, see the blue arrows.
2. Haaksbergen and Epe combined, see the red dotted arrow.
3. Leszno and Haaksbergen combined, see first two green arrows
4. Leszno, Haaksbergen and Epe combined, see green arrows.

The remaining facility will logically be supplied individually when the two other facilities belong to the same combined route. The example above is one of the many possible configurations, since the geographic location of a supplier determines which route and combinations are possible or beneficial. So it is important to track down the specific route used by the supplier and determine the warehouse related distance based on that specific route. The supplier related distances are logically supplier specific. We only include road transportation (see Section 1.4), so shipments which use other shipment modes (air or marine transportation) besides road transportation require additional proceedings. We simply “ignore” the air and marine transportation modes and take only the road transportation mode into account. Schiphol or the port of Rotterdam will be the “departure locations” for such shipments. The intercompany distances on the other hand are fixed. The intercompany linear distances are:

Epe warehouse → Production site in Leszno = 726.1 km

Haaksbergen warehouse → Production site in Leszno = 675.0 km

Epe warehouse → Haaksbergen warehouse = 54.0 km

CO2 emission factors:

We have selected the following emission factors:

1. Transport Van- 0.291 kg CO2/km
2. Small truck - 0.402 kg CO2/km
3. Medium truck - 0.758 kg CO2/km
4. Big truck - 1.101 kg CO2/km (CO2emissiefactoren.nl, 2019)

We use the so called well-to-wheel emission factors, since those factors include both the direct and indirect (due to the fuel production, transportation, etc.) emissions. It is very common to use well-to-wheel values for estimating the total green house gas emissions (EU Science Hub, 2016). A conversion factor is used to determine the emission differences between loaded and unloaded trucks (McKinnon, 2010).

4.2.2 Logistics related KPIs

Logistic related KPIs describe the supply and warehouse related aspects like, lead time, supply flexibility, etc. We have selected one logistic related KPI; the total lead time. The relation with the logistics parameter is quite obvious, so we do not explain the relationship in more detail. The measurement characteristics are given below.

Average total Lead time

Description

This is an important KPI since a lead time reduction has many benefits, see below:

- Increased internal flexibility.
- Less supply chain inventory, which leads to lower holding costs.
- The ability to serve your customers quicker.

Flexibility is valuable since it might lower the disturbances within the ordering process. We indicate the lead time by the average number of days which are required to purchase and distribute an order to the production site in Leszno. We express the average lead time per material flow based on the associated order lines, since the lead times are dependent on both the order’s specific route and the order line type (project or anonymous). The order(lines) are therefore categorized based on the associated material flow. The flows determine for instance the involved warehouses and the intercompany shipment routes. The four material flow options are (see Section 3.3.1):

1. Supplier → Leszno.
2. Supplier → Haaksbergen → Leszno.
3. Supplier → Epe → Leszno.
4. Supplier → Epe → Haaksbergen → Leszno,

The total lead time is subdivided into three lead time “types” to determine the (average) total lead time per material flow. The three-lead time “types” are:

1. Supplier related lead time.
2. Average consolidation time at the warehouse(s).
3. Lead time of intercompany transport.

The supplier related lead time of the order lines are based on the captured ERP data. The average consolidation times are dependent on two variables: the warehouse (w) and the order line type (t). The variable characteristics are:

Warehouse:
1. Epe
2. Haaksbergen

Order line types:
1. Project related items
2. Anonymous items

There are three intercompany shipment options, which are specified by the material flow, with their own lead times. Material flow option four requires intercompany shipment options one and three. We simply add up the two independent intercompany shipment lead times.

1. Epe → Haaksbergen
2. Epe → Leszno
3. Haaksbergen → Leszno

So we determine the average total lead time for each material flow option separately based on the associated order lines.

Formula 2

$$Average\ total\ lead\ time(f) = \frac{1}{O} * \left(\sum_{o=1}^{O} (S + A + I)_o\right) \qquad \textit{Formula (4.2)}$$

With

o = order lines associated to a specific material flow f, with O is total number of order lines.
f = material flow option {1,2,3,4}
S = Supplier's related lead time
A = average storage time
I = average intercompany shipment time

We use the formula from above for each material flow separately.

Measurement method

The supplier related lead times are known and captured within the database, so we can directly use them. We use the target values which are determined by the VMI for the average consolidation times. The average shipment times are known as well. So we can simply add the known parameter values to our model.

4.2.3 Cost related KPIs

The cost related KPIs describe the cost types that contribute to the total costs associated to the supply chain. The two remaining (cost) related KPIs are the transportation costs and the handling costs.

Transportation costs

Description

We selected this KPI since the transportation costs are accountable for a significant percentage of the total logistical cost, sometimes even up to 50% (Murray, 2019). There are many factors as well as supply chain decisions which influence the total transportation costs. It is therefore of great importance to analyze the transportation costs for the current supply chain configuration.

The supplier related transportation costs are based on a cost price percentage and the quantity of the shipment. The charged cost price percentages are based on the item dimensions. The intercompany transportation costs are also considered. We will measure the intercompany shipment costs separately, since these costs are based on the number of pallets.

Formula 3

$$Total\ transportation\ costs = \sum_{o=1}^{O}(Q * P * PER)_o + \sum_{r=1}^{3}(FR * SC\ )_r \qquad \textit{Formula (4.3)}$$

With

o = order lines associated to a specific material flow f, with O is total number of order lines.
r = intercompany shipment route {1,2,3}.
Q = order line quantity
P = order line cost price
PER = charged % supplier
FR = frequency
SC= shipment costs

Measurement method

The charged cost price percentages are based on the provided information by the VMI. These values will be verified with the percentages mentioned within the literature to check the clarity of the provided percentages. Historical data is used to determine the frequencies of the intercompany shipments. We will request the associated transportation costs at the transportation department. The formula itself is not complicated once the required input is acquired.

Handlings costs (per material flow)

Description

The handling costs are in general a high expense within logistics. Quality issues might arise due to unnecessary handlings, since each handling contains an error probability. So reducing the required handlings is beneficial in terms of costs and logistical quality. We will analyze the total handling costs per material flow for the current situation. The orders are supplied through several material flows. Some are supplied directly and others are first sent towards a warehouse (see Section 3.3.1). Sending orders first to a warehouse results in higher additional costs than sending them directly towards the production site in Leszno, since the warehouse orders require additional handlings like; unloading, storage and loading for transport towards Leszno. There are also orders which are first sent towards Epe then sent towards Haaksbergen before being sent towards the production site at Leszno. So we have the following four material flow options (as mentioned in Section 3.3.1):

1. Supplier → Leszno.
2. Supplier → Haaksbergen → Leszno.
3. Supplier → Epe → Leszno.
4. Supplier → Epe → Haaksbergen → Leszno.

The handling costs are determined per material flow and are based on the associated order lines. The order lines are therefore categorized over the multiple material flows. Adding up the material flow specific handling costs provides the total handling costs. We divided the handling costs over two types; inbound handling costs and outbound handling costs. These types are dependent on two variables; order line category (c) and the warehouse (w). The variable characteristics are:

Order line categories:
1. Small (Box storage)
2. Medium (EP storage)
3. Big (SP storage)
4. Very big (ZD storage)

Warehouse:
1. Epe
2. Haaksbergen

Formula 4

$$Total\ handling\ costs = \sum_{f=1}^{4} \sum_{o=1}^{O} (IN + OUT)_{of} \qquad \textit{Formula (4.4)}$$

With

o = Total number of order lines associated to a specific material flow f.
f = material flow option {1,2,3,4}
IN = Inbound handling costs
OUT = Outbound handling costs

How to measure

We first determine the total number of order lines per material flow. We then determine the total handling costs per material flow based on the two handling cost types. Finally, we measure the total handlings costs by adding up the handling costs related to the specific material flows.

4.3 Data generation

Most of the required information (see Section 4.2) can be retrieved from the ERP system (INFOR). Informal interviews and meetings were used to acquire, or compose assumptions for, the requisite data which was not stored by the ERP system. We did not use any outlines for those informal meetings, that is also the reason why the associated outcomes are not provided in the appendix. Data from the ERP system requires multiple generation and preparation steps. An overview of the main steps is given within this section.

The data which is subtracted from the ERP system is raw data, which means that some data generation and preparation is required to include only the essential data. We followed the steps of the Multidimensional Modeling Process (MMP) during the data preparation. Kimball (2007) organized MMP into the following four sub processes:

1. Choose the business process(es) to model.
2. Choose the granularity of the business process.
3. Design the dimensions.
4. Choose the measures.

The first step relates to the observation that not all business processes are equally important for the business research, there might be some prioritization. Step two implies the importance of using the data granularity that best matches the analysis needs. The third step refines the schema for each part of the grain into a complete dimension with multiple levels and attributes. The last step defines the numerical measures to capture each combination of dimension values (Kimball, 2007).

Step 1

The vital business process for this research is logically the material flow towards Leszno.

Step 2

We selected order lines as the data granularity for the material flow, because it matches best with the needs of the analysis. The specific parts could also be the granularity, however the order quantity for each specific part does not provide the essential insights. As already mentioned, a cheap SKU with high order quantities for example is not more important than an expensive SKU with low order quantities. We therefore assume that the order lines form the best granularity for this research.

Step 3

We composed the following four dimensions: Order, Product, Supplier and Facility characteristics. The attributes for each dimension are given in the table below:

Table 4.1 Dimension attributes.

Order characteristics	**Product characteristics**	**Supplier characteristics**	**Facility characteristics**
Art number	Art code	Supplier code	Facility
Art description	Art description	Supplier name	Latitude facility
Order quantity	Unit	Latitude	Longitude facility
Supplier code	Costs/unit	Longitude	Country facility
Warehouse code	Art type (anonymous/project)	Country	
Receipt date	Lead time	Transportation mode	
Delivery date Leszno	Storage zone		
Route			
Shipment code			
Combined (yes/no)			

Step 4

The measures are dependent on the available data. The data is therefore leading for the numerical measures. We prefer to use measures as specific as possible, since less specific measures are always an option by aggregating the specific measures.

4.4 KPI outcomes

We provide the KPI outcomes within this section. By using the visualization methods from 2.3.3, we aim to provide the outcomes in a clear and orderly manner. The specific visualization outcomes are analyzed and discussed within this section. All the outcomes are associated to the earlier mentioned toy problem and are based on one year. This equals 10 subs a year, since the VMI produces 10 GTRUs per year in Leszno (see Section 3.3.4). A dashboard with all the KPI visualizations for the current situation is provided as well. The figures used to visualize the specific KPI outcomes or values contain the European decimal notation due to software limitations, since the used program has no option to use dots instead of commas. An overview of the used parameters, with the associated argumentation, is provided at the end of this section.

CO2 footprint

Figure 4.3 reveals that the supplier related shipment emissions (inbound and outbound) are responsible for 79.80% of the total CO2 footprint. The supplier related transportation has due to its considerable impact a significant improvement potential in terms CO2 emission reduction. The intercompany transportation emissions are responsible for 20.20% of the total CO2 footprint, which is still a substantial percentage. We therefore conclude that both transportation types might offer considerable CO2 reduction opportunities.

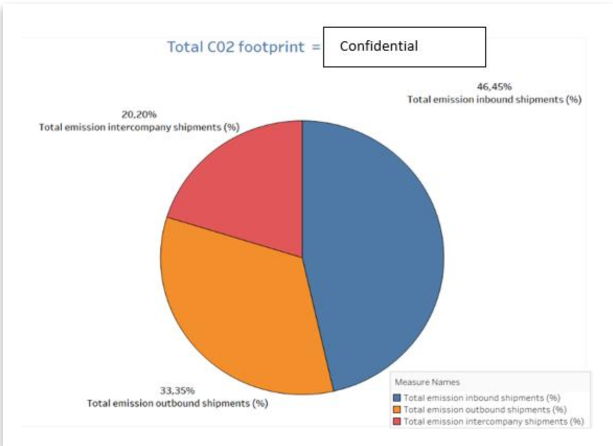

Figure 4.3 CO2 footprint visualization.

The specific vehicle type has a big influence on the total CO2 footprint, see Section 4.2.1. We therefore investigated the used vehicle types per supplier for two weeks to acquire a correct overview of the used truck types. We asked the transportation department to provide information regarding the used truck type(s) for intercompany shipments. Remark, the actual toy problem related emissions are expected to be lower due to the limited volume. Normally, a supplier would combine items for multiple machine components into one shipment instead of shipping only the items related to one SUB. So the CO2 emissions related to the toy problem are expected to be lower, since the associated items are partly responsible for the total emissions associated to the used (and selected) trucks. But this will be resolved once we take the whole material flow into account. The used formula is dependent on two variables, the shipment distance, and the CO2 emission factor(s). Both variables can be used to reduce the total CO2 footprint, since they might lead to a significant CO2 footprint reduction. We therefore look for alternatives which improve at least one of the variables.

Average total lead time

The used toy problem does not contain the following route :

Supplier → Epe warehouse → Haaksbergen warehouse → Production site Leszno.

We did mention this route before, since it is an optional route for the material flow towards Leszno (see Section 3.3.1). We therefore added 3 dummy order lines to our toy problem to show the associated effects on the average lead time. The dummy routes are constructed in such a way that they represent the route correctly. These dummy routes are not used for the comparisons since they are based on fictitious data.

Figure 4.4 shows the average total lead time for the four route options (see Section 4.2.2), so inclusive the dummy route. Each column represents a specific route option and each bar (color) represents a lead time type, see the legend in the right corner. The dummy route is visualized in the right column.

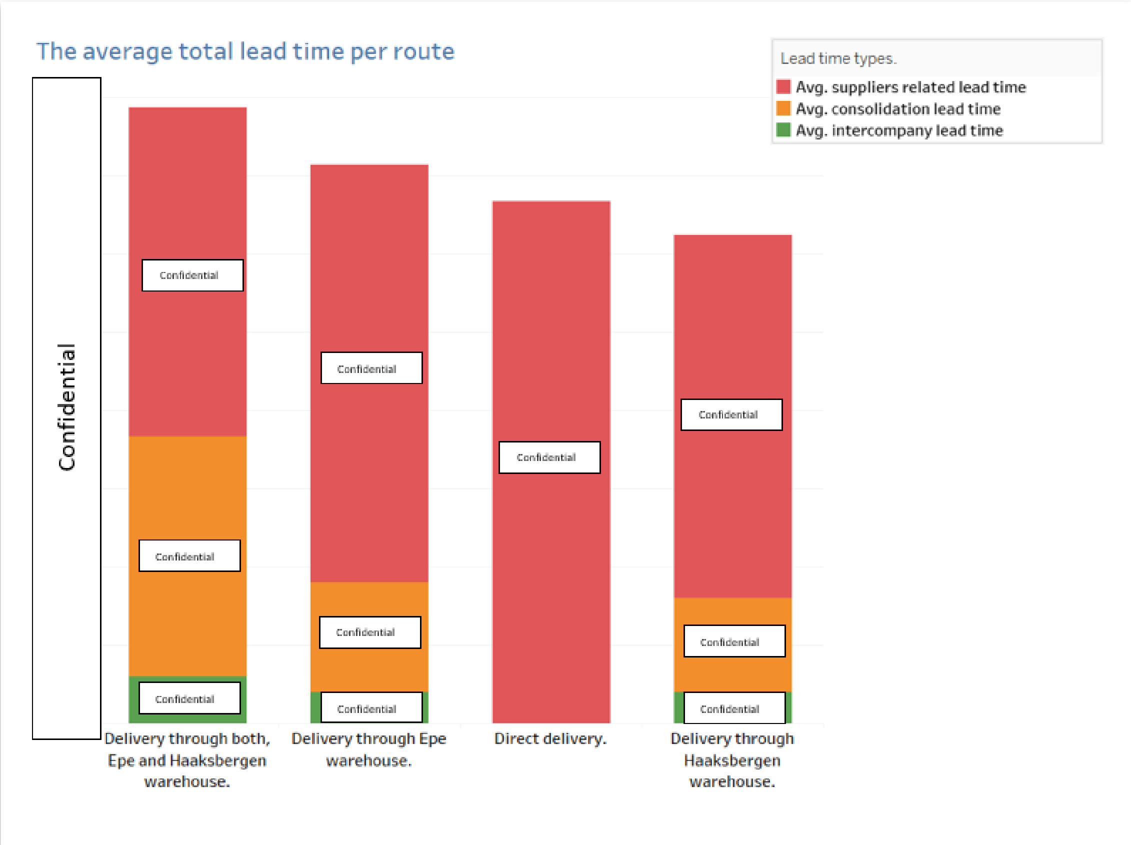

Figure 4.4 The average total lead time per route.

Figure 4.4 shows the average lead times for each of the four routes mentioned within Section 2.2.4. It confirms our expectations regarding the lead times, since it takes more time when an order line goes trough 2 warehouses instead of 1 (as with the dummy route). The figure also shows that the supplier related lead time affects the total average lead time the most. The average suppliers related lead time varies between the Confidential, which is confirmed by the values in Figure 4.4. The supplier related lead times include the entire production and tranportation process, so from production until the delivery towards the warehouse(s). The remaining lead times are significantly lower compared to the supplier related lead time. But we assume that specific supply chain configurations have a bigger impact on the the intercompany and consolidation lead times, see Section 4.2.2 We will therefore focus our research on alternatives which improve any of the specifc lead time types.

Transportation costs

Figure 4.5 shows the total yearly transportation costs for the current situation. The specific cost price factors are verified with the sourcing buyers of the VMI. The total number of pallets per GTRU per warehouse per year are verified with the transportation department.

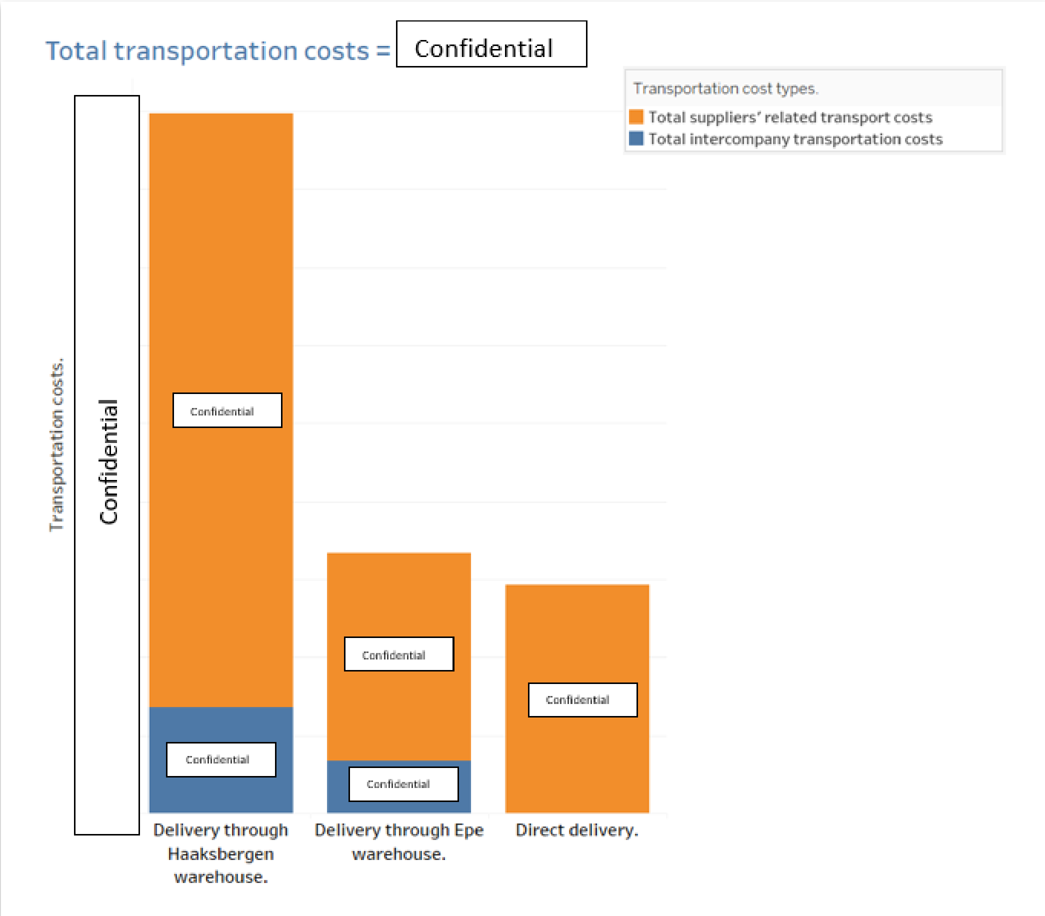

Figure 4.5 Transportation costs for the current configurations.

The overview reveals that the transportation costs related to the “supplier shipments” towards Haaksbergen are responsible for 50% of the total transportation costs (Confidential). This is a logical consequence of the current configuration where 87% of the items are supplied through Haaksbergen. The ratio between both shipment types equals 86.6% compared to 13.4% respectively. Even though the supplier related shipments are responsible for most of the transportation costs, are the intercompany shipments still responsible for a significant percentage of the total costs. So both transportation cost types have a considerable influence on the total transportation costs. The cost price percentages affect the total transportation costs significantly. So we validated these percentages with VMI representatives. These values have been verified with cost price percentages mentioned within the literature as well. Adjusting the number of intercompany pallets with 1 pallet affects the total transportation with 4.45%. This equals Confidential, which is a logical consequence of the average costs Confidential per intercompany pallet. We validated the number of intercompany pallets per year with VMI representatives as well to ensure correct model outcomes.

The outcomes show that both transportation cost types have a big influence on the total transportation costs. We will therefore examine alternatives which have the potential to reduce at least one transportation type.

Handling costs

Figure 4.6 visualizes the inbound and outbound handling costs for multiple storage zones, see Section 3.3.2.

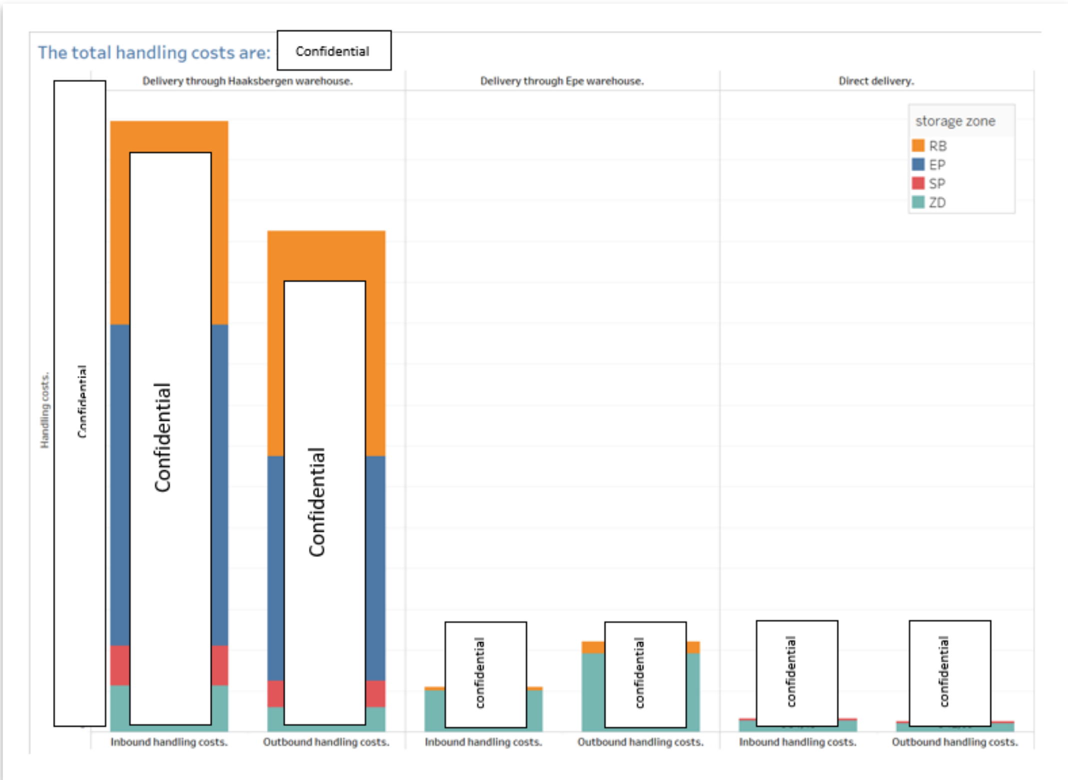

Figure 4.6 Total handling costs per route.

The figure shows that the inbound handling costs are higher compared to the outbound handling costs for the deliveries through Haaksbergen, even though the outbound frequencies are on average higher. This is a logical consequence of the lower outbound handling costs at the Haaksbergen warehouse. The inbound handling costs for the deliveries through Epe warehouse are on the other hand lower. This makes sense as well, since both, the outbound handling costs and frequencies are on average higher for the warehouse in Epe. The handling costs for the direct deliveries are a small percentage of the total handling costs. This is a logical consequence of the limited direct deliveries and the lower handling costs due to the lower salary of the Polish employees. We will look for multiple alternatives which might reduce the handling costs. This can be achieved by reducing the specific handling costs per order line or by reducing the total number of handlings. We will therefore look for alternatives for both options. As mentioned before is the quality improvement assumed to be an additional benefit.

Dashboard

We combine the specific KPI performances into one complete dashboard. This dashboard summarizes the overall performance of the current situation in a cleared and structured way. We assume that dashboards are useful for the comparisons between the multiple alternatives, since they show directly whether an alternative performs well or poor on specific KPIs. When dashboards turn out to be inefficient for the comparisons, we can still use the individual graphs like we did above.

Figure 4.7 Dashboard with overall performance of the current situation.

Parameter overview

The table below summarizes the used parameter values. The used, source, fact, person, or method used to acquire the parameter values are given as well. The parameters are grouped based on the associated KPIs. The more general assumptions regarding the material flow characteristics are provided in Appendix M.

Table 4.2 Parameter overview.

KPI.	***Parameter.***	***Source.***
CO2 footprint.	Transportation type	Two-week study.
	Co2 emission factors (per transportation type)	(CO2emissiefactoren.nl, 2019).
	Conversion factor (full truck VS less then full truck)	(CO2emissiefactoren.nl, 2019).
Average total Lead time.	Consolidation lead times (see Section 4.2.2)	SCI & Warehouse department representatives.
	Intercompany lead time.	Transportation department representatives.
Transportation costs.	Cost price percentages.	Sourcing department representatives.
	Number of intercompany pallets (Toy Problem).	Transportation department representatives.
	Intercompany transportation costs.	Transportation department representatives.
Handling costs.	Inbound handling costs per storage zone.	Warehouse department representatives.
	Outbound handling costs per storage zone.	Warehouse department representatives.
	Conversion factor Polish handling costs.	Finance department representatives.

4.5 Conclusions

Conclusions regarding the performance of the current situation are given below.

CO2 footprint

Both shipment types are responsible for a significant percentage of the total CO2 footprint. So both transportation types might offer considerable CO2 reduction opportunities. We will therefore focus on alternatives which reduce the emissions for both shipment types. This can be done by improving at least one of the two variables; total shipment distance and CO2 factor per kilometer.

Average total lead time

The outcomes reveal that the supplier related lead time affects the total lead time the most. However, we assume that thespecific supply chain configuration have a bigger impact on the intercompany and consolidation lead times. We therefore focus our research on alternatives which can improve any of the specific lead time types.

Transportation costs

The total cost ratio between both transportation types equals 86.6% compared to 13.4%. So both transportation cost types affect the total transportation costs considerably. We therefore examine alternatives which reduce both transportation cost types.

Handling costs

The outbound inbound handling cost ratio is dependent on the specific route. This is a logical consequence of the associated handling costs and the shipment frequencies, which differ per route. We therefore look for multiple alternatives which might reduce both handling cost types. This can be achieved by reducing the specific handling costs per order line or by reducing the total number of required handlings. The logistical quality improvement is assumed to be an additional benefit.

Part 2

5. What are promising alternatives or improvements

We provide multiple alternatives for the current material flow within this chapter. These alternatives will be compared with each other and with the current situation in the next chapter. Section 5.1 provides an overview of the outcomes related to the current performance which we considered during our literature study in Chapter 2. These outcomes are translated into research directions and topics which are also given in Section 5.1. The research topics were the base of the executed literature study, see Section 2.4. We then briefly recap on the alternatives, from Section 2.4. The impact of the alternatives on each KPI is analyzed in Section 5.2 as well. We used impact matrices during this analysis. Interviews were held to reduce the number of alternatives into a specific selection (short list), this short list is given in Section 5.3. The final alternatives are linked to the specific context of the material flow associated to the toy problem in Section 5.4.

5.1. Which outcomes from chapter 4 have been considered during the literature study?

Multiple conclusions have been made based on the performance of the current situation, see Section 4.5. We will give a short recap of the outcomes which we kept in mind during the literature study. The outcomes are divided over the KPIs. We use the KPI sequence from Section 4.5.

CO2 footprint

The total CO2 footprint is dependent on two variables. So optimizing these variables should reduce the CO2 footprint. We will therefore focus our literature study on alternatives which optimize either the total shipment distance or the specific emission factors.

Average total lead time

The supplier related lead time is responsible for the biggest share of the total average lead time. But we can only influence the transportation aspect, which represents a small percentage of the total supplier related lead time. However, we do have a lot of influence on the intercompany and consolidation lead times. We will therefore focus our research on alternatives which can improve any of the three specific lead times.

Transportation costs

It is important to examine alternatives which reduce both the intercompany and supplier related shipment costs, since both have a significant influence on the total transportation costs.

Handling costs

The total handling costs can be reduced by optimizing specific handling costs per order line or by reducing the total number of required handlings. So we should focus our literature study on both handling cost aspects.

The table below summarizes the main research directions which are based on the observed outcomes from the previous chapter. The corresponding KPIs are given in the second column.

Table 5.1 Research directions.

Research direction	**KPI**
Reduce the total shipment distance.	CO_2 footprint.
Reduce the CO_2 emissions of the used trucks.	CO_2 footprint.
Reduce supplier related shipment time.	Average total lead time.
Reduce intercompany shipment lead time.	Average total lead time.
Reduce consolidation lead times	Average total lead time.
Reduce both, intercompany and supplier related shipment distance/costs	Transportation costs.
Reduce total number of required handlings.	Handling costs.
Reduce the specific handling costs.	Handling costs.

The above-mentioned research directions can be divided over three literature topics which where introduced in Section 2.4 and recapped by Figure 5.1. These three literature topics formed the base of the conducted literature in Chapter 2.

Figure 5.1 Literature topics as introduced in Section 2.4.

5.2 What are interesting and promising material flow alternatives or improvements?

The conducted literature study resulted in nine potential alternatives which are provided and described in Section 2.4. As already mentioned, we did also look at some “out of the box” alternatives, to protect ourselves against a tunnel vision during the research. The potential alternatives are given below.

Material flow network alternatives:

1. Direct Shipping to Single Destination.
2. Milk-run.
3. Direct Shipping with Milk-Run(s)
4. Cross Dock Warehouse.
5. Intermodal Transportation.
6. DC Bypass Strategy.

Additional alternatives:

7. Environmentally Friendly Trucks.
8. Vendor Managed Inventory.
9. Additive Manufacturing (3d Printing).

The impact of the alternatives is analyzed on the next page.

The impact of alternatives on the KPIs

We summarized the impact of the alternatives on each KPI in one matrix to acquire some insights regarding the effects of the alternatives. The matrix is formed in consultation with the problem owners. It is basically a summary of Section 2.4. We classified the effects into three types. The 3 types are; positive effect on KPI (+ sign), negative effect on KPI (- sign) and no or unknown effect on KPI (0 sign). We used, besides some interviews, the advantages, disadvantages, and characteristics of the alternatives for composing the matrix which is visualized below. The impact of the 3d printing alternative on the KPIs is based on the products for which the technique is currently suitable.

Alternative	**CO2 footprint**	**Average total lead time**	**Handling costs**	**Transportation costs**
Direct Shipping to Single Destination.	+	+	+	+
Milk-run.	+	0	0	+
Direct Shipping with Milk-Run(s).	+	+	+	+
Cross Dock Warehouse.	+	0	-	+
Environmentally Friendly Trucks.	+	0	0	-
Vendor Managed System.	0	+	+	0
Intermodal Transportation.	+	-	-	-
Additive manufacturing (3d printing).	+	+	+	+
DC Bypass Strategy.	+	0	+	+

Figure 5.2 The impact of alternatives on the KPIs.

We also analyzed the required effort (per alternative) to acquire the specified impact. We positioned the alternatives in the matrix during a meeting with the supervisors. We obviously took the advantages, disadvantages, and characteristics of the alternatives into account during the positioning. Each number represents an alternative, the following numbering is used:

1. Direct Shipping to Single Destination.
2. Milk-run.
3. Direct Shipping with Milk-Run(s)
4. Cross Dock Warehouse.
5. Environmentally Friendly Trucks.
6. Vendor Managed Inventory.
7. Intermodal Transportation.
8. Additive Manufacturing (3d printing).
9. DC Bypass Strategy.

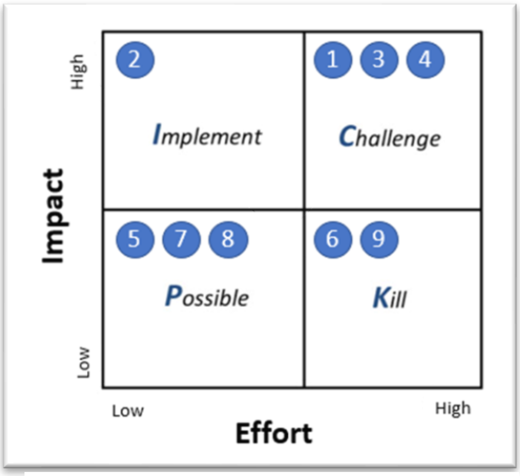

Figure 5.3 Impact effort matrix.

5.3 Final selection

The alternatives introduced above belong to the so called long-list. We have analyzed each alternative in more detail to select the most suitable and appropriate alternative for this research. The specific alternative characteristics and both matrices were taken into account during this analysis. We asked the problem owners as well to give their opinion about the alternatives during multiple meetings and discussions. This resulted in the following alternatives selection:

Material flow network alternatives:

1. Direct Shipping to Single Destination.
2. Milk-run.
3. Direct Shipping with Milk-Run(s)
4. Cross Dock Warehouse

Additional alternatives:

5. Environmentally Friendly Trucks.
6. Additive Manufacturing (3d Printing).

The first four material flow network alternatives will be analyzed quantitively within the constructed model. The remaining additional alternatives will be analyzed qualitatively, since these alternatives are not suitable for analyzing within the constructed model. The material flow network alternatives are described in more detail in the next section, because the provided information in Section 2.4. is quite abstract and theoretical. We therefore link these alternatives to the specific research context in the next section.

5.4 Alternatives translated to VMIs material flow context

We now link the abstract and theoretical information regarding the alternatives from Section 2.4 to the specific context of this research. For brevity of writing, we focus on the material flow associated to the toy problem. Multiple figures are used to illustrate the alternatives.

Direct Shipping to Single Destination (Leszno).

We apply the direct shipping configuration on the Eastern European suppliers. The production site in Leszno will be the so-called single destination. A warehouse is obviously required to handle and consolidate the incoming shipments. It is therefore important that the cost savings outweigh the fixed and variable warehouse costs. The associated Eastern European suppliers are visualized by colored dots in Figure 5.4.

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Figure 5.4 Eastern European suppliers.

Almost all the Eastern European suppliers ship their products towards the warehouse in The Netherlands before they are shipped towards the production site in Leszno, see Section 3.3.1. The current material flow of the Eastern European shipments is visualized in Figure 5.5.

Confidential

Figure 5.5 Current material flow Eastern European suppliers.

The direct shippping configuration is visualized in Figure 5.6. The figure shows that the Eastern European orders will be shipped directly towards the production site in Leszno. Both the total distance and costs are expected to drop by applying the direct shipping alternative. The exact consequences regarding the performance of the this alternative will be analyzed in the next chapter.

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Figure 5.6 Direct shipping visualization.

Milk-run (to Haaksbergen en Epe).

The milk run configuration will be applied to Eastern European suppliers as well. However, not all the Eastern European suppliers are added to the specific milk-run “route”. This is a logical consequence of the geographical location, since two suppliers are located far away from the other Eastern European suppliers. This is visualized in Figure 5.7. The two arrows are pointed at the suppliers which do not belong to the milk-run. The suppliers within the circle do belong to the milk-run. The specific milk-run is visualized on the next page.

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Figure 5.7 Milk-run suppliers.

We used a construction heuristic called nearest neighbor to compose an initial milk-run route. This initial route is visualized in Figure 5.8. The figure shows that this initial route is far from optimal. We therefore used an improvement heuristic called 2-opt to improve the initial route. This improvement heuristic swaps route segments to optimize the route.

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Figure 5.8 Initial milk-run route.

We used four swaps during the route optimization. The final and near optimal route is visualized in Figure 5.9. We expect that the milk-run alternative results in distance and costs savings.

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Figure 5.9 Near optimal milk-run route.

Direct Shipping with Milk-Run(s) (to Leszno)

We already mentioned in Section 2.4. that this alternative is a combination of the direct shipping and milk-run alternatives. We apply this alternative on the Eastern European suppliers which are already defined above. Figure 5.10 visualizes the direct shipping with milk-run(s) alternative for the associated Eastern European suppliers. Both the direct shipments and the milk-run shipments are shipped direct towards Leszno, as shown in the figure below. It is therefore important that the cost savings outweigh the fixed and variable costs of the required warehouse Leszno.

Confidential

Figure 5.10 Direct shipping with milk-run(s) visualization.

The milk-run contains the same suppliers as the milk-run which is defined above. The direct shipping aspect is applied to the two remaining suppliers which are located far away from the "milk-run suppliers". We again expect both distance and costs savings for this alternative. Both potential savings will be measured quantitatively in the next chapter.

Cross Dock Warehouse.

The cross-dock warehouse alternative will also be applied on the already mentioned Eastern European suppliers. For simplicity, we used the midpoint of the Czech and Slovak suppliers as the location of the cross-dock warehouse. This midpoint is visualized by the arrow in Figure 5.11.

Confidential

Figure 5.11 Cross dock warehouse location.

The cross-dock warehouse alternative is visualized in Figure 5.12. The Eastern suppliers will ship their orders towards the cross-dock warehouse instead of the warehouses located in The Netherlands. These orders are then handled and combined within the warehouse and directly sent (consolidated) towards the warehouses in The Netherlands.

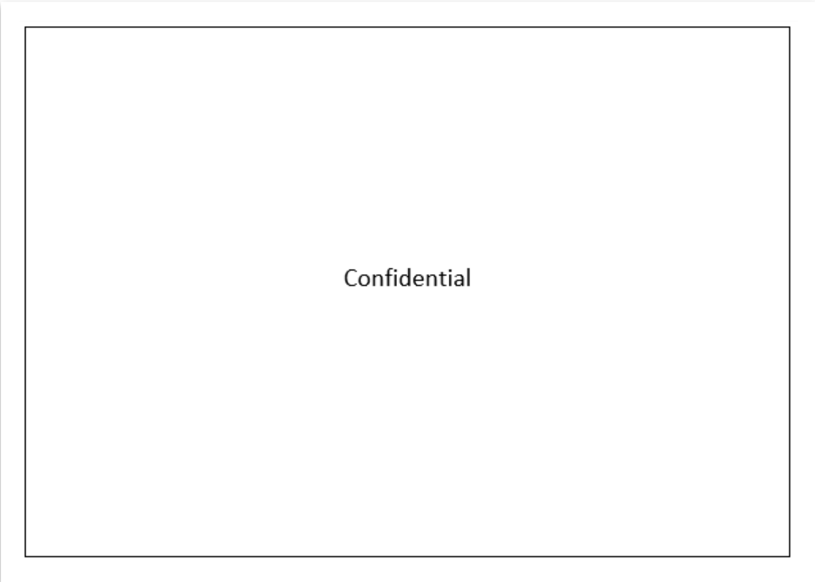

Figure 5.12 Cross Dock warehouse visualization.

We expect that the alternative advantages mentioned in Section 2.4 will result in a better material flow performance, which will be measured in the next chapter.

5.5 Conclusions

We translated the performance outcomes into research topics which were used during the conducted literature study. This literature study identified multiple alternatives, the so called long-list. We analyzed these alternatives in more detail to examine which alternatives are most suitable for this research. The impact matrices have been used as well to provide additional insights regarding the required effort and potential impact of the alternatives. We made a final alternative selection based on these analyses, the so-called short-list. We then linked the abstract and theoretical information of the four material flow network alternatives (Section 2.4), to the specific context of this research focusing on our toy-problem. This already revealed some potential improvements.

6. What is the best alternative or improvement for a specific scenario?

This chapter provides the final conclusions of this research. We first define and analyze the outcomes of the supply chain network alternatives related to the toy problem. The quantitative results as well as the associated dashboards will be given. These outcomes are all based on one year. The potential and the additional value of the remaining alternatives is also given in the first section. In Section 6.2, we analyze the performance of the current situation for the complete material flow by extrapolating the toy problem outcomes. We measure the alternative performance given the selected scenarios for the complete material flow in Section 6.3. These outcomes will be analyzed as well in Section 6.3. We have executed a sensitivity analysis to acquire insights regarding the influence of the used parameter and variable values. Section 6.5 contains the conclusions regarding the alternatives. The recommendation about the best alternative(s) given the selected scenarios will be provided as well in Section 6.5. This recommendation forms the outcome of this research.

6.1 Toy problem outcomes

This section summarizes the performance of the alternatives. The performances are based on the toy problem characteristics and values, see Section 3.3.4. The two additional alternatives which will be analyzed qualitatively are examined at the end of this section. We first analyze the four material flow network alternatives. The alternative performance is compared to the current situation.

6.1.1. Direct Shipping to Leszno.

This alternative affects each KPI positively. The specific characteristics of this alternative as well as the link to the specific context of this research are given in Section 5.4. We examine each KPI subsequently.

CO2 footprint

The total yearly transportation distance drops significantly when multiple shipments are shipped directly towards Leszno. The distance reduction for the associated Eastern European suppliers is 72.2%. But this is only the distance reduction for the Eastern European suppliers, see section 5.4. The overall distance (percentage) reduction is logically lower, since the shipment distances of the other suppliers remain the same. The overall distance reduction equals 52.1%. We already elucidated that the shipment distance affects the CO2 footprint significantly, see Section 4.4. The performance of the alternative in terms of CO2 footprint confirms this statement, since the total CO2 footprint drops with 51.5%. We therefore conclude that the direct shipping alternative affects the CO2 footprint positively.

Average total lead time

We have divided the total lead time into three types, see Section 5.4. The direct shipping alternative has a positive effect on each of the three lead time types. The items which are shipped directly have no consolidation and intercompany lead time. The supplier related lead time will be reduced as well since the shipment distance drops significantly (see above). This results in an average total lead time reduction of 8.9%.

Transportation costs

The transportation costs of both transportation types, supplier related and intercompany, are influenced by the direct shipping alternative. The supplier related transportation costs are affected since the Eastern European suppliers can ship their orders towards Leszno instead of The Netherlands. The associated distance is considerably lower. The intercompany transportation costs are affected as well, since less items are shipped between the warehouses and Leszno. This leads to a cost reduction of 27.6%, the associated overview is visualized in Figure 6.1. We can conclude that our assumption from Section 5.4 is confirmed by the quantitatively outcomes of the model.

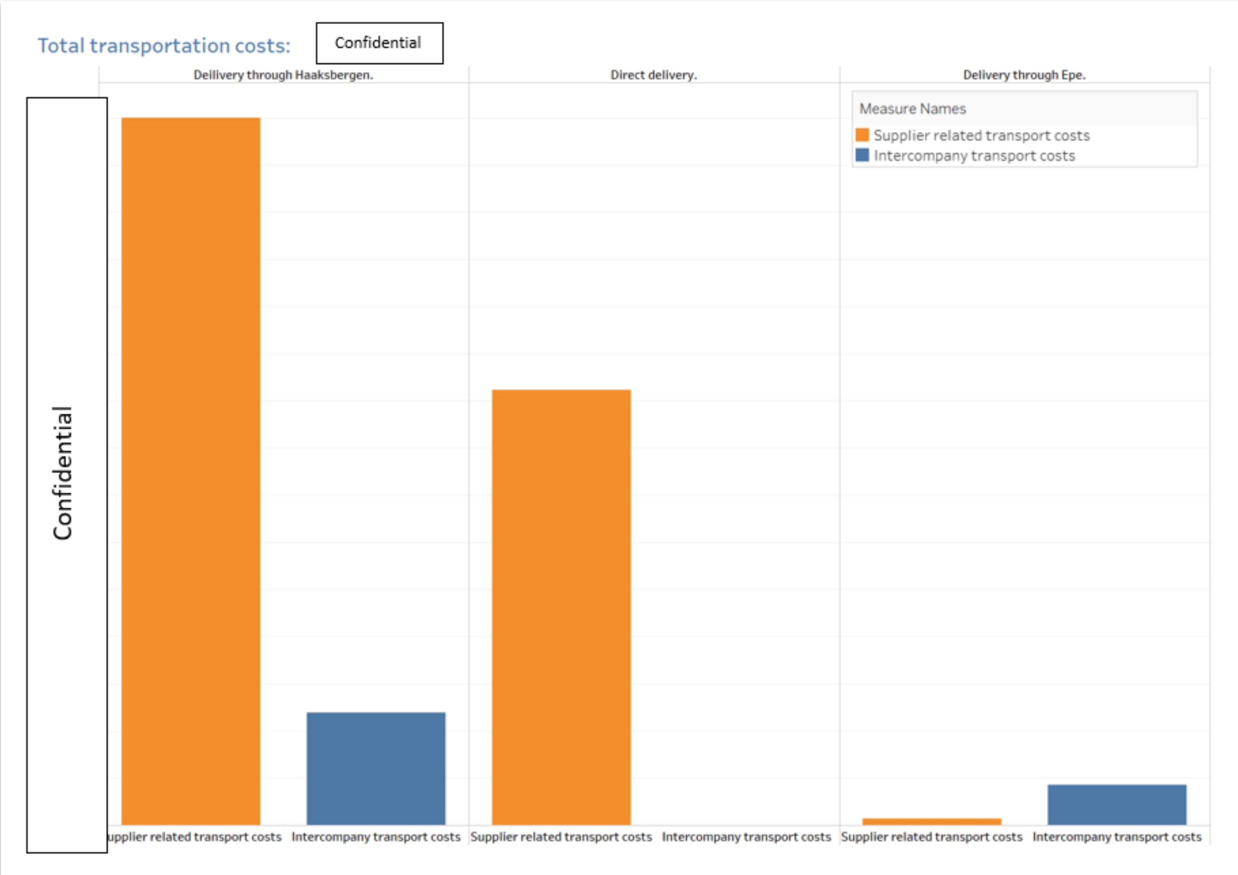

Figure 6.1 Transportation costs (direct shipping alternative)

Handling costs

The handling costs are also strongly affected by the direct shipping alternative. This is a logical consequence of the alternative characteristics, since less items have to be handled and stored in the warehouses in The Netherlands before they are sent towards the production site in Leszno. The associated (yearly) handling costs reduction is 25.0%. This significant reduction confirms our assumption from Section 5.4.

6.1.2. Milk-run (to Haaksbergen and Epe).

The milk-run alternative has a positive effect on almost every KPI, only the handling costs are not affected by the milk-run alternative. The specific effects on the KPIs are elucidated below.

CO_2 footprint

The total (yearly) transportation distance drops substantially because of the milk-run alternative. This is a consequence of the consolidated and efficient milk-run which will replace multiple trips between the suppliers and the warehouses. As already mentioned, the total transportation distance has a big influence on the total CO_2 footprint. It is therefore reasonable that the milk-run alternative has a positive effect on the total CO_2 footprint. The milk-run alternative reduces total yearly CO_2 footprint with 37.8%. The associated emission types are visualized in the figure below.

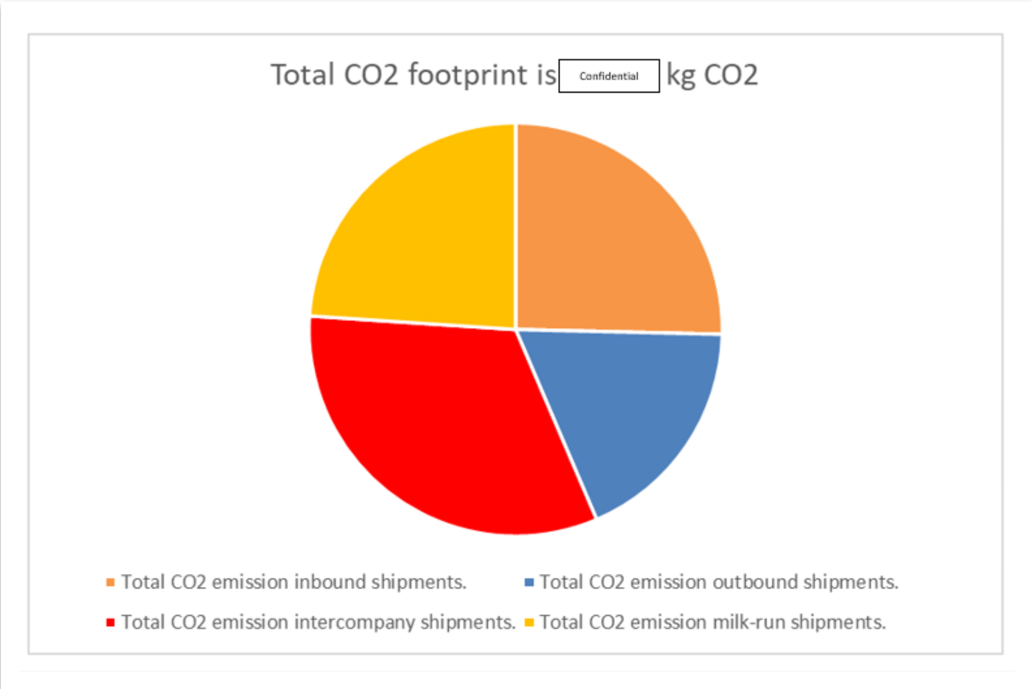

Figure 6.2 Total CO_2 footprint milk-run alternative.

Average total lead time

The milk-run alternative has almost no impact on the average total lead time, since the same number of items go through the warehouses (for storage) and the intercompany shipment sizes remain the same. The supplier related lead times reduce slightly (on average) for the milk-run shipments, because the transportation time is lower for certain shipments. This leads to an average lead time reduction of 0.3%. The total lead time might even be lower due to the milk-run characteristics since the suppliers can deliver more frequently because "milk-run truck" comes along anyway, see Section 5.4. More frequent deliveries leads in general to lead time reduction. However, our model and formulas do not take this potential lead time reduction into account. We therefore do not know how and how much the more frequent deliveries affect the average total lead time.

Transportation costs

Milk-runs have a big impact on the total transportation costs, since multiple shipments are combined. This is confirmed by a total transportation costs reduction of 24.2%. This reduction is a result of one milk-run instead of multiple separate shipments, see section 5.4.

Handling costs

This alternative has no (measurable) impact on the total handling costs. The material flow volume remains the same, since the milk-run shipments still go through the warehouses in The Netherlands. The associated handlings and the related handling costs remain reasonably the same.

6.1.3. Direct Shipping with Milk-Run(s) (to Leszno).

This alternative affects each KPI. It combines the advantages, and disadvantage, of the direct shipping and milk-run alternatives. The specific configuration is given in section 5.4.

CO2 footprint

The shipments associated to both shipment types, direct deliveries and milk-runs, are shipped directly towards the production site in Leszno. The associated transportation distances are therefore significantly lower than the current situation. This distance reduction leads to a CO2 footprint reduction. The total CO2 footprint drops with 54.6%, which is a substantial reduction.

Average total lead time

The average overall total lead time will be reduced as well, since the associated shipments are shipped directly towards the production site in Leszno. These shipments have therefore no consolidation and intercompany lead time. The supplier related lead time of the shipments will be lower as well, because the transportation times will be lower. This is a consequence of the shipments towards Leszno instead The Netherlands. The average total lead time will be reduced with 8.0%.

Transportation costs

The transportation costs will drop as well. The already mentioned distance reduction and milk-run characteristics are the main cause of this reduction. Multiple separate shipments will be combined into consolidated milk-run trucks, which can ship the items more efficient. The total transportation costs reduction equals 30.7%.

Handling costs

The handling costs are significantly lower since less shipments go through the warehouses in The Netherlands. So less items have to be handled and stored in those warehouses before they are sent towards Leszno. The associated handling costs reduction is 25,0%. The handling costs are visualized in Figure 6.3. The costs are visualized for the different storage zones separately.

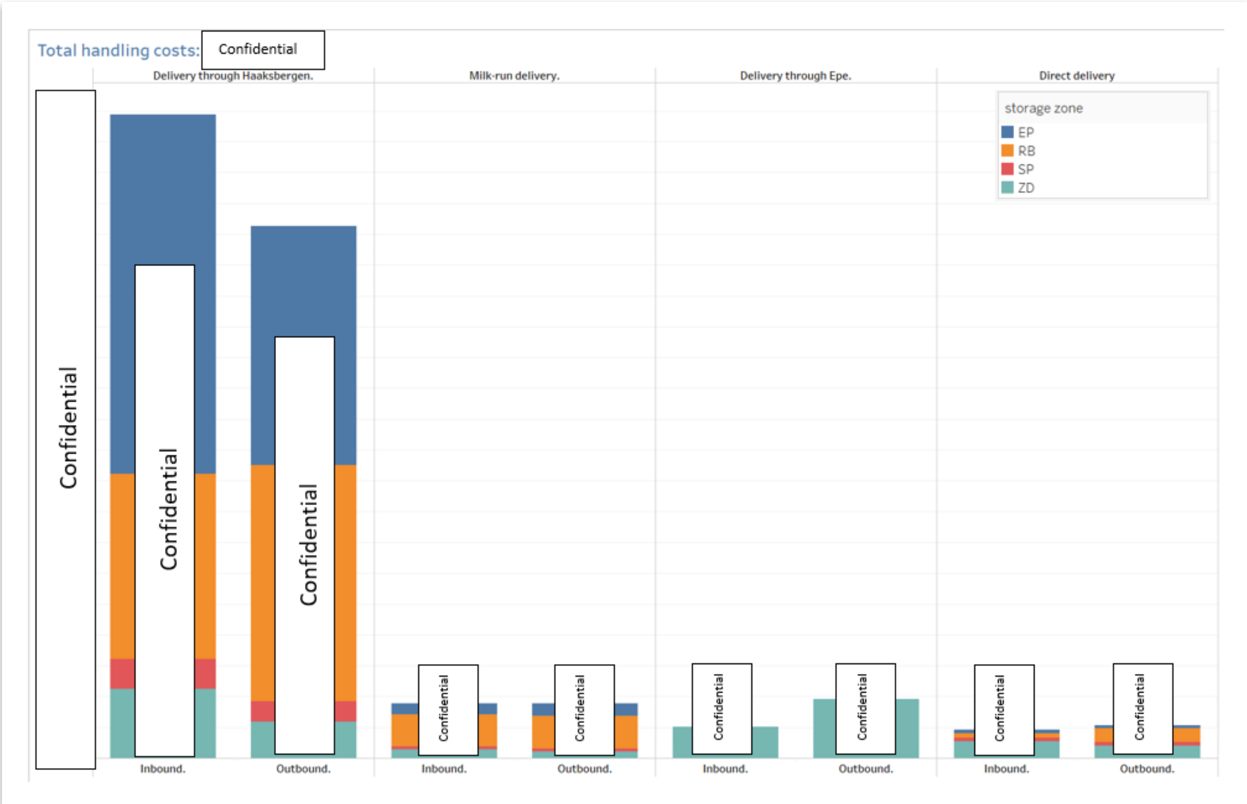

Figure 6.3 Handling costs direct shipping with milk-runs.

6.1.4. Cross Dock Warehouse.

This alternative affects each KPI as well. The cross-dock warehouse consolidates the incoming shipments into FTL shipments which are sent towards the warehouses in The Netherlands. The specific characteristics are given Section 5.4.

CO2 footprint

The total transportation distance is significantly lower than the current transportation distances due to the consolidated FTL shipments between the cross-dock warehouse and the warehouses in The Netherlands. This leads to a CO_2 footprint reduction of 39.7%.

Average total lead time

This alternative has a negative effect on the average total lead time, since the required handlings in the cross-dock DC take some time as well. The same number of items go through the warehouses and the intercompany shipment sizes remain the same. This leads to a higher average total lead time compared to the current situation. The average total lead time increase equals 1.0%. The average total lead times related to the multiple material flows are visualized in Figure 6.4. The handling time of the cross-dock DC related activities is included in the (total) consolidation lead time.

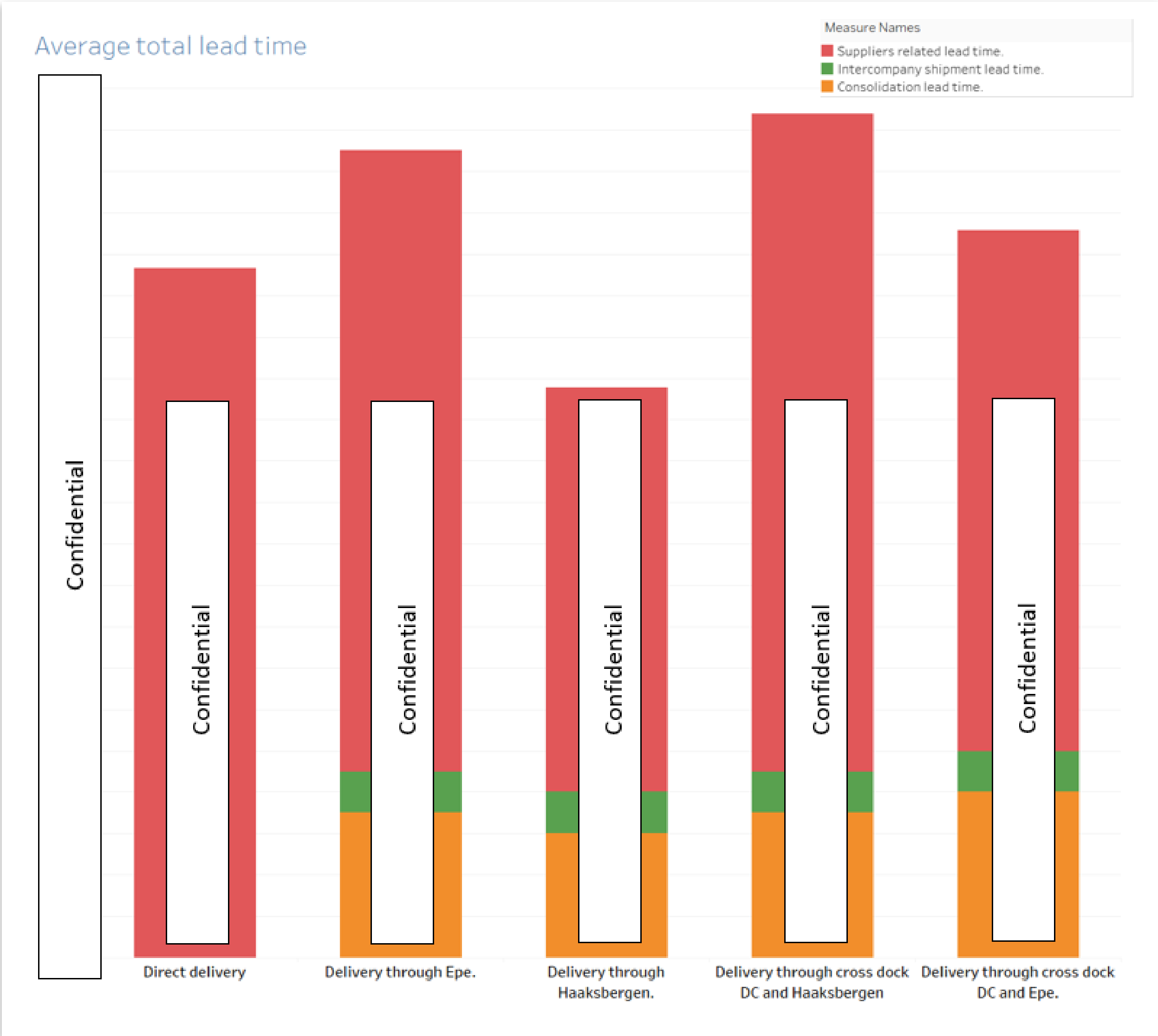

Figure 6.4 Average total lead time cross dock DC.

Transportation costs

The transportation costs are lower compared to the current situation since multiple separate shipments will be combined into consolidated trucks which ship the items from the cross-dock DC towards the warehouses in The Netherlands. These trucks are expected to ship the associated shipments more efficient. This is confirmed by transportation costs reduction of 23.4%.

Handling costs

The total handling costs increase due to the required handlings in the cross-dock DC. The current handling costs associated to the warehouses remain the same as well, since the same number of items go through the warehouses. So there are only additional handling costs associated to the required handlings in the cross-dock DC. The handling costs will therefore increase with 8.0%.

6.1.5. Environmentally Friendly Trucks.

Using environmentally friendly trucks instead of the current conservative trucks might reduce the total CO2 footprint considerably. Another main advantage of this improvement is the fact that it does not require any supply chain network adjustments. So it can be implemented without adjusting the current supply chain configuration. This alternative might be combined with the already mentioned supply chain network alternatives as well. For instance the milk run alternative(s), since using environmentally friendly trucks for the milk-runs would drop the total CO2 footprint even further. They are also suitable for the trips between the cross-dock DC and the two warehouses in The Netherlands. So environmentally friendly trucks can be implemented solely without changing the current material flow configuration. However, this alternative can be combined with other alternatives as well to acquire even more environmental benefits. There are many environmentally friendly truck types, for instance; full electric trucks, hybrid trucks, LNG trucks etc. Each type has its own advantages and disadvantages, so it is important to investigate which environmentally friendly truck type is most suitable. One of the disadvantages, as mentioned in Section 2.4, is the willingness of the suppliers when they are responsible for the used trucks. However, combining this alternative with a milk-run or DC related trips would solve this disadvantage, since the VMI would become responsible for the used trucks in such a situation. So there are multiple (truck related) opportunities for the VMI to take their responsibility regarding the climate change by becoming a green company.

6.1.6. Additive Manufacturing

We already mentioned the prediction of many supply chain professionals: “additive manufacturing will eventually rival the impact of the Henry Ford’s assembly line”. It is therefore of great importance that we examine the additive manufacturing alternative as well. The associated technology is still in a development stage, but it is developing rapidly and is expected to influence the global supply chains significantly. The limited material and size (and therefore product) selection is currently one of the main drawbacks of this alternative. However, the rapid development might solve these drawbacks in the near future. There are, besides the drawbacks, multiple advantages as well. For instance, the waste reduction which is a result of layering technique itself. Another main advantage is the lead time reduction, for small batches, since transportation and warehouse activities are no longer required when items are printed at the production facilities. The used layering technique also leads to more design freedom and product customization. However, the technique is currently restricted to only a limited material and size selection. And it is only attractive for small production batches, since the production time increases rapidly with the number of items. That is also the reason why it is currently efficient and widely used for producing spare parts. We can therefore conclude that it is currently attractive for a specific set of suitable products which are required in low batches, and for which the conventional lead time is extensive. This selection of suitable products might already be extensive enough to make it attractive to use the additive manufacturing technique at the production site in Leszno. It is also a useful technique due to its low lead time, which might be required when some last-minute design changes occur. We strongly recommend the VMI to keep the additive manufacturing technique in mind, since it is expected to develop rapidly. This could lead to high applicability of the technique for the VMI in the near future (Janssen, Blankers, Moolenburg, & Posthumus, 2014).

6.1.7. Performance overview

The table below provides an overview of the alternative performances. The alternative outcomes are compared with the current KPI values to determine the percentage differences. The third alternative seems to be the most attractive alternative based on the KPI values. But we will not draw any conclusions regarding the best alternative based on Table 6.1, since these values are only related to our toy problem. The final conclusions and recommendations should be based on the actual material flow, which will be investigated at the end of this chapter.

Table 6.1 Overview.

Percentage differences per KPI per alternative compared to the current situation.				
KPI	Direct delivery Leszno	Milk-run	Milk-run & direct delivery.	Cross-dock DC
CO2 footprint.	51.5% CO2 reduction	37.8% CO2 reduction	54.6% CO2 reduction	39.7% CO2 reduction
Handling costs.	25.0% cost reduction	No influence	25.0% cost reduction	8.0% cost increase
Average total lead time.	8.9% time reduction	0.3 % time extension	8.0 % time reduction	1.0 % time extension
Transportation costs.	27.6% cost reduction	24.2% cost reduction	30.7% cost reduction	23.4% cost reduction

6.1.8. Dashboards

The performance dashboards of the supply chain network alternatives are given below. We do not describe the specific outcomes within these sections, since we already examined the outcomes in the Sections 6.1.1. till 6.1.4.

Direct Shipping to Leszno.

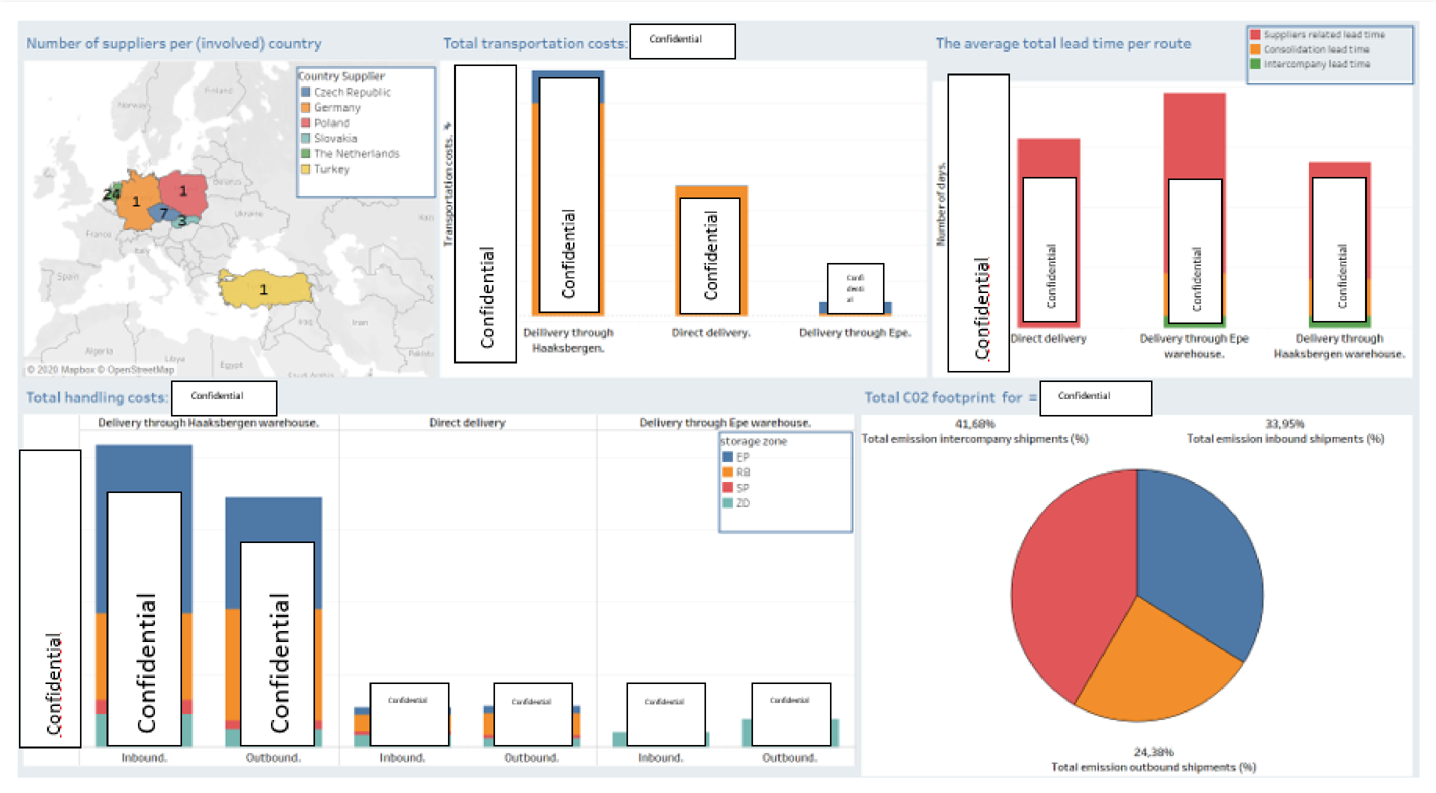

Figure 6.5 Performance dashboard Direct shipping to Leszno.

Milk-run (to Haaksbergen and Epe).

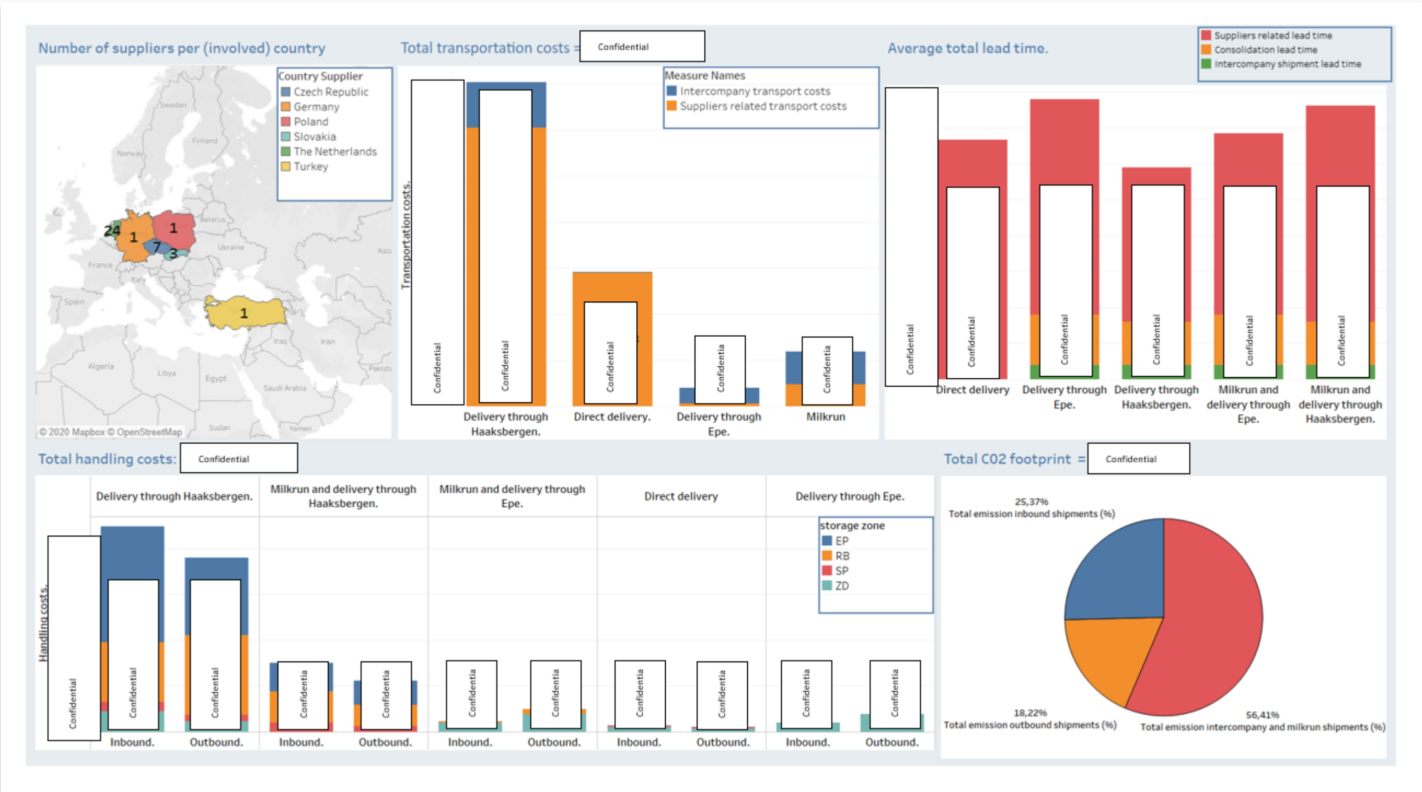

Figure 6.6 Performance dashboard Milk-run.

Direct Shipping with Milk-Run(s) (to Leszno)

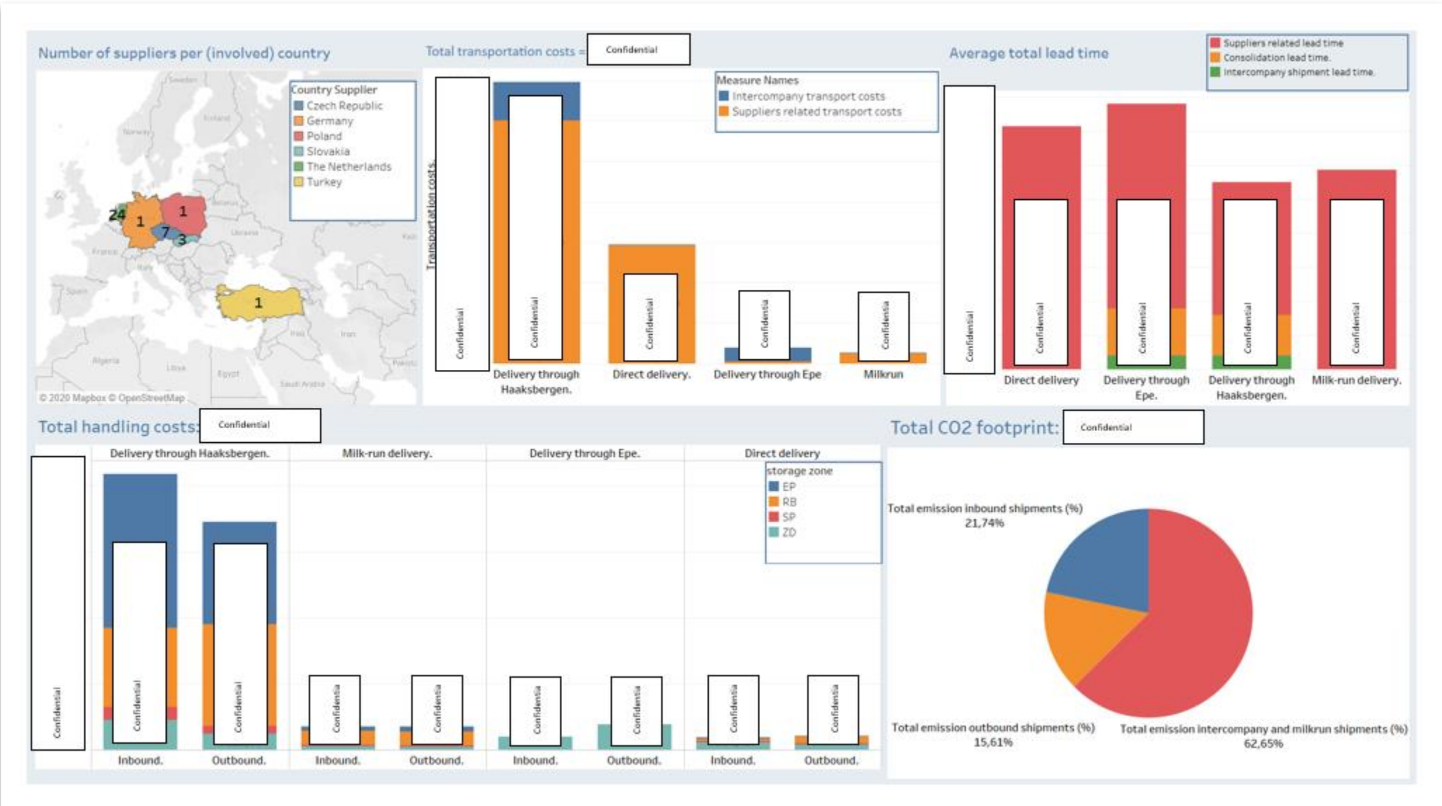

Figure 6.7 Performance dashboard Milk-run to Leszno.

Cross Dock Warehouse.

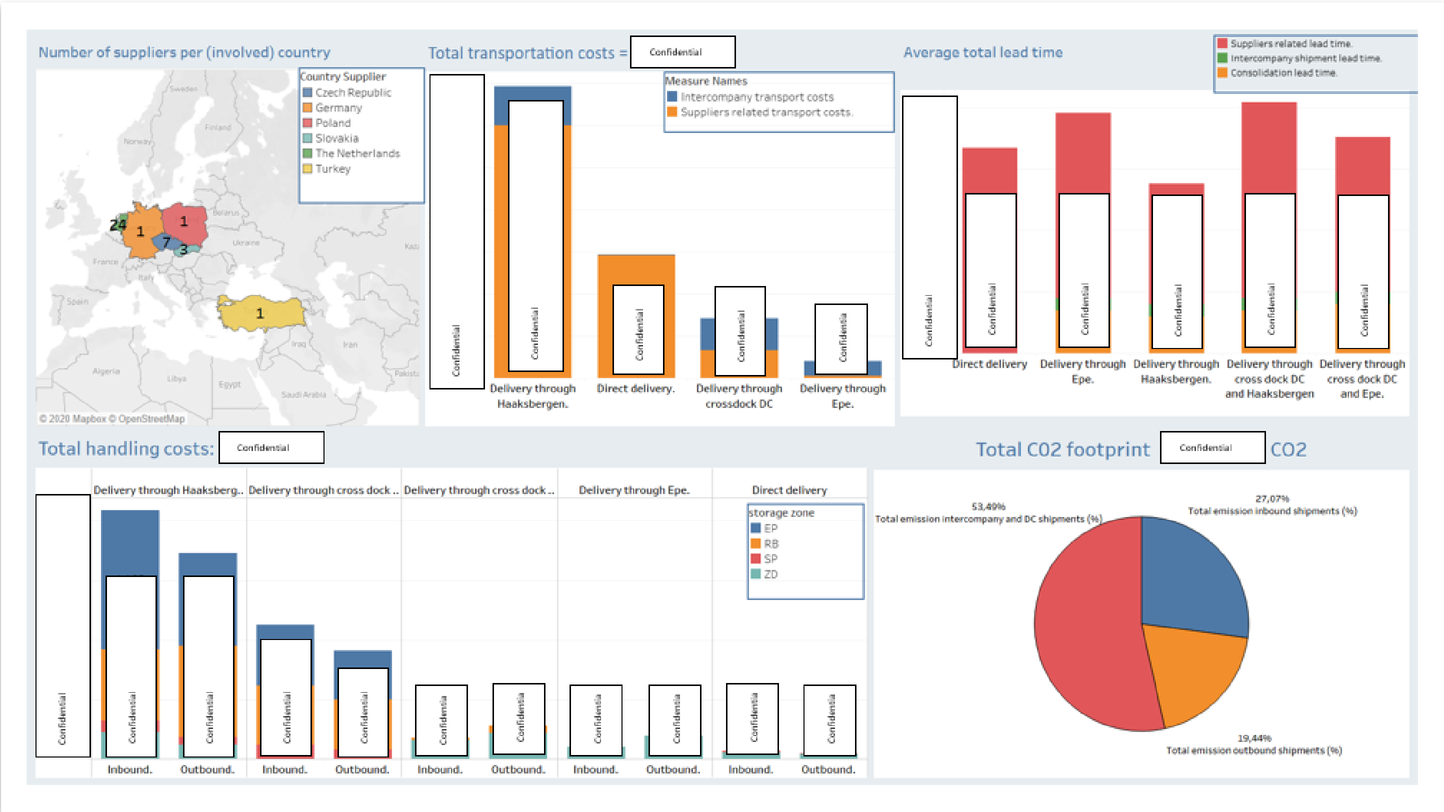

Figure 6.8 Performance dashboard Cross dock warehouse.

6.1.9. Actual material flow towards Leszno

We have visualized the actual material towards Leszno, for multiple time periods, to acquire additional insights regarding the complete material flow towards Leszno. The visualizations are provided in the Figures 6.9 till 6.11. Figure 6.12 visualizes the material flow associated to our toy problem. The material flow of the first half year of 2019 differs significantly compared to the two material flows associated to the two subsequent time periods. This confirms the statements from Section 1.3, since Epe warehouse was in the beginning responsible for most of the Leszno related items. But Haaksbergen warehouse became responsible for the biggest share of Leszno related items over the years. Table 6.2 indicates which percentage of the total supply towards Leszno (in euros) is delivered through Epe, Haaksbergen or direct. The percentages represent the specific share per flow.

Table 6.2 Supply distribution in percentages per warehouse.

	First half year of 2019.	Second half year of 2019.	First half year of 2020.	Toy problem
Epe warehouse.	47.3 %	12.9 %	10.9 %	12.8 %
Haaksbergen warehouse.	43.7 %	71.8 %	72.2 %	71.6 %
Direct delivery.	9.0 %	15.3 %	16.9 %	15.6 %

The percentages confirm the above-mentioned statement, since the number of items delivered through Epe warehouse drops significantly. The table also shows that the supply distribution of the toy problem is almost the same as the supply distributions associated to the second half year of 2019 and the first half year of 2020. The values might seem to be too perfect, but the values are only based on the material flow value. The supply distributions based on the number of order lines do differ between the actual and toy problem related material flow. But we nevertheless conclude that we should use last two time periods for the comparison with our toy problem. The supply distributions are after all almost the same and do provide an indication regarding the specific material flows.

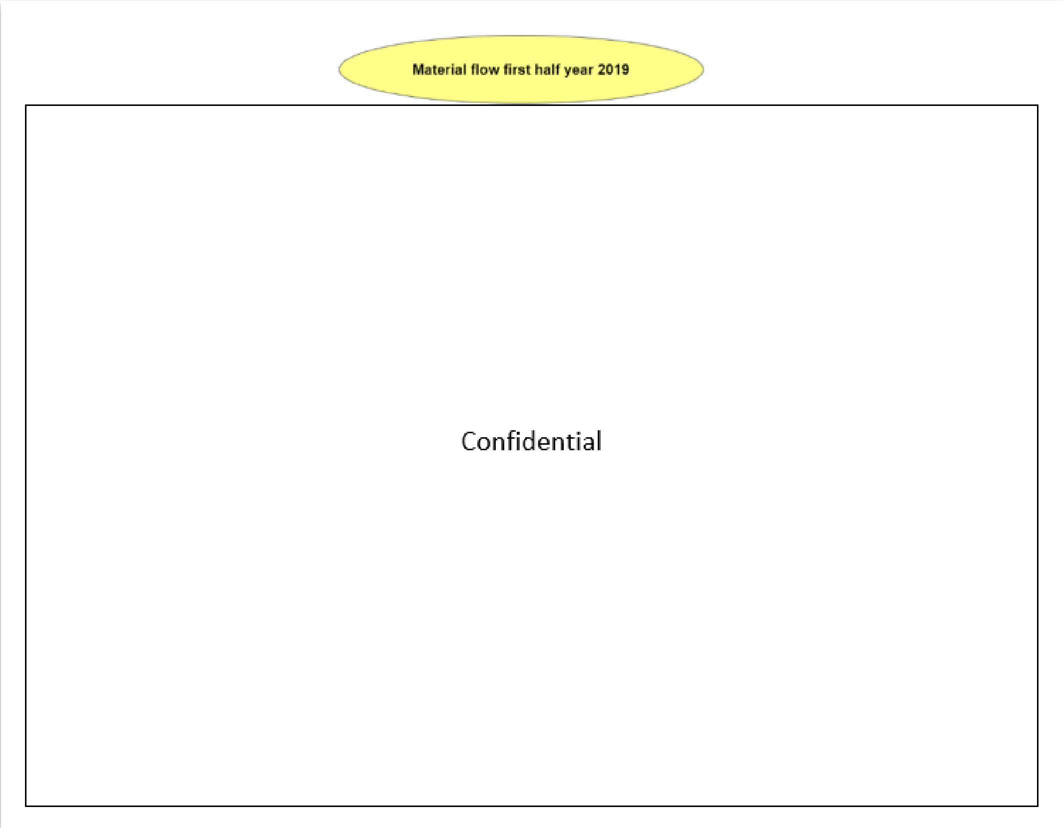

Figure 6.9 Material flow first half year 2019.

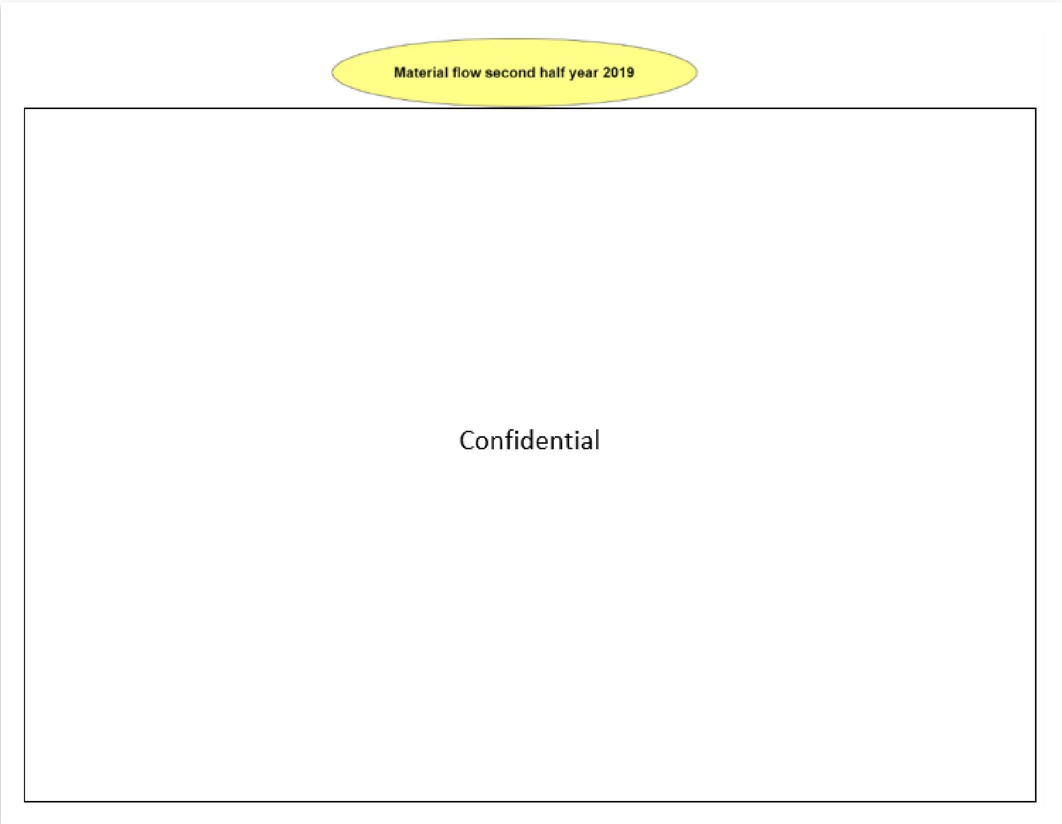

Figure 6.10 Material flow second half year 2019.

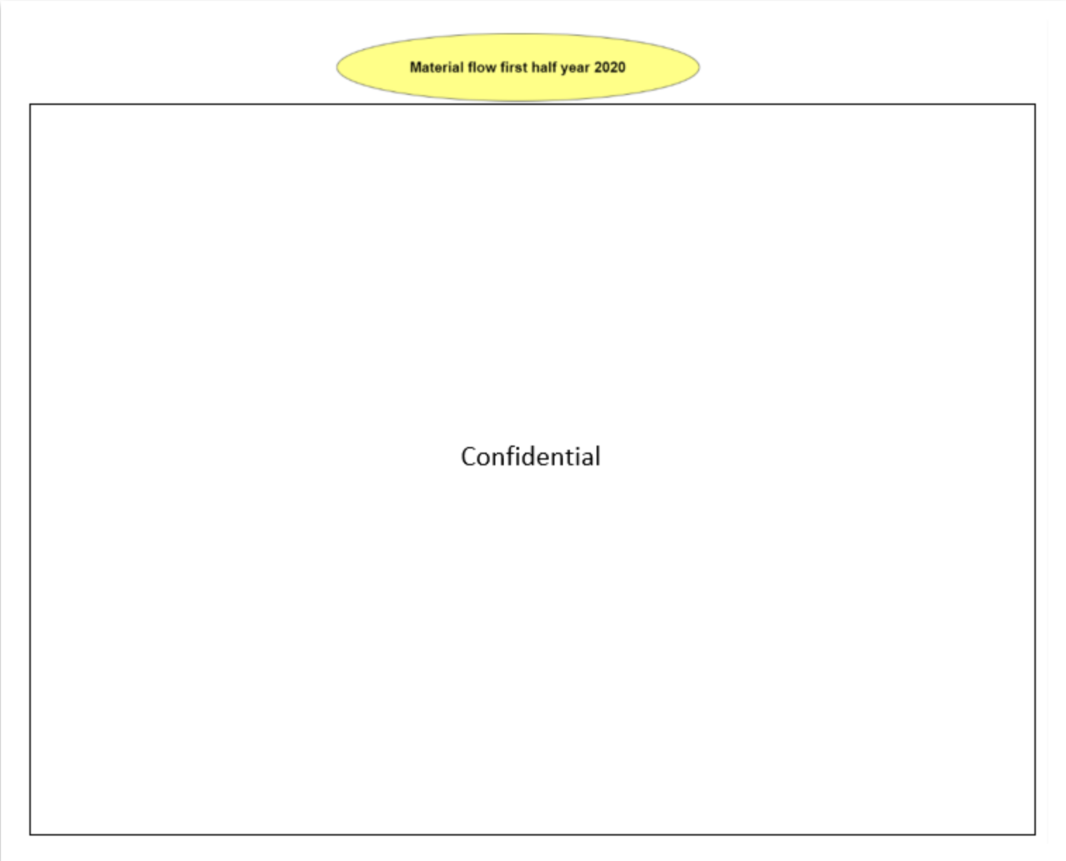

Figure 6.11 Material flow first half year 2020.

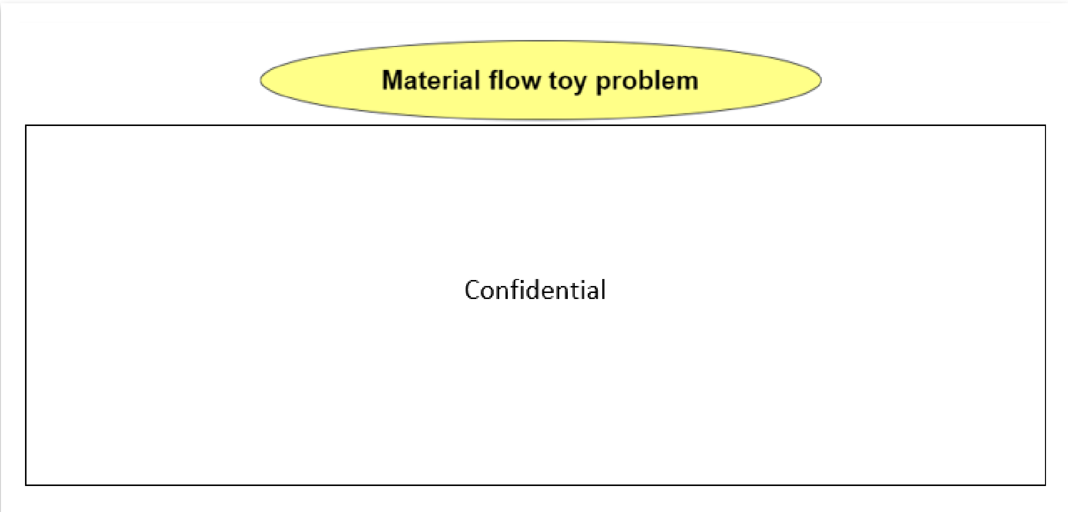

Figure 6.12 Material flow toy problem.

6.2 Current material flow performance related to the actual material flow

We first determine the current material flow performance for the actual material flow by extrapolating the toy problem outcomes. The KPI outcomes are provided subsequently. We will provide a short description regarding the extrapolation approach for each KPI, but this section focusses mostly on the associated outcomes. The specific extrapolation decisions, calculations and approach are provided in Appendix M.

6.2.1. Total CO2 footprint

It is hard to extrapolate the CO2 footprint performance based on the material flow values from Section 6.1.9. We therefore decided to extrapolate the CO2 footprint performance based on the shipment frequencies. The geographic locations of the suppliers have a significant impact on the associated footprint. We therefore use the suppliers associated to the toy problem for the real material flow. The geographic locations associated to the suppliers of the actual material flow are after all unknown. So we will use average values for the truck types, CO2 emissions and shipment distances per supplier type based on the toy problem. These averages are used to determine the total CO2 footprint of the actual material flow.

The total CO2 footprint of the actual material flow equals confidential kg CO2, which is 6.6 times higher than the footprint related to the toy problem. This is a result of the increased intercompany and supplier related shipment frequencies. The ratio between the supplier and intercompany related footprints, 28% and 72% respectively, differ only a few percent compared to the toy problem, see Section 4.4. So the used extrapolate technique leads to a correct ratio between the supplier and intercompany related footprints.

6.2.2. Average total lead time

The average total lead time per material flow will only be affected by the supplier related lead times, since the consolidation and intercompany lead times are fixed for each material flow, see Section 4.4. The supplier related lead times are unknown for the "non toy problem suppliers". So the average total lead time per material flow will remain the same since only the number of items per material flow changes. This has obviously no impact on the average lead time per material flow. But the average overall total lead time does change, since the number of order lines and the associated order line distribution is different for the actual material flow. The average overall total lead time does increase with 0.84% to confidential , which is still a small adjustment. So the order line distribution of the actual material flow is comparable to the order line distribution related to the toy problem.

6.2.3. Total transportation costs

We extrapolate the total transportation costs based on the total value of the material flow which is given in Section 6.1.9, since the supplier related transportation costs are directly influenced by the value of the associated items. The specific supplier related transportation percentages are determined by the item dimensions, which are unknown for the actual material flow. So we will approximate these dimensions based on the associated storage zone distribution from the toy problem. VMIs transportation department provided the required data to determine the transportation costs of the intercompany shipments. The total transportation costs of the actual material flow are significantly higher than the transportation costs associated to the toy problem (factor 191), confidential instead of confidential . This is a consequence of the material flow volume. The ratio between the supplier and intercompany related shipment costs (85/15) are comparable to the toy problem ratio (87/13). This supports the used method.

6.2.4. Total handling costs

We extrapolate the total handling costs based on the number of order lines per warehouse, since the handling costs are determined per order line as well. So we again use the storage zone distribution related to the toy problem. The total handling costs related to the actual material flow (confidential) are significantly higher than the toy problem related handling costs (factor 226) (confidential). This is a consequence of the increased number of order lines. We again verified the ratios of the actual material flow with the ratios of the toy problem, see Section 6.1.9. These ratios do support the used method, since the inbound/outbound ratio of the actual material flow approaches the toy problem ratio.

6.2.5. KPI outcomes overview

Table 6.3 provides a performance overview for both, the toy problem related material flow and the actual material flow. The differences are significant, which is a consequence of the increased material flow volume which is visualized in Section 6.1.9.

Table 6.3 KPI outcomes for both material flow types.

KPI outcomes for both material flow types	Toy problem	Actual material flow	Growth factor
CO_2 footprint	Confidential		6.6
Average total lead time*			1.01
Total transportation costs			191
Total handling costs			226

* The average total lead time per material flow remains the same.

6.3 Alternative performances related to the selected scenarios

This section provides the material flow network alternative outcomes for multiple scenarios. The current situation will be the baseline scenario, the related outcomes are given in Section 6.2.1. The outcomes for the selected scenarios are given in Section 6.2.2. We do not provide the specific approach and calculations since we already provided the required approach for measuring the alternative effects on the material flow in Section 6.1. The used approach and measurements for determining the alternative performances associated to the selected scenarios are given in Appendix N.

6.3.1. Alternative performances related to current situation

The alternative performances compared to the current situation, the so-called baseline scenario, are provided in Table 6.4. We compared the KPI outcomes of the alternatives with the KPI values of the actual material flow in order to determine the differences. The bold table values indicate the best performing alternative per KPI.

Table 6.4 Alternative performances compared to the current situation.

Savings per alternative per KPI	Direct delivery	Milk-run	Direct delivery with milk-run(s)	Cross dock warehouse
CO_2 footprint	51.0%	40.9%	**58.1%**	44.9%
Average overall lead time	**8.9%**	0.3%	8.0%	-1.0%
Total transportation costs	25.2%	23.6%	**28.2%**	22.9%
Total handling costs	**25.0%**	0%	**25.0%**	-8.0%

The table values reveal that the direct delivery with milk-run(s) alternative performs best on most KPIs. The cross-dock warehouse performs worst in terms of cost savings. The interviews held with the stakeholders reveal that the cost related KPIs are most crucial. We should therefore select an alternative which leads to the biggest cost savings. But we can not select the best alternative based on Table 6.4, since we should take more alternative characteristics into account. For example, the sustainability of the alternatives during potential market changes. This will be measured in Section 6.2.2. Additionally, we should consider the implementation costs as well, since these costs might differ significantly per alternative. We will take all those aspects in mind during the final conclusions regarding the alternative recommendation in Section 6.5.

6.3.2. Alternative performances related to selected scenarios

We have selected the following four potential scenarios during meetings with the supervisors: 50% increase, 50% decrease, 100% increase and 75% decrease of the actual material flow towards Leszno. We have decided to determine the consequences of the scenarios for the current situation fist. We will use those outcomes to determine the alternative performances for the scenarios. This seems to be the most efficient method, since we already know the alternative savings (%) for the current situation, see Section 6.3.1. So we should be able to determine the alternative performances, given the scenarios, directly once the current situation is analyzed for the selected scenarios. Section 6.3.2.2 provides an overview of the alternative performances given the scenarios. The outcomes are provided in Table 6.5.

6.3.2.1. Scenario consequences

The descriptions regarding the measurement method for determining the scenario effects are given for each KPI separately below. We only provide a short description of the used approach. The specific measurement approach, calculations and intermediate outcomes are provided in Appendix O.

Total CO2 footprint

We assume that it is more beneficial for a supplier to drive with a bigger truck instead of increasing the shipment frequency. The specific truck type changes are provided in Appendix O. We assume, for the same reason, that a material flow decrease will lower the shipment frequencies, since we assume that a shipment frequency reduction is more beneficial than a smaller truck type. The VMI does already use a big truck for the intercompany shipments. So the material flow adjustments will only affect the shipment frequency of the intercompany shipments.

Average total lead time

The average overall lead time will not be affected by a linear material flow increase or decrease. The average values will remain the same as long as the warehouse distribution does not change. Remark, it is assumed that the warehouses are able to handle the increased material flow within the same number of days.

Total transportation costs

The supplier related transportation costs are directly linked to the total value of the material flow. We can therefore adjust the material flow values based on the scenarios directly. We use the measurement method from Section 6.2.3 to determine the total transportation costs. The intercompany shipment costs are linked to the related volume. So we will adjust the number of trucks based on the volume changes caused by the scenarios.

Total handling costs

The total handling costs are related to the total number of order lines per warehouse are dependent on the associated storage zones. We assume that the scenarios have no effect on the storage zone distribution. We therefore determine the total number of order lines per warehouse for scenario based on the associated percentages.

6.3.2.2. Alternative performances given the scenarios

We used the above mentioned the measurement methods to determine the alternative performances for the given scenarios. We decided to summarize the outcomes in one main table, since we used the exact same methods. The outcomes are visualized as well in the Figures 6.14 till 6.16.

Table 6.5 Alternative outcomes per KPI per scenario.

CO2 footprint savings per alternative per scenario	Direct delivery	Milk-run	Direct delivery with milk-run(s)	Cross dock warehouse
75% decrease	Confidential			
50% decrease				
Current situation				
50% increase				
100% increase				

Lead time savings per alternative per scenario	Direct delivery	Milk-run	Direct delivery with milk-run(s)	Cross dock warehouse
75% decrease	Confidential			
50% decrease				
Current situation				
50% increase				
100% increase				

Transportation costs savings per alternative per scenario	Direct delivery	Milk-run	Direct delivery with milk-run(s)	Cross dock warehouse
75% decrease	Confidential			
50% decrease				
Current situation				
50% increase				
100% increase				

Handling costs savings per alternative per scenario	Direct delivery	Milk-run	Direct delivery with milk-run(s)	Cross dock warehouse
75% decrease	Confidential			
50% decrease				
Current situation				
50% increase				
100% increase				

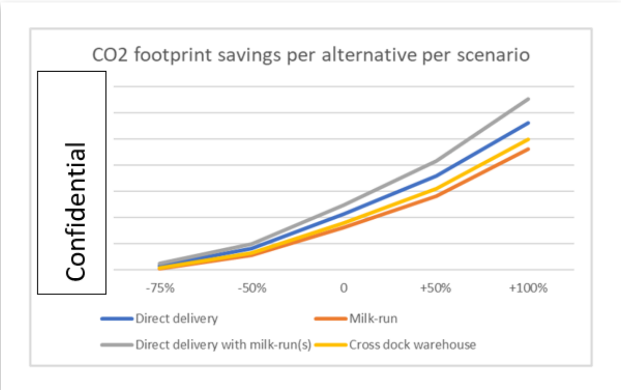

Figure 6.14 CO2 footprint savings per alternative per scenario.

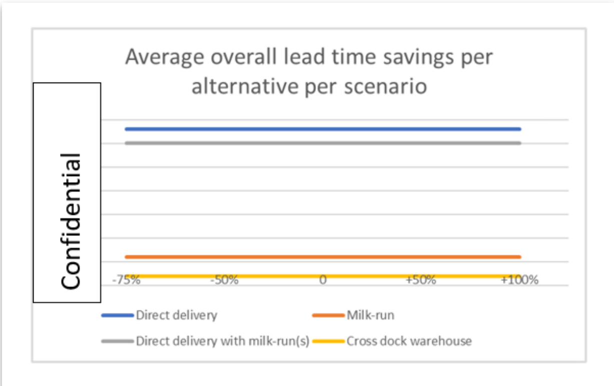

Figure 6.13 Average overall lead time savings per alternative per scenario.

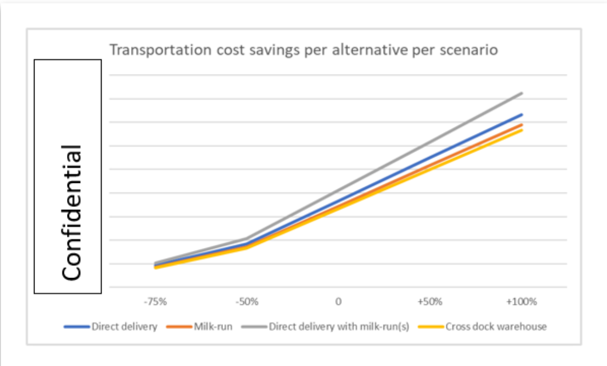

Figure 6.16 Transportation cost savings per alternative per scenario.

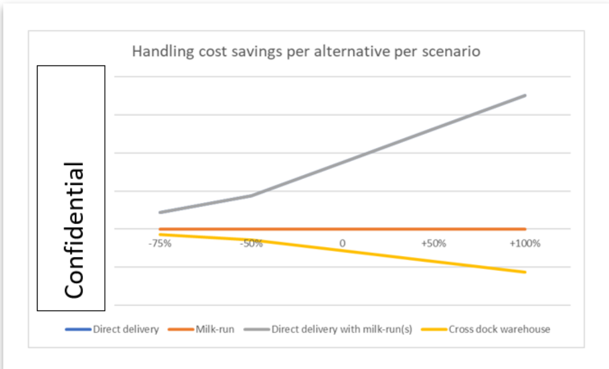

Figure 6.15 Handling cost savings per alternative per scenario.

The outcomes provided in the table and figures above do confirm the expectations regarding the alternative performances, since they are comparable to the toy problem outcomes from Section 6.1. We will analyze the outcomes for each KPI separately.

CO2 footprint

Each alternative leads to a significant CO2 emission saving. However, the specific savings related to the alternatives do differ considerably, see Table 6.4. The difference between the biggest and the smallest saving is for instance Confidential kg CO2. The sequence from the best towards the worst performing alternative is as follows:

- Direct delivery with milk-runs
- Direct delivery towards Leszno
- Cross-dock warehouse
- Milk run

The scenarios have a big impact on the alternative savings, see Figure 6.14. Table 6.4 reveals that both direct delivery alternatives perform significantly better than the remaining alternatives. The milk-run alternative leads to the lowest emission saving, but the associated implementation costs are significantly lower compared to the other three better performing alternatives, see Section 2.4.1. So there is clear tradeoff between the investment costs and the CO2 footprint optimization. We already mentioned that the alternatives which lead to the biggest cost savings are preferred by the stakeholders. So the milk-run alternative might become the most attractive alternative if the cost savings related to the remaining alternatives do not outweigh the investment costs, even though it performs worst in terms of CO2 emission.

Average overall lead time

The lead time savings provided in Table 6.14 confirm our expectations, since both direct delivery alternatives perform better than the remaining alternatives. This is a logical consequence of the direct delivery characteristics, see Section 5.4. The cross-dock warehouse causes a lead time increase due to the additional handlings. We therefore conclude that the direct delivery alternatives have the biggest (positive) effect on the average overall lead time. The milk-run alternative has almost no impact on the average overall lead time. This leads to the following performance sequence:

- Direct delivery with milk-runs
- Direct delivery towards Leszno
- Milk run
- Cross-dock warehouse

The scenarios have no impact on the alternatives, since we only take the average lead times into account, see Section 6.2.2.

Transportation costs
Analyzing the transportation costs savings from Table 6.4 reveals that the direct delivery with milk-run(s) alternative leads to the biggest savings. The other direct delivery alternative leads to high savings as well. The savings related to the other alternatives are still substantial but are less than the alternatives with the direct delivery aspect. However, we should distinguish between the alternatives which require significant investment costs and the alternatives that can be implemented without major investments. The following three alternatives require such investment costs; direct delivery, direct delivery with milk-run(s) and the cross-dock warehouse, see Section 2.4.1. These alternatives are only interesting and beneficial if the associated savings outweigh the required investment costs. The milk-run alternative does not require any considerable investments. That is a major advantage compared to the other alternatives which do require such investments. We can not select the best alternative based on the transportation costs solely, since we should first analyze all KPI outcomes. Especially the cost related outcomes, since the stakeholders declared during interviews that the cost related KPIs are most crucial. So we will combine all cost savings to determine whether those savings might outweigh the required investments. This will be done in Section 6.5.

Handling costs
The milk-run alternative has no impact on the handling costs. This is a logical consequence of the alternative characteristics, since the same number of order lines go through the Dutch warehouses. This confirms the observation from Section 6.1.2. The cross-dock warehouse performs even worse, since it has a negative effect on the total handling costs, see Table 6.4. The remaining alternatives which introduce direct shipment aspects lead to the same handling cost savings. This is an obvious result of the associated alternative characteristics which are elucidated in the Sections 6.1.1 and 6.1.3.

We have now analyzed and collect all the alternative outcomes and effects. We will combine these findings in Section 6.5. to compose a clear alternative recommendation for the VMI. We first execute some sensitivity analyses to investigate which parameters might influence the sustainability of the alternatives.

6.4 Sensitivity analysis

We have performed multiple sensitivity analyses to acquire insights about the influence of the used parameter values on the sustainability of the alternatives. We first selected for each KPI a parameter which is expected to affect the outcomes the most. We used both the formulas and KPI outcomes to select those parameters. The sensitivity analyses are provided below. The KPIs are examined separately.

CO2 footprint
We will determine the influence of the CO2 emission factors, since the acquired values are theoretical values provided within the literature. So these values might differ (slightly) for this specific supply chain. We have measured the influence (%) of the modifications on the savings associated to each alternative. The outcomes of the analysis are provided within Table 6.6. A negative percentage indicates a reduction in the associated savings.

Table 6.6 Sensitivity analysis CO2 emission factors

Modification	Direct delivery	Milk-run	Direct delivery with milk-run(s)	Cross-dock DC
10% decrease	-10.0%	-11.4%	-10.5%	-11.5%
5% decrease	-5.0%	-5.7%	-5.3%	-5.7%
5% increase	+5.0%	+5.7%	+5.3%	+5.7%
10% increase	+10.0%	+11.4%	+10.5%	+11.5%

The table values reveal that the CO_2 emission factors have a significant influence on the alternative performances. The associated relation is near linear. The values also reveal that lower CO_2 emission factors (per kilometer) lead to less savings. This makes sense, since distance reductions become less beneficial. It is therefore of great importance that the CO_2 emission factors are accurate.

Average total Lead time
The used values for determining the average total lead time are fixed and supplier related. These values are based on the provided data. The provided data is assumed to be correct. So we will not perform a sensitivity analysis for the average total lead time KPI.

Total transportation costs
We will perform a sensitivity analysis on the used cost prices percentages which are used to determine the transportation costs. Table 6.7 provides the effects on the alternative savings. We have used a large modification interval, since the cost related KPIs are eventually decisive.

Table 6.7 Sensitivity analysis cost price percentages.

Modification	Direct delivery	Milk-run	Direct delivery with milk-run(s)	Cross-dock DC
50% decrease	-41.7%	-40.0%	-41.4%	-40.1%
25% decrease	-20.9%	-20%	-20.7%	-20.0%
5% decrease	-4.2%	-4.0%	-4.1%	-4.0%
5% increase	+4.2%	+4.0%	+4.1%	+4.0%
25% increase	+20.9%	+20%	+20.7%	+20.0%
50% increase	+41.7%	+40.0%	+41.4%	+40.1%

The table values reveal that the cost price modifications have a significant influence on the alternative performances. The given outcomes can be clarified easily, since the savings will drop when transportation becomes cheaper. We will take this observation into account during the alternative recommendation.

Total handling costs
We have used a sensitivity analysis to determine the influence of the acquired handling costs. We therefore adjusted the handling costs for each facility equally to determine the effects of an overall handling costs increase or decrease. The handling costs were provided by warehouse representatives and are expected to be accurate, so we investigated relatively small modifications. The associated effects are linear. So increasing the handling costs with five percent will increase the alternative savings with five percent as well. It is therefore of great importance that the handling costs are accurate.

6.5 Conclusions

The final alternative recommendation will be cost based, since the stakeholders declared that the cost related KPIs are decisive. We will therefore combine the outcomes of both cost related KPIs to determine the total cost savings per alternative. This will be done for each alternative separately. The two remaining KPIs will become decisive when the cost savings of the alternatives are equal. The required investment costs are unknown, but we can approximate the maximum investment costs based on the return on investments.

Direct delivery
Combining the transportation and handling costs savings gives the total potential cost saving per year, which is equals Confidential.

We do not know the required investment, but we do know that an investment below the yearly savings will be earned back within one year. The savings for the worst-case scenario are 4 times lower compared to the current situation, so the required number years to earn back the investment are 4 times higher. The savings for the best-case scenario are 2 times higher, so the required number of years are 2 times lower. Table 6.5 shows the number of years which are required to earn back the investment for the current, worst-case, and best-case scenario.

Table 6.8 Required number of years to earn back investment.

Investment costs	Current situation	Worst case -75%	Best case +100%
<= yearly saving	Within 1 year.	Within 4 years	Within 0.5 year
> yearly savings <= 2*yearly savings	Within 2 years.	Within 8 years	Within 1 year
> 2*yearly savings <= 3*yearly savings	Within 3 years.	Within 12 years	Within 1.5 year
> 3*yearly savings <= 4*yearly savings	Within 4 years.	Within 16 years	Within 2 years

Table 6.5 shows that an investment of Confidential will be earned back within 4 years given the current situation. But a material flow decrease of 75%, the so-called worst-case scenario, requires 16 years to earn back the investment, which is an extensive increase. The best-case scenario on the hand requires only 2 years to earn back an investment of Confidential. We therefore conclude that the direct delivery alternative has a high potential in terms of cost savings if the current material flow does not decrease drastically. But we should keep in mind that the cost price percentages have a big impact on the savings, since the yearly savings will drop with 20.9% when the cost price percentages decrease with 25 percent. This would lower the values provided in the first column from Table 6.9. The handling costs have a big impact as well, see Section 6.4. These should be kept in mind as well.

Milk-run
A milk-run does not require serious investment costs. So the savings can be earned directly. The savings are on the other hand lower. The total cost savings are Confidential per year given the current situation. The savings associated to the worst-case and best-case scenario are Confidential and Confidential consecutively. We therefore conclude that the milk-run alternative might be a very interesting alternative if the VMI does not want to carry out a major investment. But we should mention again that the savings are strongly affected by the cost price percentages, since the yearly savings will drop with 20% when the cost price percentages decrease with 25 percent.

Direct delivery with milk-run(s)
This alternative is similar to the first alternative in terms of investment, since it also requires an additional warehouse. But this alternative leads to bigger savings, around Confidential per year. We again, do not know the associated investment costs. We therefore constructed a table which is comparable to Table 6.5. The consequences of the scenarios are also comparable to the first alternative. Table 6.6 reveals the number of years which are required to earn back the investment for the current, worst-case, and best-case scenario.

Table 6.9 Required number of years to earn back investment.

Investment costs	Current situation	Worst case -75%	Best case +100%
<= yearly saving	Within 1 year.	Within 4 years	Within 0.5 year
> yearly savings <= 2*yearly savings	Within 2 years.	Within 8 years	Within 1 year
> 2*yearly savings <= 3*yearly savings	Within 3 years.	Within 12 years	Within 1.5 year
> 3*yearly savings <= 4*yearly savings	Within 4 years.	Within 16 years	Within 2 years

The table on the previous page reveals that an investment of Confidential will be earned back within 4 years given the current situation. But the table also reveals that the scenarios have a big impact on the savings. The investment of the associated milk-run is expected to be minimal, see Section 2.4.1. We therefore conclude that this alternative has even a bigger potential than the directly delivery alternative. In addition, the alternative performs best in terms of footprint and lead time savings. However, we should mention again that the savings are strongly affected by both the cost price percentages and the specific handling costs, see Section 6.4.

Cross dock DC

The savings associated to this alternative are by far the lowest, around Confidential per year, and the alternative requires a serious investment. We will not analyze this alternative further, since the associated savings are even lower than an alternative which does not require any investments.

We recommend the VMI two alternatives which differ based on the required investment, since the directly delivery with milk-run(s) alternative does require a serious investment and the milk-run alternative does not. But the yearly savings associated to the direct delivery alternative are considerably higher than the milk-run savings. In addition, the savings in terms of CO_2 emission and lead time are higher as well. The related CO_2 emission savings are 41.5% higher and it reduces the lead time with Confidential instead of Confidential. So the choice for the “best” alternative depends on VMIs willingness to invest. Our recommendation regarding the best material flow alternative is therefore twofold:

“We recommend the directly delivery with milk-run(s) alternative if the VMI is willing to do a serious investment, since this alternative has the biggest potential. But we would recommend the milk-run alternative if the VMI is not willing to invest, since the milk-run alternative does not require a major investment.”

We also recommend the VMI to investigate the implementation of environmentally friendly trucks, since they have the potential to reduce the CO_2 footprint even further. The additive manufacturing technique might improve the supply chain performance as well, since it is developing rapidly and is expected to influence the global supply chains significantly. This could lead to high applicability of the technique for the VMI in the near future.

We have performed multiple sensitivity analyses. The associated outcomes are provided in Section 2.4. The analyses have demonstrated that specific parameters and variables have a significant influence on the alternative savings. We therefore recommend the VMI to perform a sound research to verify whether the used values are correct and accurate.

7. Final conclusions and recommendation

This chapter provides an overview of the final conclusions and recommendation. The aspects that require further research will be mentioned as well.

7.1 Final conclusions

We composed the following main research question for this study:

"What are promising alternatives given the material flow towards Leszno for multiple scenarios?"

We first identified six suitable supply chain drivers with an associated framework for analyzing supply chains in general. We performed a stakeholder analysis to acquire the driver related supply chain information which was used to analyze and clarify the current material flow towards Leszno. We also used a toy problem to acquire additional quantitative information about the current material flow towards Leszno. The specific toy problem characteristics are provided in Section 3.3.4. We concluded that the current material flow is presumably inefficient in multiple ways. These findings were used, besides other resources, during the KPI selection.

Figure 7.1 visualizes the used process steps towards the final KPI selection. The so called S.M.A.R.T. criteria are used for the final KPI selection. We have analyzed each potential KPI based on the S.M.A.R.T. criteria. This resulted in the following final KPI selection:

- Transportation costs
- Average total lead time
- Total CO2 footprint
- Handlings costs

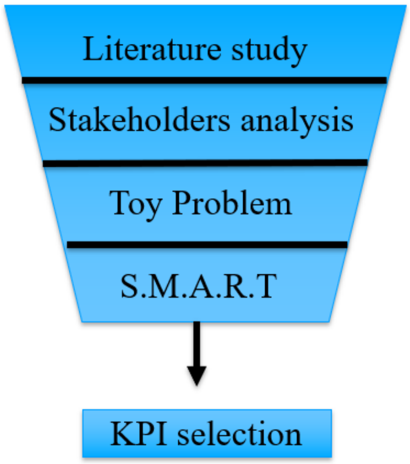

Figure 7.1 KPI selection process.

These KPIs were used to measure the performance of the current material flow towards Leszno. Specific insights regarding the KPI descriptions and the measurement methods are provided in Section 4.2. We constructed a model to analyze and measure the performance of the current material flow towards Leszno. We used the above-mentioned toy problem within our model, since the model would become too complex for the complete material flow towards Leszno. The toy problem was composed in such a way that it represents the material flow towards Leszno accurately. We have analyzed the KPI outcomes for the toy problem. The goal of this analysis was to determine which supply chain aspects affect the material flow performance significantly. We obviously checked whether the aspects could be influenced. This resulted in the following material flow aspects:

- The total shipment distance
- The CO2 emissions of the used trucks
- The Intercompany shipment lead time
- The supplier related lead time
- The consolidation lead time
- Total number of required handlings
- Specific handling costs

We have translated these findings into research directions and topics which were used during the literature study.

The conducted literature study resulted in nine potential alternatives which we divided over two alternative types, the so-called material flow network alternatives, and the additional alternatives. We have analyzed each alternative in more detail to select the most suitable and appropriate alternatives for this research. This resulted in the following selection:

Material flow network alternatives:

5 Direct Shipping to Single Destination.
6 Milk-run.
7 Direct Shipping with Milk-Run(s)
4 Cross Dock Warehouse

Additional alternatives:

7 Environmentally Friendly Trucks.
8 Additive Manufacturing (3d Printing).

We first determined the quantitative KPI outcomes of the supply chain network alternatives within our model and based on our toy problem. The potential value of the two additional alternatives has been considered as well. We then determined the performance of the alternatives for the complete material flow, given the selected scenarios, by extrapolating the toy problem outcomes. We used scenarios to measure the sustainability of the alternatives during market changes. These scenarios were composed during interviews. The alternative performances given the selected scenarios are provided in the Figures 7.2 till 7.6.

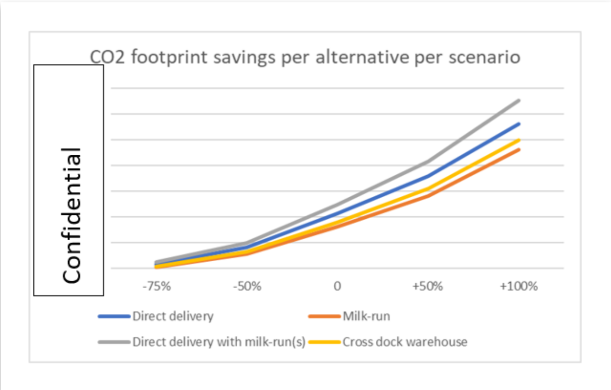

Figure 7.3 CO2 footprint savings per alternative per scenario.

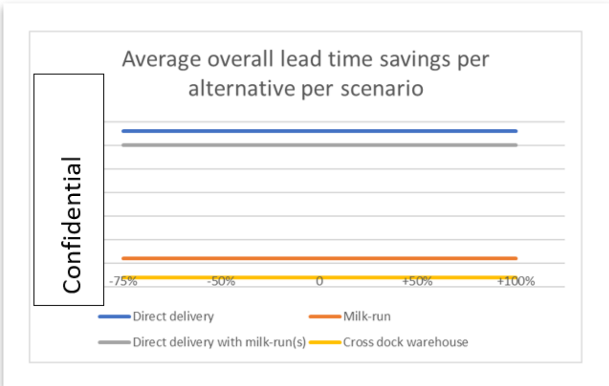

Figure 7.2 Average overall lead time savings per alternative per scenario.

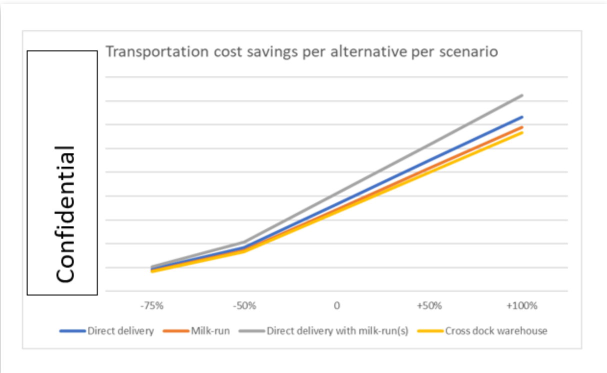

Figure 7.5 Transportation cost savings per alternative per scenario.

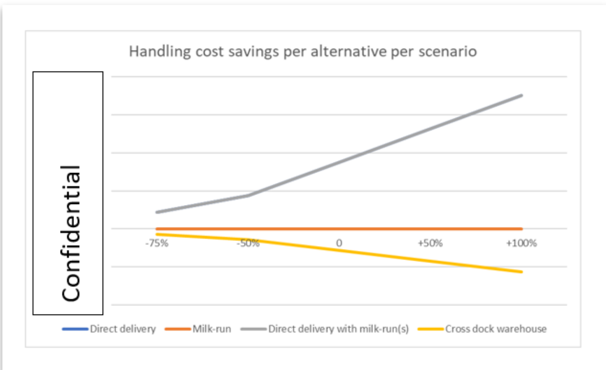

Figure 7.4 Handling cost savings per alternative per scenario.

The specific alternative outcomes have been analyzed for each KPI and scenario separately to determine which alternative should be recommended to the board of the VMI. Our final alternative recommendation is cost based, since the stakeholders declared that the cost related KPIs should be decisive. We divided the alternatives over two types which differ based on the required investment. So the choice for the “best” alternative depends on VMIs willingness to invest. Our recommendation regarding the best material flow alternative is therefore twofold:

“We recommend the directly delivery with milk-run(s) alternative if the VMI is willing to do a serious investment, since this alternative has the biggest potential. But we would recommend the milk-run alternative if the VMI is not willing to invest, since the milk-run alternative does not require a major investment.”

We also recommend the VMI to investigate the implementation of environmentally friendly trucks, since they have the potential to reduce the CO2 emissions even further. The additive manufacturing technique might improve the supply chain performance as well, since it is developing rapidly and is expected to influence the global supply chains significantly. This could lead to a high applicability of the technique for the VMI in the near future.

7.2 Recommendations

In this section, we provide the recommendations related to this research. We first provide a short overview of steps which could be taken during the implementation. The additional recommendations will be provided as well.

Alternative implementation

The above-mentioned recommendation is twofold since the board of the VMI must determine which alternative is to be implemented. That is one of the main reasons, besides the goal of this research, why we did not compose a detailed implementation plan. We simply do not know which alternative is preferred by the board of the VMI. We therefore advise the VMI to perform an additional research related to the implementation of the chosen alternative. This is elucidated in more detail in Section 7.3. That is the reason why we will only provide some general implementation steps below.

Step 1) select alternative

The VMI is advised to start with selecting the preferred improvement alternative. We already revealed that this choice is strongly affected by the willingness to invest. We therefore recommend the VMI to select the milk-run alternative first, since the other proposed alternative requires milk-runs as well. So implementing the milk-run alternative upfront would be a wise initial step, since it can be expended and combined with direct delivery aspects. This should lead to the directly delivery with milk-run(s) alternative which has the biggest improvement potential.

Step 2) perform pilot

We recommend the VMI to start with a milk-run pilot, since a pilot is a perfect opportunity to validate outcomes.

Step 3) implementation of milk-run alternative

The VMI is advised to implement the milk-run alternative when the pilot from step 2 turns out to be successful. We already mentioned that using environmentally friendly trucks for the milk-runs could drop the total CO2 footprint even further. So we recommend the VMI to investigate whether the environmentally friendly trucks should be combined with the milk-run alternative.

Step 4) implementation of direct delivery towards Leszno
The last step comprises the implementation of the direct delivery aspects, since the direct delivery with milk-run(s) alternative has the biggest improvement potential. However, we already revealed that the preference for implementing this alternative depends on VMIs willingness to invest. So it is up to the VMI whether they want to invest in the alternative with the biggest improvement potential.

Additional recommendations
We have performed some sensitivity analyses within in Section 6.4. These analyses have demonstrated that the following parameters have a significant influence on the performance of the alternatives:

- CO2 emission factors.
- Cost price percentages.
- Handling costs.

We already elucidated which strategies and methods we have used to acquire the parameter values. Additionally, we provided our sources within Section 4.4. We are convinced that these sources were proper and objective. We are therefore convinced about the used research for acquiring the parameter values. However, the sensitivity analysis revealed the significant impact of the parameters. So we still recommend the VMI to perform an additional research in order to validate the used parameter values.

7.3 Suggestions for further research

Our research is based on a toy problem which is composed in such a way that it represents the actual material flow towards Leszno accurately. This was in our opinion, given the limited time, the best method to provide correct and accurate insights about the potential of the proposed alternatives. However, it might be valuable to model the complete material flow, since we expect that the associated outcomes would even be more precise and accurate.

We also recommend the VMI to investigate how the recommended alternative(s) should be implemented correctly within the actual material flow. This research did provide some recommendations about the alternative implementations, but these were limited and related to the used toy problem. We therefore did not provide a specific roadmap for the alternative implementation. This has multiple reasons. But the main reason is the goal of the assignment. Namely, a recommendation on a strategic level about the best alternative(s) for the current material flow. So we advise the VMI to perform further research related to the specific implementation of the (chosen) alternative(s). Multiple implementation aspects may be considered. For instance, the specific approach, the required workforce capacity, the associated implementation costs, the responsible departments, the required timeframe, the milestones etc. A sound implementation plan would be a serious contribution to this research.

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7 Appendices

A) Complete process from machine request towards end customer (simplified)

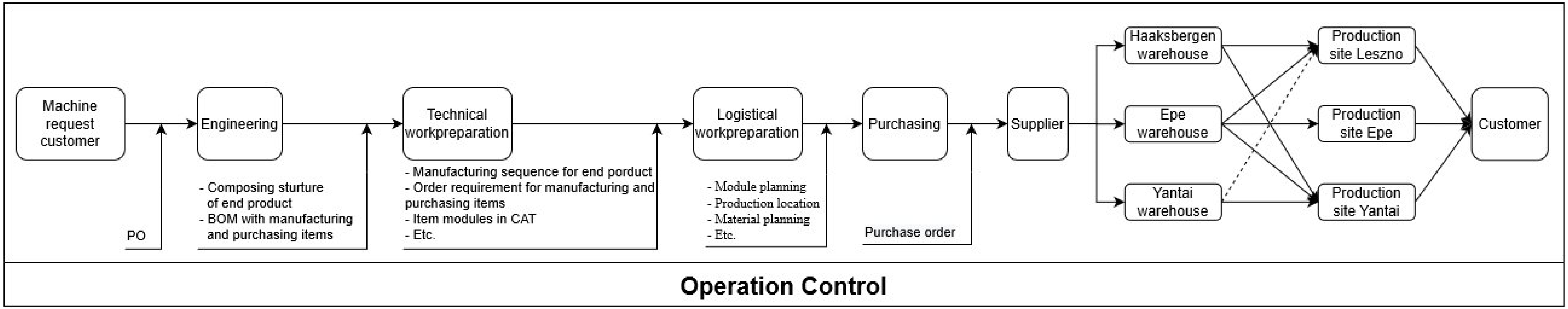


Figure 0.1 Complete process from machine request towards end customer (simplified)

B) Quantitative metrics for the supply chain drivers

All the quantitative metrics for the supply chain drivers which from (Chopra & Meindl, 2013) are listed for each driver separately.

Facilities

Table 0.2 Facility related metrics

Facility related metrics	
Metric	**Description**
Capacity	Maximum amount a facility can process
Utilization	Fraction of capacity that is currently used.
Processing/setup/down/idle time	Fraction of time a facility is processing units, being set up to process , unavailable or idle.
Production cost per unit	Average costs to produce a unit of output. Measured per unit, case or pound.
Quality losses	Fraction of production lost due to defects.
Theoretical flow/cycle time of production	Time required to process a unit without any delay at any stage.
Actual average flow/cycle time	Average actual processing time over a specified duration.
Flow time efficiency	Ratio of theoretical and actual average flow time.
Product variety	Number of products/product families processed in a facility.
Volume contribution of top 20% SKU's/customers	Fraction of total volume processed which comes from top 20% SKUs or customers.
Average production batch size	Average amount produced in each production batch.
Production service level	Fraction of production orders completed on time and in full.

Inventory

Table 0.1 Inventory related metrics

Inventory related metrics	
Metric	**Description**
Cash-to-cash cycle time	High-level metric that includes inventories, accounts payable and receivables.
Average inventory	Measures average amount of inventory carried. Measured in units, days of demand, and financial volume.
Products with more than a specified number of days of inventory.	Identifies the products for which the firm is carrying a high level of inventory.
Average replenishment batch size	Average amount in each replenishment order.
Average safety inventory	Average amount of inventory on hand when a replenishment order arrives.
Seasonal inventory	Difference between the inflow of product and its sales that is purchased solely to deal with anticipated spikes in demand.
Fill rate	Fraction of orders/demand that were met on time from inventory.
Fraction of time out of stock	Fraction of time that a particular SKU had zero inventory.
Obsolete inventory	Fraction of inventory older than a specified obsolescence date.

Transportation

Table 0.4 Transportation related metrics

Transportation related metrics	
Metric	**Description**
Average inbound transportation cost	The cost of bringing product into a facility as a percentage of sales or costs of goods sold.
Average incoming shipment size	Average number of units or dollars in each incoming shipment at a facility.
Average inbound transportation cost per shipment	Average transportation cost of each incoming delivery.
Average outbound transportation cost	The cost of sending product out of a facility to the customer.
Average outbound shipment size	Average number of units or dollars on each outbound shipment at facility.
Average outbound transportation cost per shipment.	Average transportation cost of each outgoing delivery.
Fraction transported by mode	Fraction of transportation (units or dollars) using each mode of transportation.

Information

Table 0.3 Information related metrics

Information related metrics	
Metric	**Description**
Forecast horizon	How far in advance of the actual event a forecast is made.
Frequency of update	How frequently each forecast is updated.
Forecast error	The difference between the forecast and actual demand.
Seasonal factors	The extend to which the average demand in a season is above or below the average in the year.
Variance from plan	The difference between the planned production/inventory and the actual values.
Ratio of demand variability to order variability	The standard deviation of incoming demand and supply orders placed.

Sourcing

Table 0.5 Sourcing related metrics

Sourcing related metrics	
Metric	**Description**
Days payable outstanding	The number of days between a supplier performed a supply chain task and when it was paid.
Average purchase price	The average price at which a good or services was purchased during the year.
Range of purchase price	The fluctuation in purchase price during a specified period.
Average purchase quantity	The average amount purchased per order.
Supply quality	The quality of product supply.
Supply lead time	The average time between when an order is placed and when the product arrives.
Fraction of on-time deliveries	The fraction of deliveries from the supplier that were on time.
Supplier reliability	The variability of the supplier's lead time as well as the delivered quantity relative to plan.

Pricing

Table 0.6 Pricing related metrics

Pricing related metrics	
Metric	**Description**
Profit margin	Profit as a percentage of revenue.
Days sales outstanding	The average time between when a sale is made and when the cash is collected.
Incremental fixed cost per order	The incremental costs that are independent of the size of the order.
Incremental variable cost per unit	The incremental costs that vary with the size of the order.
Average sale price	the average price at which a supply chain activity was performed in a given period.
Average order size	the average quantity per order.
Range of sale price	The maximum and minimum of sale price per unit over a specified time horizon.
Range of periodic sales	The maximum and minimum of the quantity sold per period during a specified time horizon.

C) Overview of the drivers' effects on the responsiveness/efficiency balance

- Using more facilities generally makes a supply chain more responsive.
- Using less (central) facilities creates higher efficiency.
- Holding higher levels of inventory increases the responsiveness of a supply chain.
- Keeping low levels of inventory increases the supply chain's efficiency.
- Using faster modes of transportation increases the supply chain's responsiveness
- Using slower modes of transportation generally increases the efficiency.
- Investing in information can vastly improve the supply chain performance on both dimensions.
- Appropriate sourcing decisions raise supply chain profits by assigning supply chain functions to the right party, which brings higher economies of scale or higher level of aggregation of uncertainty.
- Pricing can be used to attract the right target customer segment.
- Differential pricing can be used to attract customers who value responsiveness as well as customers who prefer efficiency. The supply chain can then be structured to provide responsiveness to some customers while improving the overall efficiency.

D) Overview of suitable performance charts

The given overview is based on: *Guide to Chars for Written reports* (Cooper & Schindler, 2011).

Bar chart

Compares different entities on the same variable or component of a variable.

Bullet bar chart

Compares different entities on the same variable or component of a variable.

Column chart

Compares different entities on the same variable or component of a variable.

Deviations (bar or column) chart

Positions categories on X axis and values on Y axis. Deviations distinguish positive from negative values.

Mirror image bar chart

Positions categories on X axis and values on Y axis as mirror images for different entities.

Area (surface) chart

Like line chart, compares changing values but emphasis relative value of each series.

Bubble chart

Used to introduce third variable (dots of different sizes). Axis could be sales, profits; bubbles are assets.

Line chart

Compares values over time to show changes in trends

Filled line chart

Similar to line chart, but uses fill to highlight series.

Boxplots chart

Displays distribution(s) and compares characteristics of shape.

Step chart

Compares discrete points on the value axis with vertical lines showing difference between points. Not for showing a trend.

Side-by-Side stacked bar chart

Compares components of two or more items of interest.

Column with line chart

Item of most interest is presented in bars and compared to items represented by lines; categories on X axis and values on Y axis.

Stacked pie chart

Same as pie but displays 2 or more data series.

Multiple pie chart

Uses the same data as stacked pie but plots separate pies for each column of data without stacking.

Scatter chart

Shows if relationship between variables follows a pattern. May be used with one variable at different times.

Spider chart

Radiating lines are categories; values are distances from center (shows multiple variables like; performance, ratings and progress).

E) Interview(s) outline

Supply chain driver metrics' related questions:

Which of driver metric(s) should be used for analyzing and visualizing the current material flow towards Leszno? This can be bottlenecks or metrics for which the performance is currently unknown.

* Facility	* Transportation	* Sourcing
* Information	* Sourcing	* Inventory

Would you recommend some other metrics in addition to the current ones?

Qualitative supply chain driver aspects questions:

Questions about the qualitative driver (related) aspects.

Facilities

- How many and which facilities are part of the scope?
- Are VMI's facilities centralized or decentralized, and why?
- Are VMI's production facilities flexible, dedicated or a combination of both?
  - *Flexible facilities can be used for many product types.*
  - *Dedicated facilities can be used for only a limited number of products.*
- Are VMI's production facilities product or functional focused?
  - *Product focused: all the product related functions are performed in the same facility.*
  - *Functional focused: only a given set of functions are performed in a facility.*
- Are VMI's warehousing facilities cross dock, storage or both?
  - *Cross dock warehouse: inbound trucks are directly unloaded and broken into smaller lots and quickly loaded onto store-bound trucks.*
  - *Storage warehouse: products are stored for a longer period of time.*

Inventory

- Are there multiple products/inventory types and, if so, why?
  - *For example: anonymous, raw materials, WIP, finished goods, project inventory etc.*
  - *What determines where a product should be consolidated?*
  - *What are the main differences between the inventory types (in case of multiple types)*
- What are the current storage options?
  - *Type of storage.*
  - *Dedicated, random or class based storage?*
  - *Reserve/bulk area (storage) or forward pick area (or both).*
- Are the (cycle) inventory levels generally high or low? (responsive/efficient)
  - *E.G., excess capacity for possible demand peaks.*
  - *What are the general (inventory) sojourn times. Does it vary per product type?*
- Does the VMI use safety stocks?
- Has each VMI's production site its own warehouse?
- Are the inventory characteristics the same for each warehouse within the scope?
  - *Inventory types, required handlings etc.*

Transportation

- Are the transportation activities outsourced (third party logistics), or in-house?
- Which transportation modes are currently used (within the scope)?
    - *Trucks, airplanes, vessels, electronic transportation etc.*
- Are the used transportation modes based on specific delivery/product characteristics?
    - *Distance, volume, urgency, dimensions etc.*
- Are most of the transportation modes (trucks) fully loaded, or (partly) empty?
- What does the general transportation network look like?
    - *Supply source direct linked to demand point or linked to intermediate points?*
    - *Milk runs between multiple (Eastern Europe) suppliers?*
    - *Are the orders bundled for some suppliers' deliveries?*
- Which transportation aspects are currently monitored?
    - *Is there some sort of traceability or visibility?*
- JUST-IN-TIME delivery, or specific delivery days/windows?
- Are there many urgent/back orders?

Information

- What type of information/ERP system is currently used by the VMI?
- Who has access to this system?
- Does each supply chain facility use the same information system?
- What determines whether access is allowed or possible?
- Is the available information real time, or updated by periodic runs?

Sourcing

- Which suppliers are currently preferred: efficient, responsive or both?
    - *Efficient suppliers: focused on cost and quality.*
    - *Responsive suppliers: focused on speed, flexibility, reliability etc.*
- Are the required parts produced in-house, outsourced or both?
    - *In case of IP sensitive products?*
- Play suppliers a role in the product development phase, or do they just receive purchase orders?
- Are the (different) product types purchased based on: forecasts, actual orders or both?
    - *E.G. forecasts are used to acquire economies of scale.*
- How and based on what criteria are the suppliers selected?
    - *Requests for proposals?*
    - *Selection and decision methods?*
- Different purchasing methods for fast-movers compared to slow-movers?
    - *ABC analysis*
- Are long-term or short-term contracts preferred with suppliers?
    - *Long-term contracts: efficient*
    - *Short-term: best performance and price*
- Which suppliers' tiers are preferred?
    - *First tier or second tier.*
- How many suppliers are used for the same part/product
    - *Single versus portfolio (for risk pooling)*

Pricing

- Does the VMI use machine discount or not?
    - *Everyday low pricing or high-low pricing?*
- Fixed pricing or variable/menu pricing?
- Margins between internal departments?

Would you recommend other supply chain characteristic in addition to the current drivers?

F) Selected metrics per interview

Table 0.7 Selected metrics per interview

Pricing	*Inventory*	*Transportation*	*Information*	*Sourcing*	*Facility*	*Additional*
		Average incoming shipment size		Supply lead time	Capacity	CO2 footprint
		Average inbound transportation cost			Processing times	
					Production cost per unit	
					Volume contribution of top 20% Suppliers	

Driver metrics selecition based on meeting Sourcing manager

Pricing	*Inventory*	*Transportation*	*Information*	*Sourcing*	*Facility*	*Additional*
		Average inbound transportation cost		Average purchase price		
				Supply quality		
				Supply lead time		
				Supplier reliability		

Driver metrics selecition based on meeting Supply manager

Pricing	*Inventory*	*Transportation*	*Information*	*Sourcing*	*Facility*	*Additional*
Incemental variable cost per unit	Average inventory	Average inbound transportation cost		Supply lead time (transport mode)	Volume contribution of top 20% Suppliers	Quality losses due to loading and unloading
		Average outbound shipment size		Fraction on time delivery	Additional costs due to loading and unloading	Transportation mode (CO2)
		Fraction transported by mode		Supplier reliablitiy		Order completeness (warehouse-production site)

Driver metrics selecition based on meeting Production engineer

Pricing	*Inventory*	*Transportation*	*Information*	*Sourcing*	*Facility*	*Additional*
Incemental fixid cost per order		Average incoming shipment size		Supply quality		CO2 footprint
Incemental variable cost per unit		Average inbound transportation cost		Supplier reliability		
				Fraction on time delivery		

Driver metrics selecition based on meeting Warehouse coördinator

Pricing	*Inventory*	*Transportation*	*Information*	*Sourcing*	*Facility*	*Additional*
Incemental fixid cost per order	Average inventory	Average inbound transportation cost	Forecast Horizon	Supply quality	Capacity	
Incemental variable cost per unit		Average outbound shipment size	Forecast error	Supply lead time	Utilization	
				Supplier reliablitiy	Additional costs due to loading and unloading	

Driver metrics selecition based on meeting Transport manager

Pricing	*Inventory*	*Transportation*	*Information*	*Sourcing*	*Facility*	*Additional*
		Average inbound transportation cost		Average purchase price	Capacity	CO2 footprint
		Average incoming shipment size		Supply quality	Additional costs due to loading and unloading	
		Fraction transported by mode		Supply lead time	Volume contribution of top 20% Suppliers	

G) Metric intensity for each individual metric

Table 0.8 Metric intensity for each individual metric

Individual metrics:	Metrics mentiond 2 times	Metrics mentiond 3 times	Metrics mentiond 4 times	Metrics mentiond 5 times	Metrics mentiond 6 times
Utilization	Variable costs per route option	Incremental variable cost per unit	CO2 footprint (per shipment mode)	Supply lead time	Average inbound transportation cost
Processing times	Incremental fixid cost per order	Average incoming shipment size	Supplier reliability		
Production cost per unit	Fraction transported by mode	Supply quality			
Order completeness (warehouse-production)	Fraction on time delivery	Capacity			
Average inventory	Average outbound shipment size	Additional costs due to loading and unloading			
Forecast error	Average purchase price	Volume contribution of top 20% Suppliers			

H) BPMN visualization of the current material flow towards Leszno (expanded)

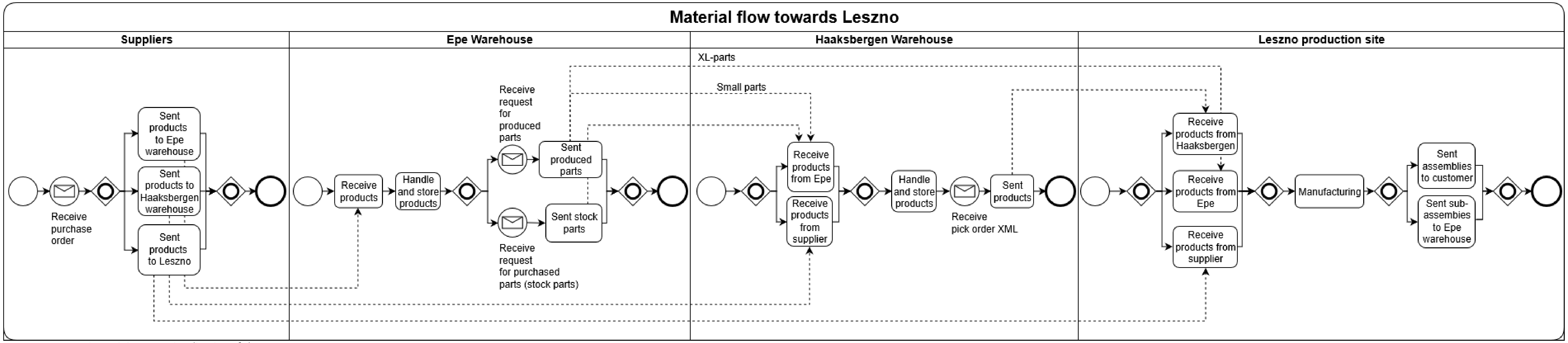


Figure 0.2 BPMN visualization of the current material flow towards Leszno (expanded)

I) Interviews outcomes of the qualitative

Question outcomes about the qualitative driver (related) aspects with respect to the scope.

Facilities

- How many and which facilities are part of the scope?

Two warehouses in Epe and Haaksbergen and one production site in Leszno are part of the scope.

- Are VMI's facilities centralized or decentralized, and why?

The warehouse facilities within the scope are centralized. The production site in Poland is on the other hand decentralized due to cost and lead time reduction. The warehouse in Epe is a logical consequence of the headquarters being located in Epe. The location of the second warehouse in Haaksbergen (close to Epe) is argumentative as well, since this warehouse is part of TKH. The production site in Leszno is decentralized. This site is located in Poland for cost and lead time reduction. The production site in Poland contradicts a pure centralized supply chain. So the facilities are not purely decentralized due to the limited amount of facilities and the low dispersion. A hybrid form is therefore most applicable in this situation.

- Are VMI's production facilities flexible, dedicated or a combination of both?
    - *Flexible facilities can be used for many product types.*
    - *Dedicated facilities can be used for only a limited number of products.*

VMI's production facilities are in general flexible, since each facility has, or should be able to gather, the knowledge and tools to produce each machine type. The production facilities are therefore not restricted to produce some specific machine type.

- Are VMI's production facilities product or functional focused?
    - *Product focused: all the product related functions are performed in the same facility.*
    - *Functional focused: only a given set of functions are performed in a facility.*

The production facilities are product focused, since all the product related functions can be performed in the same production facility.

- Are VMI's warehousing facilities cross dock, storage or both?
    - *Cross dock warehouse: inbound trucks are directly unloaded and broken into smaller lots and quickly loaded onto store-bound trucks.*
    - *Storage warehouse: products are stored for a longer period of time.*

VMI's warehousing facilities are storage warehouses which store and consolidate items for a longer period of time.

Inventory

- Are there multiple products/inventory types?
    - *For example, anonymous and project inventory.*

The VMI currently uses two main inventory types; anonymous and project inventory.

- What are the current storage options?

The warehouses possess multiple storage options. The storage options regarding anonymous and project inventory are divided for readability. The storage options related to Epe warehouse are:

Anonymous inventory

- Vertical Lift Module (VLM).
- Bin (40 cm*30 cm*12 cm) Rack.
- Euro pallet (EP) Storage Racks for: 1 EP, 1/2 EP and 1/4 EP.
- Floor Stock

Project inventory

- Bin (40 cm*30 cm*12 cm) Rack.
- EP Storage Racks for: 1 EP, 1/2 EP, 1/4 EP.
- Steel Pallets (SP) storage
- Self-supporting (ZD) parts stored on SPs.
- ZD XL parts stored on the ground
- Bar and Tube Storage Rack
- Cantilever Rack

Haaksbergen warehouse stores only project related parts. The related storage options are:

- Bin (60 cm*40 cm*18 cm) Rack, with 1 Bin, 1/2 Bin or 1/4 Bin.
- EP Storage Racks
- Bar and Tube Storage Rack
- Cantilever Rack
- Limited amount of ground locations

The product characteristics, weight and dimensions determine the most suitable storage option.

- Are VMI's (cycle) inventory levels generally high or low? (responsive/efficient)
    - E.G., excess capacity for possible demand peaks.

The product type determines whether a high or low inventory level is preferred. Anonymous inventory has on average high inventory levels. The inventory levels of project related parts are generally low.

- Does the VMI use safety stocks?

Safety stocks are used for the following items:

- Items with high minimum order quantities.
- Items that should be forecasted and ordered upfront due to their long lead times.
- Forecasted items for which it is economically attractive to order multiple items at once.

Has each VMI's production site its own warehouse?
No, the production site in Leszno has no warehouse.

- Are the inventory characteristics the same for each warehouse within the scope?

No, see above.

Transportation

- Which transportation modes are currently used by the VMI (within the scope)?
    - *Trucks, airplanes, vessels, etc.*

The following three transportation modes are currently used:

1. Road transportation (Trucks)
2. Marine transportation (Vessels)
3. Air transportation (Airplanes)

- Are the current transportation modes based on specific delivery characteristics?
    - *Distance, volume, urgency, etc.*

The following characteristics determine which transportation mode is most appropriate:

- Geographic location of the supplier.
- Total volume of an order.
- Total weight of an order
- Total (financial) value of an order.

- What does the general transportation network look like?
    - Supply source direct linked to demand point or linked to intermediate points?

The transportation mode determines the material flow and linkage to the warehouses or production location. Transportation by truck has 3 delivery options; Epe warehouse, Haaksbergen warehouse and Leszno production site. The supplier and product combination is leading for the used delivery option (see Section 3.3.1). The remaining transportation modes have only 2 options. Marine transportation ends at the port of Rotterdam, the ordered products are thereafter sent by truck towards Epe warehouse or Haaksbergen warehouse. For air transportation holds almost the same. This ends at Schiphol from which the order products are sent towards Epe warehouse or Haaksbergen warehouse.

- External or own transportation modes?
    - E.G. external supplier trucks or own trucks.

Only external

Information

- What type of information/ERP system is currently used by the VMI?

VMI uses an ERP system called INFOR.

- Who has access to this system?

Each department/employee has basically access to INFOR.

- Does each supply chain facility use the same information system?

The ERP system is company-wide. But the side systems for generating input, reports, etc. are not company-wide integrated. These systems/programs are used and maintained by a group of people who are responsible for such a system/program.

- What determines whether access is allowed or possible?

The function and tasks of an employee determines whether specific information of INFOR is accessible.

Sourcing

- Which suppliers are currently preferred: efficient, responsive or both?
    - Efficient suppliers: focused on cost and quality.
    - Responsive suppliers: focused on speed, flexibility, reliability etc.

VMI prefers in most cases efficient suppliers which excel in the following aspects:

1. Supplier quality expressed in technical and logistical rejection rates.
2. The quality of the deliveries themselves.
3. Total cost of ownership.

However, for some specific parts are responsive suppliers preferred. These parts relate to the 10-30% of a machine that is engineered and designed based on the wishes and characteristics of a customer (see Section 3.3.2). These specific parts are unknown once an order for a machine is placed, so a responsive supplier with low lead times is preferred. The parts would otherwise be too late.

- Are the required parts produced in-house, outsourced or both?

Almost all the required parts are outsourced.

- Are the (different) product types purchased based on: forecasts, actual orders or both?

VMI uses multiple methods for purchasing its products. Forecasts are for example used for products with long lead-times. Products with short lead times are ordered once an order comes in. Some products are on the other hand ordered based on a two bin system.

How and based on what are the suppliers selected?

- Which method, based on what criteria etc.

VMI uses an extensive selection procedure. A flowchart of this complete process is given in Appendix K. The sequence of the main steps is as follow:

11. Request for new supplier.
12. Composing a Longlist with potential suppliers.
13. Generating short list based on a supplier assessment list.
14. Performing multiple checks.
15. On site supplier audit.
16. Sending a Request for quotation (RFQ) towards supplier.
17. Ordering and inspecting an order sample.
18. Meeting between Sourcing, Supply and Supplier Quality Assurance (SQA) representatives about supplier selection.
19. Multiple shipment inspections.
20. Final approval.

The selection procedure can be terminated at any time when a supplier does not comply with something.

- Which suppliers' tiers are preferred?
    - First tier or second tier.

VMI is a so called Original Equipment Manufacturer (OEM). Ordering at first tier suppliers is a logical consequence of being an OEM.

- How many suppliers are used for the same part/product
    - 1 or more (for risk pooling)

VMI prefers two or three suppliers for risk pooling. But it is not possible for all products. Multiple aspects determine whether risk pooling is an option. The technical characteristics of products might be unattractive for risk pooling. There are also some products that are standardized for specific suppliers. In such cases, it is prescribed by VMI that only one supplier is allowed to produce a particular product.

Pricing

- Does the VMI use machine discount or not?
    - Everyday low pricing or high-low pricing?

The VMI does not use machine discounts.

- Fixed pricing or variable/menu pricing?

VMI's machine prices are not fixed, since the prices depend on the machine configurations. The configurations are unique due to the (customer specific) engineered part of each machine

- Margins between internal departments?

VMI does not take any price margins between internal departments, within the scope, into account.

J) Pictures of multiple storage options for both warehouses

Epe

Figure 0.3 Vertical Lift Module (VLM).

Figure 0.4 Bin Rack.

Figure 0.5 Euro Pallet Rack.

Figure 0.6 Steel Pallet storage.

Figure 0.7 Self-Supporting (ZD) Parts stored on long Steel Pallets.

Figure 0.8 Cantilever Rack.

Haaksbergen

Figure 0.9 Miniload(s)

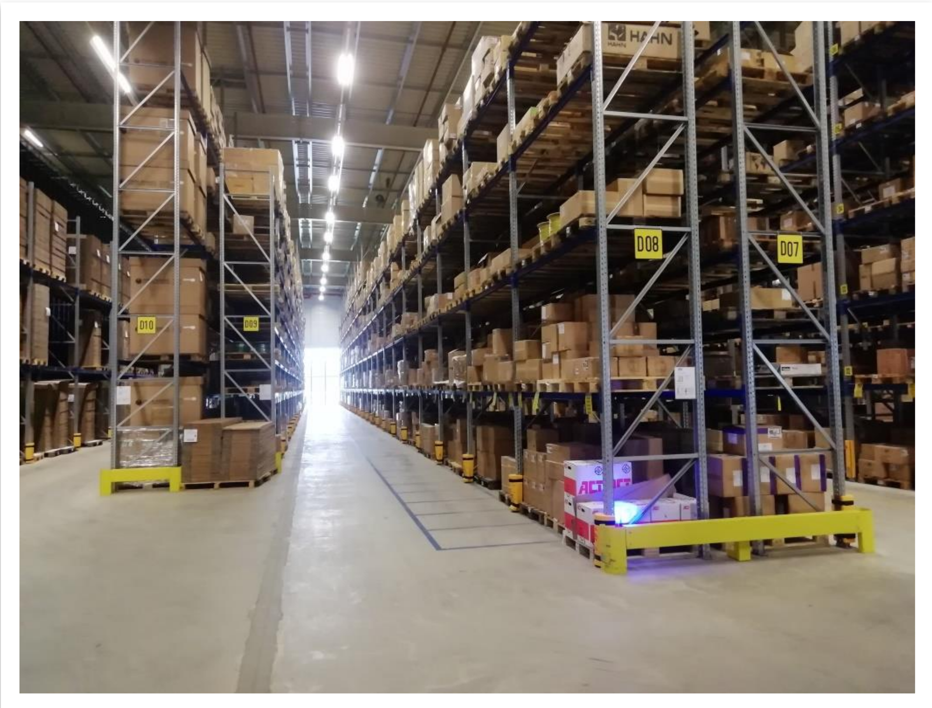


Figure 0.10 Euro Pallet Storage Racks

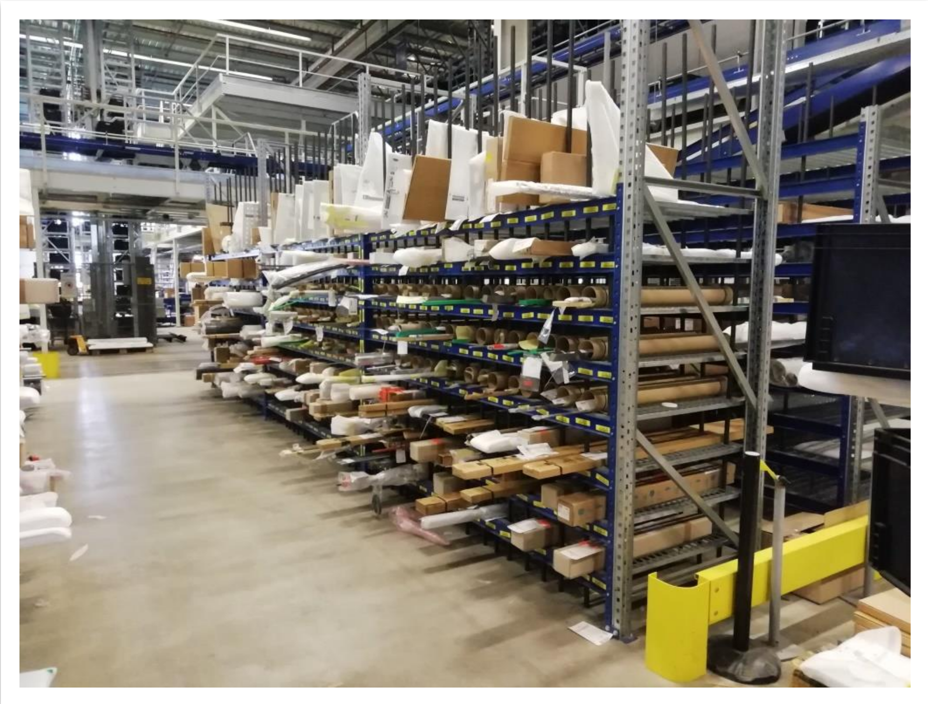


Figure 0.11 Exceptional Storage Rack (Bar and Tube Storage)

Figure 0.12 Cantilever Rack

Figure 0.13 Floor Storage

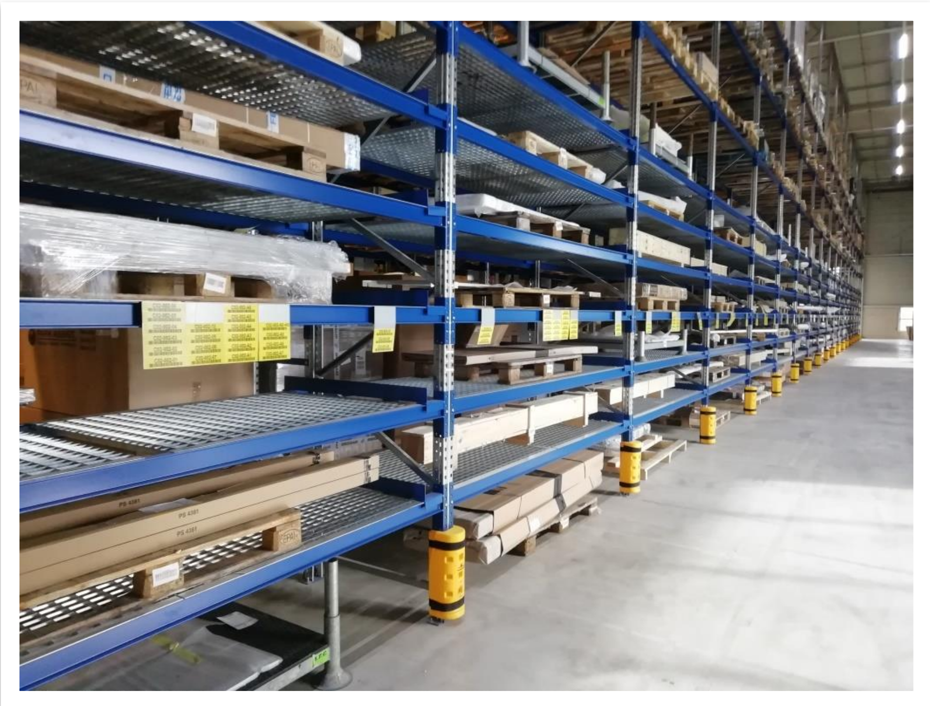
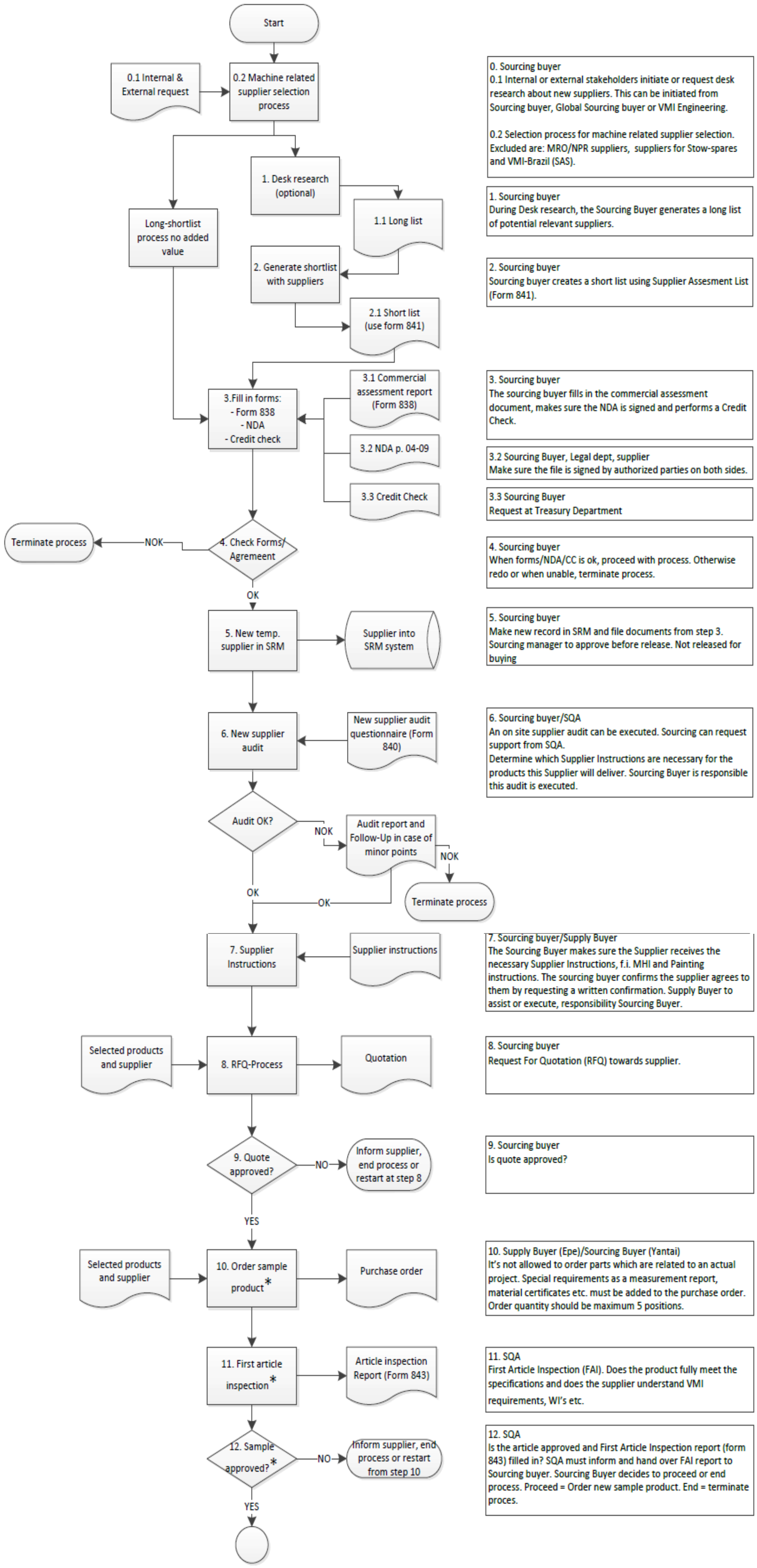


Figure 0.14 Steel Wire Pallet Rack

K) Flow chart supplier selection process



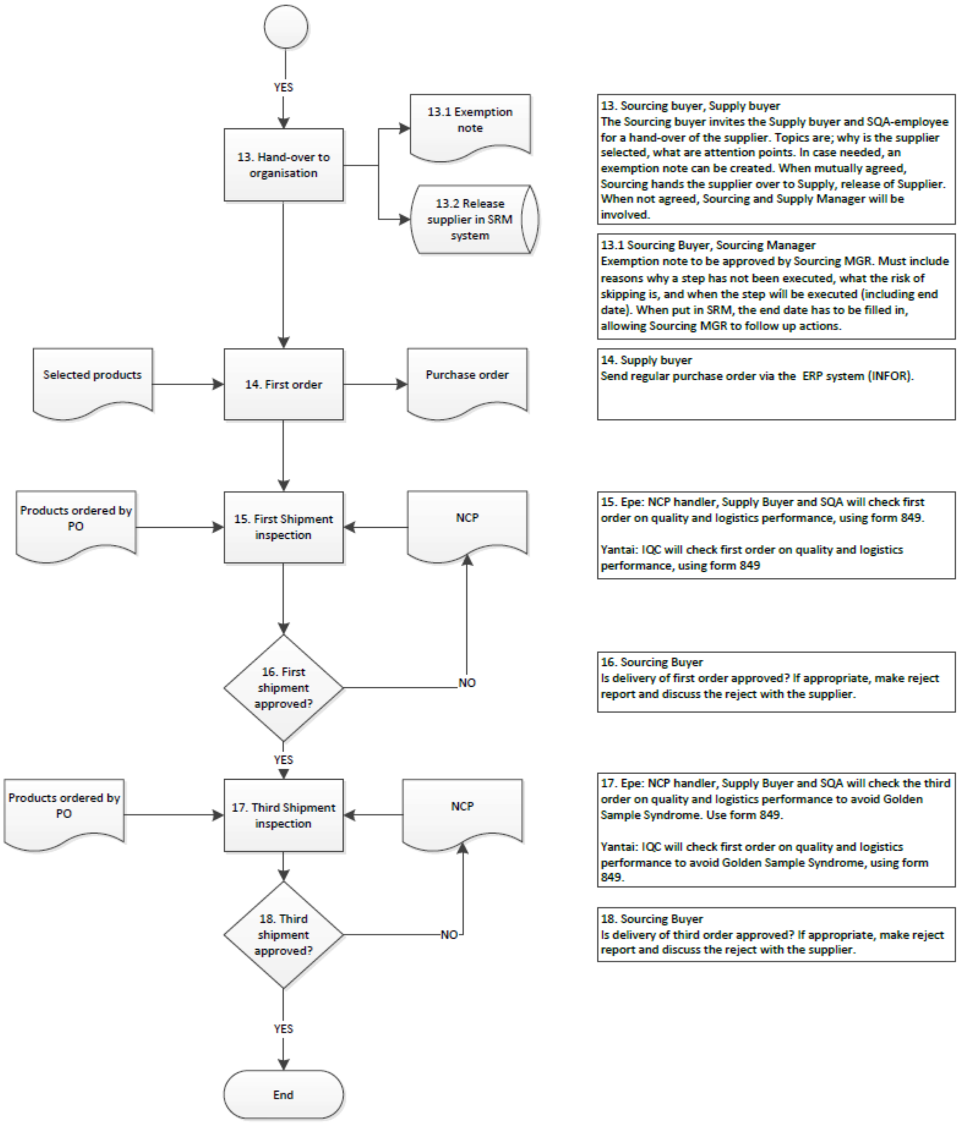


Figure 0.15 Flow chart supplier selection process

L) Metric analysis based on S.M.A.R.T. criteria

Transportation costs

The metric transportation costs has a clear area for measurement, the total number of shipments with the associated costs. The total number of shipments can be measured based on the historical data. Assumptions can be made to determine the number of shipments for other future configurations. We assume that our research capabilities combined with the available resources should be sufficient to determine the total transportation costs. The transport KPI is in our opinion a relevant and valid metric for the material flow. The given timeframe for the research should be enough to measure both the current as well as potential transportation costs. This metric is selected, since it clearly meets all the criteria.

Total Lead time

This metric has also a clear target for measurement, the total or average time that is required to get a SKU from the supplier towards Leszno. Time is reasonably a very appropriate indicator for measurement, even for new configurations. Again, we assume that we have the capabilities as well as the resources to determine the average lead time. Lead time affects the overall material flow which makes it both, a relevant and valid metric for this research. The timeframe should be sufficient as well. This metric meets all the criteria, so we add this metric to our selection as well.

Total CO2 footprint

This metric requires almost the same measurements as the first metric, since this metric is based on the total distance as well. Determining the total distance should provide a significant part of the required information to determine the total CO_2 footprint. We definitely add this metric to our selection since it meets, like the transportation metric, all the criteria.

Supplier reliability

The supplier reliability should at least remain the same for new configurations. However, it is hard to express and measure supplier reliability for new configurations. We will therefore not add this metric to our selection.

Variable and fixed ordering costs

We decided that we do not add the variable and fixed ordering costs to our selection. Afterall, it does not say much about the performance of the (current) material flow, which makes it an irrelevant metric for now. We do keep the metric in mind, since there might be improvements which do affect the variable and fixed ordering costs. We can always decide to determine the variable and fixed ordering costs for the current situation later on, when such a situation occurs.

Average incoming shipment size

The incoming shipment sizes contain a clear measurement target, namely the amount of orders or SKUs which arrive at each facility on average. But we will not add the average shipment sizes to our selection, since we think that it is more useful to use this metric as input for other KPIs. For instance the transportation costs. The transportation costs are for example affected by the average incoming shipment sizes. So we will determine this metric to provide the required input for other KPI(s).

Warehouse capacity

The (utilized) capacity of the warehouses comprises a clear target for measurement and it is presumed that it can be measured quite easily. The capacity for example, can be determined in number of square meters or storage racks and the utilization can easily be expressed in a ratio or percentage. We assume that our capabilities combined with the available resources should be sufficient for determining the warehouse capacity as well as the utilization ratio. Determining both variables should therefore be a realistic goal for the given timeframe. However, it is not a relevant metric for our material flow optimization research. It will therefore be used as a constraint, since the improvements or alternatives should meet the capacity restrictions. So we will not add this metric to our selection.

Volume contribution of top 20% suppliers

We will not add the volume contribution of the top 20% suppliers to our selection, since it is supposed to be an irrelevant metric for our research initially. This metric does not provide interesting insights regarding the performance of the (current) material flow. Again, we can always decide to determine this metric for the current situation later on if it is essential for a performance comparison with a specific improvement. So we do not add this metric to our selection, but it might become part of it in the future.

Handling costs(per material flow)

The handling costs are expected to be a clear measurement target. Especially with the available resources and capabilities should determining the handling costs be a realistic goal for this research, even within the given timeframe. This metric is definitely relevant for our research, since each of the material flow options lead to a specific number logistic handlings. We will obviously add this metric to our selection.

Fraction transported by transportation mode.

This metric might comply to all the S.M.A.R.T. criteria but we will not add this metric to our selection. The fraction transported by transportation mode is namely an import input factor for multiple KPIs, especially the total CO_2 footprint. The transportation modes affect the CO_2 footprint strongly, since each mode has a different emission rate. So determining this metric is only required to provide relevant input for other KPI(s).

M) Extrapolate approach

Total CO2 footprint

It is hard to extrapolate the CO2 footprint performance based on the material flow values form Section 6.1.9. We therefore decided to extrapolate the CO2 footprint performance based the shipment frequencies. The geographic locations of the suppliers has a significant impact on the associated footprint. So we will use the suppliers from the toy problem for the real material flow. The geographic locations associated to the suppliers of the actual material flow are after all unknown. Besides, the alternatives are based on the toy problem related suppliers as well. We already mentioned in Section 4.4 that the truck types used for the toy problem are equal to the actual truck types used by the suppliers. We therefore only adjust the shipment frequencies to analyze the total CO2 footprint for the real material flow. So the suppliers and used truck types remain the same. This resolves the issue mentioned in Section 4.4, since the supplier related shipments are now based on the actual shipment sizes.

The shipment frequencies are higher for the real material flow compared to the toy problem, since almost all suppliers have (at least) one fixed delivery day per week. This equals a yearly shipment frequency of 52, which is significantly higher than the toy problem related frequencies which vary between nine and ten. The intercompany shipment frequencies are higher as well. The intercompany shipment frequencies are retrieved from the data which was provided by a transportation department representative. The provided frequencies were related to the total material flow, we therefore determined the frequencies related to the “toy problem suppliers” based on the associated material flow share. The other input variables are based on the toy problem averages. An overview of the input variables is provided in Table 0.9.

Table 0.9 Input variables CO2 footprint real material flow.

Number of suppliers per supplier type per warehouse	Epe	ETKH	Leszno
Dutch suppliers	1	24	0
Eastern European suppliers	2	11	2
Other suppliers	0	2	0

Average (linear) distance per supplier type	Epe	ETKH	Leszno
Dutch suppliers	109	118	0
Eastern European suppliers	818	784	269
Other suppliers	0	1133	0

Average CO2 factor per supplier type	Epe	ETKH	Leszno
Dutch suppliers	1.10	0.32	0.00
Eastern European suppliers	0.75	0.53	1.10
Other suppliers	0.00	0.29	0.00

Average shipment frequency per supplier type	Epe	ETKH	Leszno
Dutch suppliers	52	52	0
Eastern European suppliers	52	52	52
Other suppliers	0	52	0

Average intercompany shipment frequency per warehouse	Leszno
Epe	72
Haaksbergen	116

We use the same CO2 footprint formula as before, see Section 4.1. The CO2 emissions per shipment type are provided in Table 0.10 on the next page.

Table 0.10 Total CO2 emissions per shipment type for the actual material flow.

Total CO2 footprint inbound shipments.

Total CO2 emission per supplier type per warehouse	Epe	Haaksbergen	Leszno
Dutch suppliers	6,240	47,831	0
Eastern European suppliers	63,932	237,274	30,802
Other suppliers	0	34,289	0

Total CO2 footprint outboun shipments.

Total CO2 emission per supplier type per warehouse	Epe	Haaksbergen	Leszno
Dutch suppliers	4,481	34,343	0
Eastern European suppliers	45,903	170,363	22,116
Other suppliers	0	24,620	0

Total CO2 footprint intercompany shipments.

Total CO2 emission per intercompany shipment option	Leszno
Epe	115,119
Haaksbergen	172,417

Adding up all values from Table 0.10 provides the total CO2 footprint for the actual material flow based on the same suppliers. The total CO2 footprint equals: Confidential kg CO2. The total CO2 footprint associated to the toy problem equals Confidential kg CO2, see Section 5.1. Taking the actual material flow into account for the same suppliers results in a CO2 footprint which is 6.6 times higher. This is a result of the higher intercompany and supplier related shipment frequencies. The ratio between the supplier and intercompany related footprints, 28% and 72% respectively, differs only a few percent compared to the toy problem, see Section 4.4. So the used extrapolate technique leads to a correct ratio between the supplier and intercompany related footprints.

Average total lead time

The average total lead time per material flow will only be affected by the supplier related lead times, since the consolidation and intercompany lead times are fixed for each material flow, see Section 4.4. The supplier related lead times are unknown for the "non toy problem suppliers". We therefore use the average supplier lead times based on the toy problem. The consolidation lead times are different per item type (project or anonymous), so we use the project/anonymous ratio from the toy problem for the actual material flow. The average total lead time per material flow will remain the same since only the number of items per material flow changes, this has obviously no impact on the average. This is visualized in Table 0.11. The complete material flow contains more order lines per material flow (red) compared the toy problem. However, this has no effect on the average lead time per material flow.

Table 0.11 Average total lead time per material flow.

Toy problem

Lead time types per flow	Consolidation lead time	Intercompany lead time	Average suppliers related lead time	Number of order lines	Avg. average total lead time per route
Direct delivery.	Confidential				
Delivery through Epe warehouse.					
Delivery through Haaksbergen warehouse.					

Complete material flow

Lead time types per flow	Consolidation lead time	Intercompany lead time	Average suppliers related lead time	Number of order lines	Avg. average total lead time per route
Direct delivery.	Confidential				
Delivery through Epe warehouse.					
Delivery through Haaksbergen warehouse.					

The average overall total lead time does change, since the number of order lines and the associated order line distribution is different for the actual material flow. The average overall lead equals Confidential for the toy problem and Confidential for the actual material flow, which is an increase of 0.84%.

So we can conclude that the actual material flow does not affect the average total lead time per material flow. However, the average overall total lead time does increase with 0.84% to 31.62 days, which is still a small adjustment. So the order line distribution of the actual material flow is comparable to the order line distribution related to the toy problem.

Total transportation costs

We extrapolate the total transportation costs based on the total value of the material flow which is given in Section 6.1.9, since the supplier related transportation costs are directly influenced by the value of the associated items. The specific supplier related transportation percentages are determined by the item dimensions. The specific item dimensions are unknown, so we will approximate these dimensions based on the associated storage zones. So we need to know the total value as well as the storage zone distribution of the actual material flow in order to determine the total supplier related transportation costs, see Section 4.2.3. We do know the actual material flow value, see Section 6.1.9. But the storage zone distribution is unknown for the actual material flow. We therefore use the storage zone distribution of the toy problem to approximate the storage zone distribution for the actual material flow. Table 0.12 provides the storage zone distribution per warehouse based on the toy problem.

Table 0.12 Storage zone distribution per warehouse.

Number of items per storage zone per warehouse	RB	EP	SP	ZD
Epe warehouse	10	0	0	20
Haaksbergen warehouse	2,393	210	30	20
Direct	0	0	10	20
Storage zone distribution per warehouse	RB	EP	SP	ZD
Epe warehouse	33.33%	0.00%	0.00%	66.67%
Haaksbergen warehouse	90.20%	7.92%	1.13%	0.75%
Direct	0.00%	0.00%	33.33%	66.67%

The total cost prices per warehouse are determined by multiplying the total value per warehouse with the associated storage zone percentages. Multiplying these values with the charged transportation cost price percentages provides the total supplier related transportation costs per warehouse. We also need to determine the total intercompany transportation costs. VMIs transportation department provided the required data to acquire the total number of intercompany trucks used during the associated period of time. We also received the costs per truck per intercompany shipment. So multiplying both gives the total intercompany transportation costs per warehouse. Table 0.13 provides the supplier and intercompany transportation costs per warehouse for the actual material flow.

Table 0.13 Total transportation costs of the actual material flow.

Total transportation costs per warehouse	Supplier related transport costs	Intercompany transport costs	Total
Delivery through Epe warehouse.	Confidential		
Delivery through Haaksbergen warehouse.			
Direct delivery.			
Grand Total			

The total transportation costs of the actual material flow are significantly higher than the transportation costs associated to the toy problem, Confidential instead of Confidential. This is a consequence of the material flow sizes. This is reflected by the associated transportation costs. But the ratio between the supplier and intercompany related shipment costs (85/15) are almost exactly the same as the associated toy problem ratio (87/13). This supports the used method.

Total handling costs

We extrapolate the total handling costs based on the number of order lines per warehouse, since the handling costs are determined per order line as well. The handling costs are also dependent on the item dimensions. We therefore use the storage zone distribution, based on the toy problem, to determine the total handling costs. This zone distribution differs from the storage zone distribution used for the transportation costs determination, since this zone distribution is based on order lines instead of items. The associated storage zone distribution is provided in Table 0.14.

Table 0.14 Storage zone distribution per warehouse.

Number of orderlines per storage zone per warehouse	RB	EP	SP	ZD
Epe warehouse	10	0	0	20
Haaksbergen warehouse	1,050	170	20	10
Direct	0	0	10	20

Storage zone distribution per warehouse	RB	EP	SP	ZD
Epe warehouse	33.33%	0.00%	0.00%	66.67%
Haaksbergen warehouse	84.00%	13.60%	1.60%	0.80%
Direct	0.00%	0.00%	33.33%	66.67%

Multiplying the total number of order lines with the associated storage zone percentage provides the number of order lines per warehouse per zone, as shown in Table 0.15.

Table 0.15 Number of order lines per storage zone.

Number of order lines per storage zone per warehouse (actual material flow)	RB	EP	SP	ZD
Epe warehouse	Confidential			
Haaksbergen warehouse				
Direct				

Multiplying the total number of order lines with the associated handling costs gives the total handling costs per warehouse. Table 0.16 provides an overview of the total handling costs for the actual material flow.

Table 0.16 Total handling costs for the actual material flow.

Total handling costs per sotrage zone per warehouse (actual material flow)	RB	EP	SP	ZD
Epe warehouse:	Confidential			
Haaksbergen warehouse:				
Direct:				
Total handling costs				

The total handling costs related to the actual material flow are significantly higher than the toy problem related handling costs Confidential. The total handling costs for the actual material flow equal Confidential, which is a consequence of the increased number of order lines. We again verified the ratios of the actual material flow with the ratios of the toy problem. These ratios do support the used method, since the inbound/outbound ratio of the actual material flow (52.6/47.4) is almost exactly the same as the toy problem ratio (52.7/47.3)

N) Approach for determining the alternative performances for the current situation

Direct Shipping to Leszno

Total CO2 footprint

The total CO2 footprint is Confidential kg CO2 for the current situation. We measure the direct shipping effect on the total CO2 footprint for the supplier and intercompany shipments separately, since the frequency of the intercompany shipments is not directly linked to the supplier related shipment frequency. The direct delivery might even affect the intercompany shipments more than the supplier related shipments, since less intercompany shipments are required. The direct delivery alternative reduces the supplier related CO2 footprint (inbound and outbound) with 64.6%. So the supplier related footprint becomes Confidential kg CO2 instead of Confidential kg CO2. The direct delivery alternatives reduces the total volume of the intercompany shipments with 19.4%. We therefore assume this alternative reduces the number of required intercompany trucks with 19.4%. This leads to a CO2 footprint of Confidential kg CO2 for the intercompany shipments. So the total CO2 footprint becomes Confidential kg CO2, which is a reduction of Confidential kg CO2 which equals 52.3%.

Average total lead time

We already revealed in Section 6.2.2 that the average overall lead reduces with 8.9 % by applying the direct delivery alternative. This is a result of multiple items which will be supplied directly instead of through an intermediate warehouse. Multiple items which were initially supplied through Epe or Haaksbergen will be supplied directly by applying the alternative. So the average overall lead time will drop from Confidential towards Confidential by applying the direct delivery alternative.

Total transportation costs

The transportation costs are expected to drop significantly due to the implementation of the direct delivery alternative. We will determine the supplier related and intercompany transportation costs separately. The total supplier related transportation costs will drop with 26.2%. We already determined that the number of required intercompany trucks drops with 19.4%. So the total transportation costs associated to the direct delivery alternative are Confidential. This is a reduction of Confidential, which equals 25.2%.

Total handling costs

We already determined that the total handling costs will reduce with 25.0% due to the direct delivery alternative, see Section 6.1.7. The current total handling costs related to the actual material flow are Confidential. So the total handling costs associated to the direct delivery alternative are Confidential. We therefore conclude that applying the direct delivery alternative saves Confidential.

Milk-run (to Haaksbergen and Epe)

Total CO2 footprint

We divided the total CO2 footprint over three types: supplier related CO2 footprint, intercompany related CO2 footprint and the CO2 footprint associated to the milk-run. We measure the CO2 footprint for each type separately. The supplier related CO2 footprint becomes less, since the milk-run replaces multiple (original) supplier shipments. The associated reduction equals 66.0%. The supplier related CO2 footprint becomes Confidential kg CO2 instead of Confidential kg CO2. The CO2 footprint related to the intercompany shipments does not change, since the associated volume remains the same for the milk-run alternative. We determined the required trucks for the milk-run based on the intercompany shipments. The volume share of the milk-run is 13.6%, which equals Confidential per year. The associated CO2 footprint will be Confidential kg CO2. So the total CO2 footprint related to the milk-run alternative becomes Confidential kg CO2, which is a reduction of 41.4%.

Average total lead time

We already mentioned that the milk-run alternative leads to an average overall lead reduction of 0.3%. This is caused by the changed transportation lead times of the orders which will be supplied by the milk-run trucks. So the average overall total lead time will drop from Confidential to Confidential.

Total transportation costs

We will divide the transportation costs over 2 types; supplier and intercompany related transportation costs. The milk-run costs belong to the supplier related transportation costs, since we determined these costs based on the current supplier related transportation costs. The supplier related transportation costs drop with 27.9% to Confidential. The intercompany transportation costs will not be affected, since the associated volume remains the same for the milk-run alternative. So the total transportation costs related to the milk-run alternative are Confidential, which is a reduction of 24%.

Total handling costs

The total handling costs remain the same since material flow volumes are not influenced by the milk-run alternative, see Section 5.4.

Direct Shipping with Milk-Run(s) (to Leszno)

Total CO2 footprint

We again divide the total CO2 footprint over three different types: supplier related CO2 footprint, intercompany related CO2 footprint and the CO2 footprint associated to the milk-run. The supplier related CO2 footprint reduces with equals 78.7%. The associated (supplier related) CO2 footprint becomes Confidential kg CO2 instead of Confidential kg CO2. The CO2 footprint related to the intercompany shipments decreases with 19.4 %, see Section 6.3.1. This leads to a CO2 footprint of Confidential kg CO2 for the intercompany shipments. The milk-run of this alternative is equal to the milk-run from Section 6.3.2 in terms of volume. This is a consequence of the associated suppliers, which are equal for both milk-run alternatives, see Section 5.4. So the milk-run requires 25.6 trucks per year. The associated CO2 footprint will be Confidential kg CO2. Summing up the three CO2 footprint types provides a total CO2 footprint of Confidential kg CO2, which is a reduction of 58.6 %.

Average total lead time

We already revealed in Section 6.1.7 that this alternate leads to an average overall lead reduction of 8.0%. The transportation lead time reductions are the main cause of this reduction. The overall lead time reduction leads to an average overall total lead time of Confidential.

Total transportation costs

We use the following two transportation types for determining the total transportation costs; supplier and intercompany related transportation costs. The transportation costs of the milk-run are included in the supplier related transportation costs, see Section 6.3.2. This alternative reduces the supplier related transportation costs reduction with 29.8% to Confidential. The intercompany transportation costs will reduce as well. The associated reduction equals 19.4%, see above. The related intercompany transportation costs are Confidential. So the total transportation costs related to the direct shipping with milk-run alternative are Confidential, which is a reduction of 28%.

Total handling costs

This alternative leads to the same handling costs reduction as the direct delivery alternative, see Section 6.1.7. The associated total handling costs are therefore Confidential, see Section 6.3.1. So introducing the direct delivery in combination with a milk-run saves Confidential.

Cross Dock Warehouse.

Total CO_2 footprint

We will use three different CO_2 footprint types to determine the total CO_2 footprint. The used types are: supplier related CO_2 footprint, intercompany related CO_2 footprint and the CO_2 footprint associated to DC related shipments. The cross-dock warehouse alternative reduces the supplier related footprint with 64.8% to Confidential kg CO_2. The CO_2 footprint related to the intercompany shipments decreases with 19.4 %, see Section 6.3.1. This leads to a CO_2 footprint of Confidential kg CO_2 for the intercompany shipments. The volume share of the dc related shipments equals 19.2%, which equals 36 trucks per year. The associated DC related CO_2 footprint will be Confidential kg CO_2. Summing up the three CO_2 footprint types provides a total CO_2 footprint of Confidential kg CO_2, which is a reduction of 45.3 %.

Average total lead time

We already revealed in Section 6.1.7 that this alternative increases the average overall lead with 1.0%. The lead time associated to the cross-dock DC is the main cause of this increase. The overall lead time expansion leads to an average overall total lead time of Confidential.

Total transportation costs

We will divide the transportation costs over 2 types, supplier related and intercompany transportation costs. The transportation associated to the DC related shipments are included in the supplier related transportation costs. The supplier related transportation costs drop with 27.0%. The associated supplier related transportation costs are Confidential. The intercompany transportation costs will not be affected, since the associated volume remains the same for the cross-dock DC alternative. So the total transportation costs related to this alternative are Confidential, which is a reduction of 22.9%.

Total handling costs

This alternative increases the total handling costs with 8%. This increase is caused by the additional cross dock DC handlings. So the associated total handling costs are Confidential, which is an increase of Confidential.

O) Approach for determining the scenario consequences

Total CO2 footprint

We assume that it is more beneficial for a supplier to drive with a bigger truck instead of increasing the shipment frequency. So a material flow increase of 50% leads to the following truck type changes:

Van → small truck
Small truck → medium truck
Medium truck → big truck

We also assume that supplier which already use a big truck will use an additional small truck to supply their goods. Additionally, we assume that a material increase of 100% leads to the following truck type changes:

Van → medium truck
Small truck → big truck

The suppliers which already use a medium or big truck require an additional truck with the same dimensions, it is after all a material increase of 100 %. We assume, for the same reason, that a material flow decrease will lower the shipment frequencies. The VMI uses already a big truck for the intercompany shipments. So the material flow adjustments will only affect the shipment frequency of the intercompany shipments.

50% decrease

Only the shipment frequencies will change due to this scenario, so the remaining input factors from Section 6.2.1 remain the same. Table 0.17 provides an overview of the new shipment frequencies.

Table 0.17 Adjusted shipment frequencies.

Average shipment frequency per supplier type	Epe	ETKH	Leszno
Dutch suppliers	26	26	0
Eastern European suppliers	26	26	26
Other suppliers	0	26	0

Average intercompany shipment frequency per warehouse	Leszno
Epe	36
Haaksbergen	58

We use the same measurement method from Section 6.2.1 to determine the total CO2 footprint. A material flow decrease of 50% leads to a total CO2 footprint of Confidential kg CO2. This a reduction of 50%.

75% decrease

We used the method the same method as mention above. A material flow decrease of 75% reduces the total CO2 footprint with 75%. The associated total CO2 footprint is Confidential kg CO2.

50% increase

We adjusted the used truck types for the toy problem supplier in order to determine the average CO2 emission factors per supplier type. We add the CO2 factors of a small truck to the big truck CO2 emission factors, since we assume that those supplier will use an addition small truck to delivery their goods, see above. Table 0.18 provides an overview of the adjusted average CO2 emission factors per supplier type as well as the adjusted intercompany shipment frequencies.

Table 0.18 Adjusted input values.

Average CO2 factor per supplier type	Epe	ETKH	Leszno
Dutch suppliers	1.503	0.568	0.000
Eastern European suppliers	1.131	0.857	1.503
Other suppliers	0.000	0.402	0.000

Average intercompany shipment frequency per warehouse	Leszno
Epe	108
Haaksbergen	174

This increases the total CO2 footprint with 55.4%. The associated total CO2 footprint is 1,568,821kg CO2.

100% increase

Increasing the material flow with 100% leads to an total CO2 footprint increase of 128%. The associated total CO2 footprint is Confidential kg CO2

Average total lead time

The average overall lead time will not be affected by a linear material flow increase or decrease. The average values will remain the same as long as the warehouse distribution does not change. Remark, it is assumed that the warehouses are able to handle an increased material flow within the same number of days.

Total transportation costs

The supplier related transportation costs are directly linked to the total value of the material flow. We can therefore adjust the material flow values based on the scenarios directly. We use the measurement method from Section 6.2.3 to determine the total transportation costs. It is assumed that the material flow increase or decrease does not influence the storage zone distribution. We therefore use the storage zone distribution from Section 6.2.3. The intercompany shipment costs are linked to the related volume, we therefore adjust the number of trucks based on the scenarios.

50% decrease

A 50% material flow reduction reduces the total transportation costs with 50%, since the transportation costs are directly linked to the material flow. The associated transportation costs are Confidential. Remark, this is a result of our extrapolate technique and used formulas.

75% decrease

The associated transportation costs are Confidential, which equals 25% of the original transportation costs.

50% increase

The associated transportation costs are Confidential.

100% increase

The associated transportation costs are Confidential.

Total handling costs

The total handling costs are related to the total number of order lines per warehouse and is dependent the associated storage zones. We assume that the scenarios have no effect on the storage zone distribution. We there use the distribution given in Section 6.2.4. We determine the total number of order lines scenario based on the associated percentages.

50% decrease

The scenarios have the same effect on the handling costs as on the transportation costs. So a material flow reduction of 50% equals a handling cost reduction of 50% as well. The associated handling costs are Confidential.

75% decrease

The associated handling costs are Confidential, which equals 25% of the original transportation costs.

50% increase

The associated handling costs are Confidential.

100% increase

The associated handling costs are Confidential.