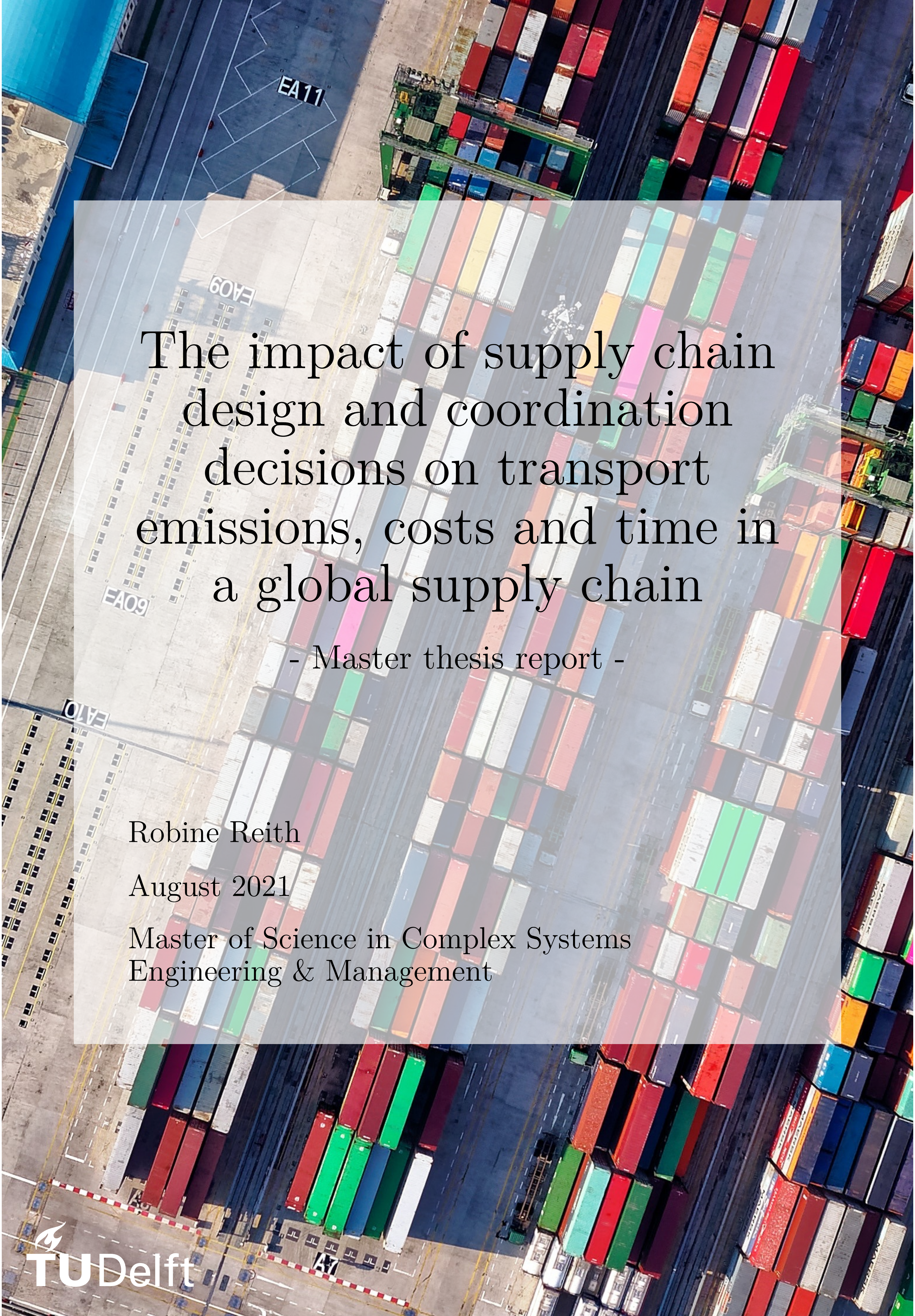

The impact of supply chain design and coordination decisions on transport emissions, costs and time in a global supply chain

- Master thesis report -

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Master of Science in Complex Systems
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THE IMPACT OF SUPPLY CHAIN DESIGN AND COORDINATION DECISIONS ON TRANSPORT EMISSIONS, COSTS AND TIME IN A GLOBAL SUPPLY CHAIN

A thesis submitted to the Delft University of Technology in partial fulfillment
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by

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EXECUTIVE SUMMARY

Environmental concerns have increased within the last decades. Supply chain activities have contributed to these global environmental problems. Namely, the production, transport, storage and consumption of goods have caused harm to the environment. Companies are therefore pushed to rethink their existing supply chain (SC) to contribute to the environmental challenges. Companies have to balance business performance measures with environmental performance measures. This issue is part of the green supply chain management (GSCM) field, which deals with supply chain management, where environmental considerations are taken into account [Sarkis et al., 2011]. One of the main environmental considerations within GSCM of companies is decreasing the supply chain's emissions. From the literature review, a knowledge gap is identified where further research should focus on the impact of specifically supply chain design/coordination (SCD/C) decisions on emissions in global supply chains [Chelly et al., 2019]. These decisions include routing decisions, transport mode selection and facility location, to name a few. The consumer goods industry is an industry lacking such research [Ansari and Kant, 2017]. Next to emissions, the business performance criteria costs and transport times are included in the research question. Therefore, the main research question is: *what impact do supply chain design and coordination (SCD/C) decisions in a global supply chain have on the supply chain's emissions, costs and transport times?*

This question is answered by building a quantitative emission model of a part of the supply chain of L, a company that creates loyalty programmes for international retailers. In this way, a case-study methodology is applied in this research. The designed model is applied to the supply chain of L, but the model can also be applied to a different supply chain. Therefore the model can be seen as a tool that a company can use to understand the impact of SCD/C decisions on emissions, costs and time. After first defining a theoretical conceptual model and a case-specific conceptual model, the scope of the research was set up. Figure 0.1 shows a high-level visualisation of the emissions and criteria (green) included in the model and the parameters (blue) and variables (white) that influence these criteria. Based on this diagram, the model is created in the tool Excel.

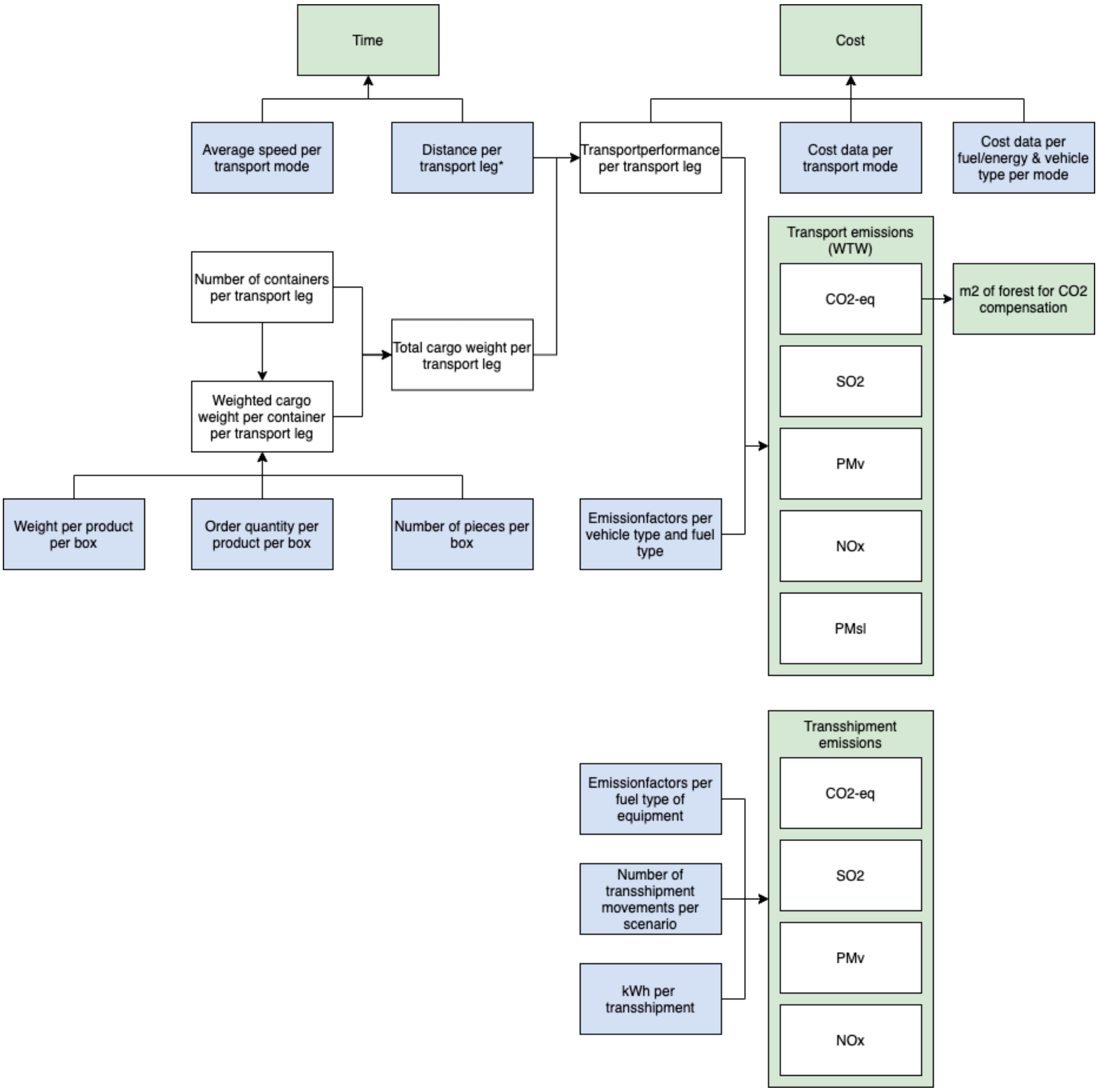

Figure 0.1: Model structure

The model input is based on the selected case of L, a specific loyalty program for a client of L. The inbounds of the selected case originate from China, France and Portugal. Therefore, there are three flows in the model, called the CHN, FR and PRT flows. Once the model was built, the model was verified through a scenario analysis of the case study, in which alternative scenarios were set up and tested. Next to this, a sensitivity analysis was conducted. Both analyses showed that the model behaved as expected. Regarding the validation of the model, a validation meeting was set up to validate the model with the case experts.

Once the emission model was verified and validated, the decision impact analysis could be performed. The model's main function is to calculate the emissions, costs, and times based on the input given. The main dials of the model, which also represent the types of decisions to be made and therefore the different options per type of decision, are the transport mode, the fuel/engine type and the vehicle type, see Figure 0.2. These three main dials represent the three SCD/C taken into account in this research as those decisions were most relevant to the case study. For each transport leg, the model user has to enter a.o. the weight per container, number of containers, origin and destination and the model's 'dials', namely modality type, vehicle type and fuel/engine type. Appendix B shows all options within the dials, each table namely represents a transport mode (dial 1), and within each table, all the options for vehicle types (dial 2) and fuel/engine types (dial 3) can be found. Once this information is entered, all emissions, costs and times are calculated. Because of these functions of the model, a clear overview of results can be gathered as the output changes when a different input is given (when one of the dials has turned).

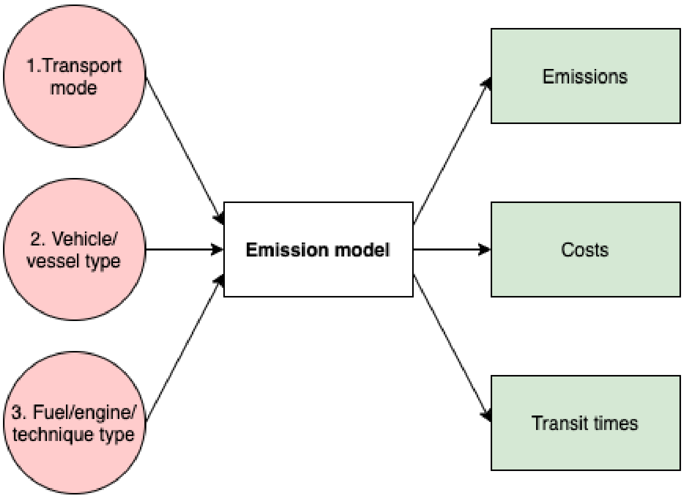

Figure 0.2: Model dials

By performing the decision impact analysis, the following findings were made. The three types of decisions that were most relevant for the case were analysed; these are mode selection decisions, fuel/energy/engine type decisions and vehicle type decisions. Table 0.1 shows a short overview of the results from the decision impact analysis. It shows the ranges in which the impact percentages vary for that particular type of decision in that particular flow. So, for the first row, the percentages for the impact on emissions vary between 9-16330%. This means that in some alternative mode options for the CHN flow, the alternative options impact the emissions between 9-16330% compared to the base case option, which is a massive impact. When overlooking this overview of results, it can be concluded that the decision mode selection impacts all three criteria, emissions, cost and time. The fuel type and vehicle type decisions have no impact on the criteria time. Secondly, it can be concluded that the most crucial decision from this specific case analysis is the mode selection decision. Not only because it impacts all three criteria but also because the emission range, especially in the analysis for the CHN flow, is extensive. On the other hand, it must also be stated that the other two decisions also make an undeniable impact on emissions and cost and must therefore not be neglected but should, on the contrary, also be taken into account. Fuel type selection can make the biggest positive impact on emissions from these two decision types, looking at the smallest percentages. At the same time, the changes in costs for road and maritime transport are not that big. This indicates a feasible outcome; fewer emissions with minimum extra cost. Finally, it can be concluded that all three decision types have an impact and therefore matter and that it is recommended for the case to take all three types of decisions into account. Mode selection is the decision type that is most commonly considered within companies. However, if companies influenced carriers to select a specific fuel or vehicle type, the transportation sector as a whole would be activated to change to using more sustainable fuel or vehicle options. Imagine what positive change this would bring to the transportation sector if companies start imposing fuel/vehicle requirements on carriers. This would bring more incentives to the transportation sector to act more sustainably and offer more sustainable transportation options.

Table 0.1: Results overview table - impact ranges per SCD/C decision type

	Emissions	Cost	Time
Mode selection CHN flow	9-16330%	985-3541%	10-39%
Mode selection FR flow	56-247%	57-94%	300-303%
Mode selection PRT flow	13-303%	14-58%	326-400%
Fuel/engine type selection FR flow (road)	49-294%	93-110%	no impact
Fuel/engine type selection CHN flow (maritime)	2-196%	91-102%	no impact
Fuel/engine type selection CHN flor (air)	12-146%	163%	no impact
Vehicle type selection FR flow (road)	75-100%	80%	no impact
Vehicle type selection (inland waterway)	71-254%	177-254%	no impact

Regarding the added value of the model, the following can be concluded. As the mode selection decision is already commonly considered in companies, decision-makers are already familiar with especially the cost and time differences of the different modalities. Nevertheless, from the case study, it appeared that this knowledge is not present concerning the cost differences of the different fuel and vehicle types. This leads to the first added value point of the model, the added value of getting insight into the cost differences when using different fuel/engine types or vehicle types in transporting goods. The second added value point is that it first appeared from the case study that knowledge was only present on a general level concerning emissions. The value of the emission model is that it contributes to a much more accurate view of the impact on emissions among decision-makers. Because of this accurate overview, the model outcomes can function as a handle for the decision-makers to see the impact of their decisions. The model can compare different possibilities for transporting goods; it can compare different modalities, vehicle types per modality and fuel/engine types per modality and express its impact on emissions, costs and time. As a result, the model can identify not only sustainability measures but also business measures. Consequently, the impact (positive/negative) of certain decisions within the supply chain on emissions, costs, and time can be made clear at a glance. If the company starts using this model, conscious choices may be made more often if the business measures allow it. The model also provides a handle for communication about different options (in terms of modalities, type of fuels and type of vehicles) within different company departments. The model and the results provide a tool for making decisions and an overview in a table of this impact, which can be communicated to relevant departments. As a result, it can make stakeholders more aware of their impact when making a certain decision.

Specifically for this case study, it is recommended to consider the outcomes regarding the impact of the different analysed decisions when deciding upon transport of the goods. For this case, the outcomes are interpreted in detail in Chapter 7. Within the boundaries of cost and time, the most sustainable decisions should be made to contribute to society positively. The outcomes can function as a handle to making these decisions. Therefore it is recommended to use them in general when deciding upon the transport for this specific program. If it appears imposing certain fuel types or vehicle types as a requirement at carriers seems difficult, then first focus on the mode selection decision. This decision appeared to be most crucial when it comes to impact on emissions, cost and time. Besides this, it is recommended to apply this model to every program. This research shows massive impact can be made on emissions, cost and time. When the model becomes part of the business process of deciding upon transportation of goods for every program, the impact on emissions can be big. In this way, a big contribution to society can be made by making sustainable decisions within the business boundaries. If all companies started doing this, a big movement in the whole sector could be started.

Regarding recommendations for the transportation sector in general, it is recommended for decision-makers within companies to generate knowledge about the impact of decisions they make. The knowledge of costs and time is already embedded in their business way of thinking. However, knowledge of emissions and the impact of decisions on them is important to be updated. However, decision-makers alone cannot improve the freight transport market. It requires cooperation in the whole sector. The study showed that some fuels positively impact emissions, for example, bio-kerosene, but sometimes these fuels can be costly. This makes it impossible for companies and vehicle owners to use these fuels. The whole sector needs to think about solutions to bring these costs down. Policymakers, fuel producers, vehicle owners, companies and researchers must work together to bring about this change.

Finally, several recommendations for further research include the investigation of the quality of certain input parameters. This applies to data concerning fuel costs, vehicle costs, average speed per transport mode and assumptions regarding transhipment emissions. It is also recommended to apply the model for other SCD/C decisions, such as routing and facility location decisions. Furthermore, the model itself could be made more user-friendly, the improvements to be made can be found in Section 6.2.2. It is also recommended when the model is put into use by companies to initiate a continuous improvement of the input portfolio concerning vehicle types and fuel types as the freight transport sector continues to develop. The input parameters concerning the emission rates should be updated annually, using the most recent data.

ACKNOWLEDGEMENTS

This thesis is my final work for completing the master in Complex Systems Engineering and Management at the TU Delft. At the same time, this is a goodbye to my student years, as I will start working from the 1st of October. Due to the covid situation, three quarters of my master's, namely 1.5 years, took place online. This certainly had its disadvantages, namely to constantly study from home. But thanks to the case study at L founders of loyalty, I had the opportunity to go to the office every Wednesday. The advantages of this situation were, on the other hand, that I was flexible in terms of the places where I could work on my thesis. This way, I was able to work from Amsterdam, Den Bosch and in the final phase from Moraira, which is also a unique experience. Ironically, not from Delft, as I moved to Amsterdam the previous year. I want to express my gratitude towards Erik Visser for all the knowledge, guidance and for attending all the graduation meetings. But definitely also towards Marcel Wijnhoven, Linda de Jong, Patrick van Bergen, and Christan Maccarrone, all working at L founders of loyalty. Thank you all a lot for your guidance and all the nice Wednesdays at the office. From the TU Delft, I would like to thank Jan-Anne Annema, as my first supervisor, for all the excellent support, quick responses, guidance, and knowledge through the many online meetings. Moreover, I want to thank Bert van Wee and Ivo Bouwmans for providing excellent guidance and knowledge during and around the graduation committee meetings. I could not have wished for a better graduation committee than the one I had, as all of you together perfectly guided me. Finally, I would like to thank my friends and family for their support and patience as I was sometimes so busy working on my thesis. I really enjoyed working on this thesis from February onwards, and I hope you will enjoy reading it.

. . . R.M.M.A. Reith, Amsterdam, August 2021

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ACRONYMS

CoSEM	Complex Systems Engineering and Management	1
SC	supply chain	iv
GSCM	green supply chain management	iv
LCSCM	low-carbon supply chain management	1
SLR	systematic literature review	6
SSCM	sustainable supply chain management	2
SSND	supply chain network design	9
SCD/C	supply chain design/coordination	iv
TI	technological innovation	2
OM	operational management	2
GHG	greenhouse gas	1
SRSCM	socially responsible supply chain management	7
TTW	thank to wheel	18
WTT	well to thank	18

1 INTRODUCTION

This chapter first describes the problem at hand in this study. This is followed by an outline of the main findings regarding identifying knowledge gaps, followed by the main research question and the sub-questions. This is followed by a brief description of the research approach, method and strategy. Finally, the relevance of the problem concerning society, science and the Complex Systems Engineering and Management (CoSEM) master's degree is given in this chapter.

1.1 PROBLEM

Environmental concerns have increased in recent decades. An increase in industrialisation, population and therefore supply chain activities have led to increased greenhouse gas (GHG) emissions, contributing to climate change and global warming [IPCC, 2014]. This means that supply chain activities, the production, transportation, storage and consumption of goods, contribute to these global environmental problems. Companies are therefore pushed to rethink their existing SC to make an effort to overcome the environmental challenges. In adapting their existing SC, companies need to balance business performance and environmental performance measures. A problem for companies is how to address strategic decisions and operations while balancing the aforementioned performance measures [Chelly et al., 2019].

This issue is part of the GSCM field that deals with SC management, where environmental considerations are considered [Sarkis et al., 2011]. One of the main environmental considerations within corporate GSCM is to reduce emissions. This is the primary focus of low-carbon supply chain management (LCSCM), which is concerned with rethinking SC's and implementing green practices to reduce carbon emissions. The goal of LCSCM is to reduce carbon emissions from SC activities without compromising the overall economic interest of the company [Das and Jharkharia, 2018].

1.2 KNOWLEDGE GAP AND RESEARCH QUESTIONS

The literature shows that there is consensus on the importance of GSCM and LCSCM. Although much research has already been done within this domain, there are still several knowledge gaps to be filled. The full literature review will be provided in Chapter 2, but the main findings regarding the knowledge gaps will be presented here.

In a literature review, an analysis was conducted based on categorising the type of supply chain decisions; SCD/C decisions, technological innovation (TI) decisions and operational management (OM) decisions [Chelly et al., 2019]. Briefly, the first type of decisions, SCD/C decisions, includes transport mode selection, location of facilities and supplier selection. The second type, TI decisions, include technology investments and outsourcing. The third type of decisions, OM decisions, includes transportation planning, production planning and inventory planning.

The literature review by Chelly et al. [2019] identified a gap in research regarding SCD/C decisions in particular within LCSCM. In addition to this knowledge gap, another gap is present concerning modelling global SCs, as more research can be done specifically on global SC, compared to national SCs. When examining studies conducted within different industries, some industries were more prevalent than others. Ansari and Kant [2017]'s review stated that the most prominent industries present in the field of sustainable supply chain management (SSCM) included the manufacturing, food, electrical and automotive industries. In contrast, the consumer goods industry is an industry where research on SSCM is lacking compared to the more prominent industries. In terms of the type of emissions, the focus should not only be on GHG emissions, but it may be useful to also consider other emissions in the SC [Eskandarpour et al., 2015]. Moreover, the final knowledge gap is that further research should incorporate uncertainty, this includes uncertainty in terms of emission rates of different modes, as well as uncertainty in terms of demand for the goods in the SC.

The main research question that follows from the literature review (Chapter 2) with the thereby identified knowledge gap as mentioned above, and which is also supported by the literature reviews of Chelly et al. [2019], Ansari and Kant [2017] and Eskandarpour et al. [2015], reads:

what impact do supply chain design and coordination (SCD/C) decisions in a global supply chain have on the supply chain's emissions, costs and transport times?

As described in the problem section above, the difficulty is to find a balance between business performance and environmental performance measures while companies are reconsidering their existing SC. Therefore, in this study, not solely emissions are included as a criterion but also costs and transport times.

To answer this main research question, several sub-questions are defined that will help determine the steps to be taken to ultimately reach the main objective, answering the main research question of the thesis. These sub-questions are as follows:

1. How are transport-related emissions from global supply chains previously modelled?
2. What are the causes of emissions within the supply chain of the case study?
3. Which emissions and criteria should be taken into account in the emission model?

4. Which parameters and variables influence the criteria in the emission model?
5. What is the base case scenario of the case study?
6. What do the alternative scenarios entail with regards to the scenario analysis for verification means?
7. What impact has uncertainty in emission factors?
8. Which SCD/C decisions' impact are relevant to the case to model and analyse?

1.3 RESEARCH APPROACH, METHOD AND STRATEGY

1.3.1 Suitability of case-study method

In order to answer the main research question, a quantitative research approach is needed to gain insight into SC emissions, cost and lead times. The main question of the research asks to conduct research on supply chains. Since this is a master thesis project and the time frame for completing the project is several months, it is impossible to conduct research on many different supply chains. Therefore, it is chosen to conduct the research on one SC of one particular company. This makes the research method of a case study very appropriate. According to Siau and Rossi [2011], a case study can be used to observe organisations using modelling methods. This is exactly the role that the case study should play in this research. More specifically, a case study can be used to observe a company's SC emissions, cost and lead times related to the transportation of its products and to observe the impact on these emissions when it makes changes to its existing SC depending on different SCD/C decisions. However, the research method of a case study also has its limitations. One limitation of the case study method is the subjectivity of the researchers' interpretation, due to the use of a rarely randomly selected case [Siau and Rossi, 2011].

1.3.2 Case selection

The case must meet two main criteria. The first criterion is that the case study must be located in the consumer goods industry, as this industry was identified in the knowledge gap as one that scored significantly lower in the number of research papers present within that industry compared to other industries in the field of SSCM. The second criterion is that the case must have a global SC, as this also covers a part of the knowledge gap.

The case that meets the two criteria is to study (a part of) the SC of the company 'L founders of loyalty', from now on called L. L provides loyalty programs for the largest supermarkets on a global level. For these loyalty programs, they provide the supermarkets with everything needed to execute these loyalty programs. Thus, L also buys or designs the goods for which the supermarkets' customers can save credits and arrange the transport of the goods. Typical examples of such goods are consumer goods such as kitchen knives, frying pans and wine glasses. The service they provide results in a global SC, which is another reason for selecting this case. Since this case fulfils both criteria, thus partially filling the gap in knowledge, this case study will also be of scientific relevance in addition to its relevance to the company itself. When designing alternatives for the case study, only feasible and realistic alternatives will be designed. This means that cost and time will be considered two important criteria in the emission model. The exact scope of the case study, which parts of the supply chain and what type of products, to name a few scope decisions, will be determined further in the study. The results of this case study will be generalised into recommendations and findings that are also suitable for SC's of other companies.

1.3.3 Research strategy

The following strategy is applied in the study. Firstly, with the results of the first two sub-questions, a conceptual model can be built that represents a conceptual visualisation of all SC processes that cause emissions in a SC in general. This general conceptual model will be based on the literature. In this way, the theoretical aspect of the emissions occurring in SC's will be clarified. Afterwards, this conceptual model is specified for the SC of the case study. This can be done through a desk study of company documents and interviews. Based on the conceptual model of the case study, the emission model can be created in the Excel tool (sub-questions 3,4,5). Finally, a sensitivity analysis can be carried out (sub-questions 6 and 7). Chapter 3 explains the research method and the data collection methods in more detail.

1.4 SOCIETAL RELEVANCE

LCSCM research helps companies to make the right strategic decisions while reducing their emissions. When companies succeed in adapting their existing SC to take into account environmental considerations, in particular the reduction of emissions, those actions will contribute to a better environment. This immediately outlines the societal contribution of research in the field of LCSCM. The eventual reduction of emissions due to companies rethinking SC's will contribute to solving environmental problems.

1.5 SCIENTIFIC RELEVANCE

Besides societal relevance, this thesis will also be scientifically relevant, as this research will contribute to the existing literature in the field of GSCM and LCSCM. More specifically, the main result of the research is to answer the main research question. This research aims to analyse the impact of SCD/C decisions on transport-related emissions in a global SC within the consumer goods industry. In achieving this goal by answering this main research question, a big contribution will be made to the existing literature as this question covers several knowledge gaps; the impact of SCD/C decisions on emissions and the study of a global SC within the consumer goods industry. Moreover, the research will also evaluate the impact of uncertainty related to emission rates of different transport modes and demand for goods, where both aspects are also knowledge gaps.

1.6 COSEM RELEVANCE

This topic meets the criteria of a CoSEM student because it addresses complex issues, namely complex issues related to LCSCM. The management of a SC itself is already a very complex process, and this complexity increases, even more when multiple objectives are considered in the decision-making process (e.g. environmental factors in addition to traditional factors such as time and cost)[Das and Jharkharia, 2018]. In addition, the topic also has a large social context; the knowledge gained within this thesis could help reduce emissions in SC's of companies, which will contribute to environmental problems. Moreover, a scientific approach will be used to obtain results and insights.

A typical CoSEM thesis includes both a design/engineering component and a technology component. In this study, the design/engineering component is the emission model, which models the emissions within a (part of) the SC, with different design alternatives and scenarios. The technology component investigates in which parts of the SC the most emissions are emitted or which alternatives positively impact SC performance, both in terms of emissions and profitability. The exact design/engineering and technology components of the proposed research will depend on the knowledge gap and the research question, as these aspects determine the exact scope of this research. This will be clarified in Chapter 2.

1.7 STRUCTURE

The next chapter, Chapter 2, contains a literature review. In the next chapter, Chapter 3, the research approach, methods and data gathering processes are provided. The following chapter, Chapter 4, provides the conceptual model of all SC processes causing emissions in a SC in general, based on existing theories. Thereafter, the conceptual model will be specified for the SC of the case study. The design of the emission model, with the criteria included, data used for input and the model structure and calculations used are presented in Chapter 5. This is followed by the emission model verification and validation in Chapter 6. Next, the decision impact analysis is shown, Chapter 7 and the report ends with the conclusion, discussion, and recommendations Chapter 8.

2 LITERATURE REVIEW

This chapter provides an analysis of the literature review. First, the method of the literature review is explained. This is followed by an analysis of the literature consisting of an introduction to the core concepts, an analysis of emissions in supply chains, an overview of the main findings of previous literature reviews, and an analysis of SCD/C decisions and associated modelling techniques.

2.1 LITERATURE REVIEW METHOD

The review of several articles in the field of emissions in SC or transportation studies, will form the basis of this literature review and is at the same time the scope of this literature review. All studies outside the SC or transportation field are left out of scope. A systematic literature review (SLR) is ”a manner of evaluating and interpreting all available and relevant research on a particular research question, topic or phenomenon”[Kitchenham, 2004]. First, different mixes of the following search terms were used on research databases Scopus & Web of Science: ’emissions, transport, supply chain, green, low-carbon, modelling, sustainable, carbon, pollutants, model, simulation, international, worldwide, global’ to name a few. In this way, an impression of the accessible articles was generated by searching with different mixes of the above-mentioned search terms. In the next section, Section 2.2, the core concepts and emissions in supply chains in general are analysed on the basis of articles found with the above-mentioned search terms. In addition to individual research articles, previous literature searches were also conducted. After these previous literature reviews have been analysed, a more specified selection of articles is made for the literature analysis with regard to the type of SCD/C decision and the modelling technique.

2.2 LITERATURE REVIEW ANALYSIS

2.2.1 Introducing core concepts

To provide the reader with the necessary background knowledge, this literature analysis will first describe a number of key concepts within the scope of the literature review.

The term corporate sustainability has many definitions in the literature. Often, the term is used interchangeably with corporate social responsibility. Two well-known definitions of sustainability are the triple-bottom-line of managing social, environmental and economic dimensions in organisations [Elkington, 1998] and inter-generational philosophical perspective of considering the needs of today without compromising the needs of future generations [Brundtland, 1987]. An important and ongoing concern within the literature on corporate sustainability is the concern about the specific economic consequences, both negative and positive, associated with companies' sustainability efforts [Sarkis et al., 2011].

Sarkis et al. [2011] have written a literature review on GSCM. This is a very broad concept that has different definitions in the literature. Since Sarkis et al. [2011] have written a literature review on the concept, their definition will be explained. GSCM is defined as the integration of environmental considerations into the inter-organisational practices of supply chain management, including reverse logistics [Sarkis et al., 2011]. Organisational theories seem well suited to investigate and promote research on GSCM. This resonates because another way to define GSCM is to describe the concept as organisational activities carried out to manage the SC system, from material sources to customer service, in such a way that it is environmentally friendly [Wang and Sarkis, 2013]. The same definition can be used for the concept of socially responsible supply chain management socially responsible supply chain management (SRSCM), namely as organisational activities carried out to manage the SC system, from material sources to customer service, in such a way that it is socially responsive. Together, GSCM and SRSCM are considered components of the wider concept of SSCM.

The concept of SSCM is seen as the arrival of a new era that encompasses environmental, social and economic performance, as an intersection of three areas of sustainable development. The concept also has several definitions. One is that it can be described as "the strategic, transparent integration and achievement of an organisation's social, environmental and economic objectives in the systemic coordination of key inter-organisational business processes to improve the long-term economic performance of the individual firm and its SC's" [Carter and Rogers, 2008].

Besides GSCM and SRSCM, LCSCM is another concept within SSCM. This concept specifically focuses on implementing green practices and rethinking SC decisions to reduce carbon emissions. This research field focuses on making the right SC decisions while reducing carbon emissions with the aim of improving their overall economic performance [Wang and Sarkis, 2013].

The concepts described above together form the research field of which this research is part of. It turns out that there is a lot of overlap within these different research fields. But one aspect that recurs in all of them is the triangle between environmental, social and economic performance. These three aspects must be in balance within organisations that wish to be sustainable in their various (SC) processes.

2.2.2 Emissions in supply chains

GHG emissions are emissions that drive climate change [WRI and WBCSD, 2011]. These GHG emissions occur at many stages within the SC of companies. In Chapter 4, the conceptual model specifies where exactly the emissions occur; which activities in the SC cause the emissions. According to the GHG protocol and the associated corporate standard [WRI and WBCSD, 2011], GHG emissions for companies are categorised into three scopes for companies.

- Scope 1 emissions are direct emissions of a company, from its own or controlled sources
- Scope 2 emissions are indirect emissions of a company from the generation of purchased energy that is consumed by the company
- Scope 3 emissions are all other indirect emissions that occur in the value chain of a company

Figure 2.1 provides an overview of the GHG emissions and the activities/-sources per scope that cause the GHG emissions.

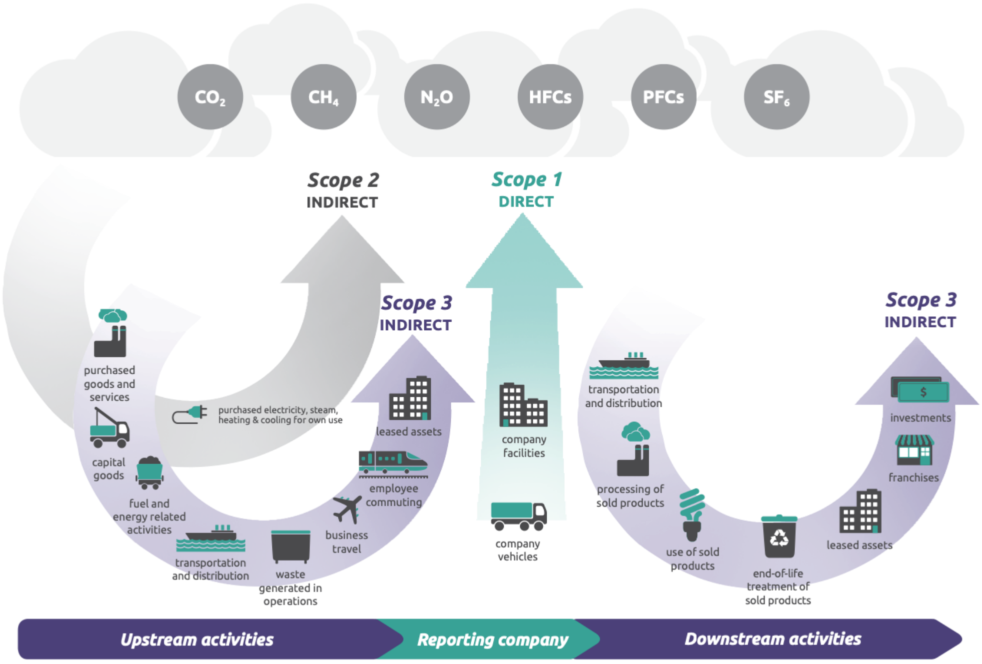

Figure 2.1: GHG protocol scopes and emissions across the value chain [WRI and WBCSD, 2011]

In addition to GHG emissions, which are harmful to the climate, air polluting emissions also occur within the SC of companies. These emissions include nitrogen oxides including NO, NO_2 and NO_3, often these three emissions together are called NO_x. In addition, another air polluting emission is the particular matter PM_{10}, which is released both from the combustion of fuels and from the wear and tear of vehicles or equipment. The last includes sulphur dioxide SO_2. These emissions are considered the most harmful emissions in the context of air pollution policy [CE Delft, 2021]. The same applies to the GHG emissions shown in Figure 2.1, which are considered the most damaging emissions with regard to climate policy [WRI and WBCSD, 2011, 2013].

2.2.3 Findings previous literature reviews

Table 2.1 provides an overview of the three literature reviews already in place. Within the field of LCSCM, Chelly et al. [2019] presents a well cited literature review, with a focus on quantitative modelling of GSCM with low carbon issues. This literature review provides a good basis for the literature review for this master thesis research. Two other literature reviews were also consulted. Namely, the literature reviews of Ansari and Kant [2017] and Eskandarpour et al. [2015]. Ansari and Kant [2017] focused on SSCM, and reviewed methodologies, data analysis techniques, types of industries considered, key enablers and key barriers to SSCM. The review by Eskandarpour et al. [2015] focuses on supply chain network design (SSND), and assessed mathematical models that include economic, environmental and social dimensions to determine which criteria are considered in SSND research.

Table 2.1: Previous literature reviews

	Focus of review
Eskandarpour et al. (2015)	Papers on sustainable SCND in which they assess mathematical models to determine the criteria to be considered in SCND research
Ansari and Kant (2017)	Papers on SSCM identifying methods, data analysis techniques, types of industries and key drivers and barriers
Chelly et al. (2019)	Papers providing quantitative modelling of GSCM with low carbon aspects

Firstly, Chelly et al. [2019] stress the importance of modelling global supply chains. Different locations of companies apply different carbon policies and can influence the SSND. These SSND's have an impact on the carbon footprint of the products and also on the total cost of the SC [Chelly et al., 2019]. This same review identified a gap in research related to global studies; they argue that more global SC's should be modelled.

The review by Chelly et al. [2019] contains an analysis based on the categorisation of the type of supply chain decisions; SCD/C decisions, TI decisions and OM decisions. Briefly, the first type of decisions, SCD/C decisions, includes decisions related to the choice of transport mode, location of facilities and choice of suppliers. The second type, TI decisions, includes technology investments and outsourcing. The third type of decisions, OM decisions, includes decisions related to transportation planning, production planning and inventory planning. The review by Chelly et al. [2019] identified a gap in research related to SCD/C decisions within LCSCM. The other types of decisions received more attention within LCSCM research compared to SCD/C decisions. As this knowledge gap is defined, an emphasis on this category of decisions may be beneficial. According to Kouvelis et al. [2006], theSCD/C category includes strategic decisions related to the location of facilities (e.g. production, storage, distribution), how to handle the capacities of the different facilities, how to design supplier and distribution channels, and how to organise communication and process between the different parties in the SC. Managing the carbon emissions associated with these decisions could help companies improve their environmental performance and achieve their carbon emission reduction target [Chelly et al., 2019]. This reinforces the importance of conducting more research on the impact of SCD/C decisions within LCSCM on supply chain emissions. This same review also reinforces the importance of specifically transport-related emissions, versus inventory- or production-related emissions. Hoen et al. [2014] also state that transport emissions have become responsible for a significant proportion of total carbon emissions and an even greater proportion of the projected increase in carbon emissions. This reinforces the critical importance of considering carbon emissions from transport when studying LCSCM.

In addition to the findings and gaps described above, several other research directions were identified in the various literature reviews. The review by Ansari and Kant [2017] stated that the most prominent industries present in the reviewed papers included manufacturing, food, electrical and automotive industries. To contribute to the literature in this research area, another industry could be consulted. Research within the consumer goods industry is lacking in this area, as this industry scored significantly lower in the amount of research papers present within it compared to other industries in the field of SSCM. In addition to this potential research direction, another one was found in previously conducted literature reviews. The review by Eskandarpour et al. [2015] found that the focus of all reviewed articles included modelling of CO_2 emissions. However, it may be useful to consider emissions other than GHG emissions [Eskandarpour et al., 2015]. Moreover, both Chelly et al. [2019] and Eskandarpour et al. [2015] mentioned that further research needs to include uncertainty in the emission values of different transport modes and uncertainty in the demand for goods. Incorporating these types of uncertainty should also be consulted in this master thesis research.

In summary, taking into account all the above findings and possible research directions, current literature in the field of LCSCM lacks research on modelling a global SC within the consumer goods industry. Further research on modelling this kind of SC should focus on SCD/C decisions and with regard to emissions it should also focus on emissions other than GHG emissions. Moreover, further research should take into account uncertainty about the emission values of the different modes and uncertainty about the demand for the goods in the SC.

2.2.4 Type of SCDC decisions and modelling technique

Within the above-mentioned research direction, derived from previous literature reviews, studies focusing on SCD/C decisions were sought (criterion 1 for article selection). Eventually, 19 important, prominent and recent research articles were analysed based on different points of analysis. Table A.1 provides an overview of these 19 articles. The table also shows the analysis points. The first includes the type of SCD/C decisions (e.g. choice of transport mode, choice of facility location, routing decision). Secondly, the modelling technique is shown in the table (e.g. MINLP, MOLP, MILP, algebraic equation, input-output model) as a point of analysis.

As mentioned above, transport is a major source of carbon emissions [Hoen et al., 2014]. Therefore, all 19 articles included in this analysis are transport-related studies (criterion 2 for selecting an article). By reviewing all articles, it is found that carbon emissions can be reduced through effective management of routing decision [Validi et al., 2014; Glock and Kim, 2015; Kumar et al., 2016; Suzuki, 2016; Qiu et al., 2017], transport mode selection [Bauer et al., 2010; Harris et al., 2011; Hoen et al., 2013, 2014], location selection [Lam et al., 2009; Musavi and Bozorgi-Amiri, 2017], freight size [Rudi et al., 2016] and logistic outsourcing [Ameknassi et al., 2016; Li et al., 2017]. Within transport decisions, traditionally only cost and lead time were considered important criteria. But now, carbon emissions are also included as an important criterion for deciding on transport modes [Chen and Wang, 2016]. In addition to the transport mode, carbon emissions also depend on other logistics parameters; load factor, cargo size and more product-specific characteristics such as weight and volume [Rudi et al., 2016]. All 19 studies looked at the effectiveness of the particular type of SCD/C decision as found in Table A.1 (e.g. transport mode selection, facility location selection, routing decision, freight management), in reducing carbon emissions.

The 19 analysed studies all focus on different SCD/C decisions, all of which can lead to carbon emission reductions in SC's. It can also be concluded from the analysis that the focus on a particular type of SCD/C decision determines the choice of a particular modelling technique. Some types can be modelled with several techniques and other types are regularly modelled with the same technique. The studies that focus on routing decisions all appear to use a programming modelling technique; either MOLP, MINLP or MILP. This phenomenon is not surprising as the routing decisions are decisions where an optimal route needs to be found. MOLP, MINLP and MILP are all modelling techniques where an optimal solution can be found. For all other SCD/C decisions, different modelling techniques can be used, as shown inTable A.1. It is therefore important to decide on the primary focus of the research with respect to the type of SCD/C decisions and the models purpose (optimisation or not), and then decide on the modelling technique. This will be further explained in the next chapter.

3 RESEARCH METHODOLOGY

The purpose of this chapter is to clarify the research approach and research methods. Furthermore, the overall research process is presented, and it is explained in which chapters which sub-research questions are addressed. Finally, the data collection processes are described.

3.1 RESEARCH APPROACH

This research aims to clarify the impact of so-called SCD/C decisions on emissions, costs, and time. To achieve this goal, a quantitative research approach is needed, as in this way, emissions, costs and time can be measured, and the impact can be displayed in numbers. The purpose of the model to be constructed is to show this impact in numbers, not specifically to optimise single or multiple criteria. A finding from the previous chapter is that the purpose of the model determines the modelling technique. In this case, the purpose is to create a model that shows the impact of SCD/C decisions on emissions, costs and time in a clear manner. This can be achieved by creating a model that consists of a system of equations, which are equations concerning distance, transhipment etc. If done correctly, one can eventually do an optimisation, but this is not the purpose of the model. Therefore no programming modelling technique is applied like MILP or MOLP where optimisation of certain criteria is the purpose.

The main research question corresponds with the above-stated goal. To answer the main research question, sub-questions will be addressed to eventually gather all information needed to achieve the aim of this research.

Figure 3.1 shows the visualisation of the research process. The main research question just mentioned is shown at the top of the diagram. Below are the steps that need to be taken to explore, conceptualise, develop, test and apply the model. Under each of these steps in the overall process, all of the sub-questions that will be answered are listed. This research is structured so that the steps taken and the sub-questions answered are described and addressed in chronological order. The next section will elaborate on the methods used.

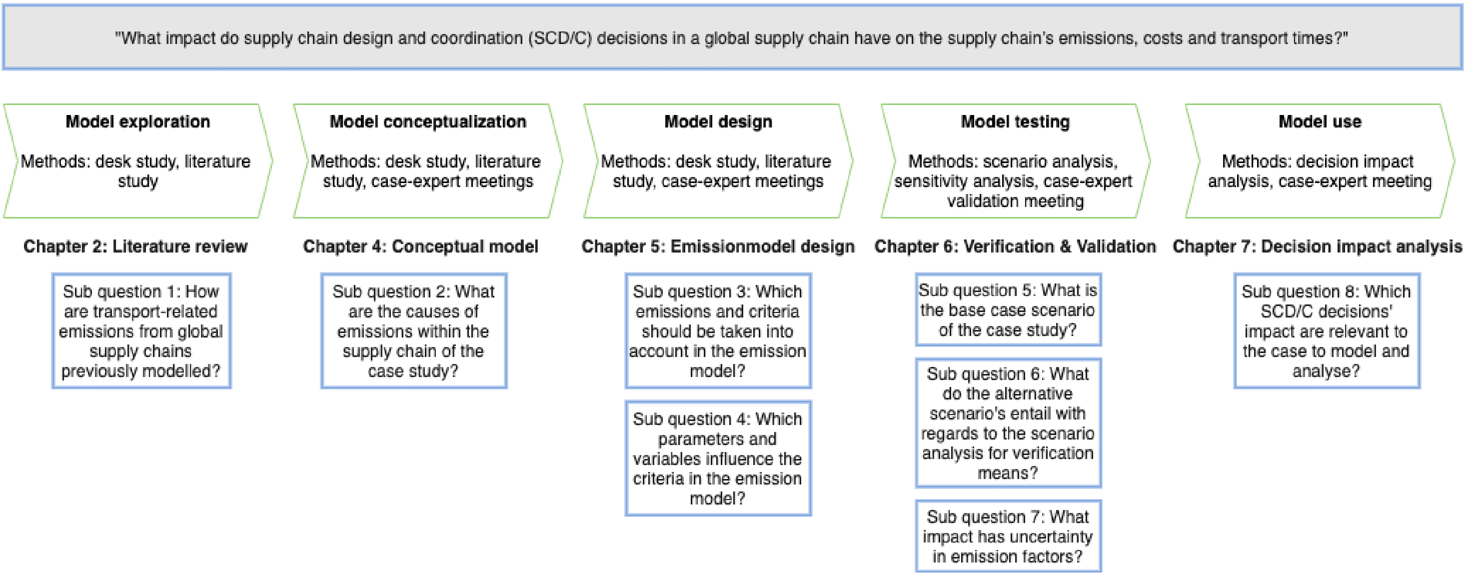

Figure 3.1: Research process

3.2 RESEARCH METHODS

In this section, the overarching research method, the case study methodology, will be explained. In addition, the other research methods, as shown in Figure 3.1, will also be explained, except the literature study and desk study, as these methods do not require a specific explanation for this research. These include the case-expert meetings, scenario analysis, sensitivity analysis and decision impact analysis. Next to this, the analysis method in this study will be explained, and finally, the data collection methods are also discussed in this section per sub-question.

3.2.1 Case-study methodology

The main research questions will be answered in this research employing the case-study methodology. Becker [1970] explains, the case study is usually conducted to generate general relevant findings beyond the individual case [Fidel, 1984]. This also applies to this research. The case study is conducted on the supply chain of company L, but the findings regarding the impact of SCD/C decisions on emissions, costs, and time apply to supply chains in general.

This research method is ideally suited to measure the impacts mentioned in the main research questions. The designed model was applied to the supply chain of L but can also be applied to a supply chain of another company. In this sense, the model can also be seen as a tool that a company can use to understand the impact of SCD/C decisions on emissions, costs and time. By selecting and applying the model to a specific case, this use can be clearly demonstrated, and the results can be correctly interpreted. Because the case study method is applied in this research, the so-called case experts were also involved. Data was collected from them, and the model was validated, and the use of the model was analysed. Naturally, the impact of decisions was also discussed with the case experts.

3.2.2 Case-expert meetings

The case experts were approached at different times. This started with the conceptual model. After the general conceptual model was drawn based on the theory, the conceptual model was specified and made concrete for the case study with the help of the case experts. As a method to achieve this, conversations were held with the case experts in the company to understand how the supply chain works. This also made it clear where emissions take place for this concrete supply chain. Once this concrete conceptual model had been created, the basis for the emissions model was established.

The case experts were also consulted in collecting data for the emission model, especially for the so-called transport leg data and product data. To determine the distances, the locations of all transport legs were needed. To calculate the cargo weight and the number of containers, logistic data per box was needed and the planned order quantity and number of containers per delivery. Emission data and cost and time data were, on the other hand, gathered from literature.

In addition, a meeting was held with the carrier platform that the company uses to obtain realistic data to validate the model and hear how some aspects work in practice. Namely, to what extent can carriers be selected that exclusively use a certain type of fuel or vehicle. In this way, the meeting provided practical insights and realistic data that was used to validate the model.

Finally, the case experts were also consulted to validate the model when it was running and generating results. A case-experts validation meeting was set up where several outcomes were discussed, the usefulness of the model was discussed, and possible additions/simplifications that would make the model more useful.

3.2.3 Scenario analysis

To perform scenario analysis, scenarios needed to be designed. A distinction was made between a base case scenario and alternative scenarios. In this research, where a case-study method is used as the overall method and where the case concerns the supply chain of L, an even more specific case was chosen for the scenario analysis. Namely, within the supply chain of L, a specific loyalty programme, hence for a specific retailer who is a client of L, is used for the scenario analysis. The purpose of the scenario analysis, in this case, is to check whether the model covers everything that needs to be calculated and whether the model obtains the correct output that was intended. Scenario analysis can also be used to check whether the outcomes realistically relate to each other. The first goal refers to verification of the model, and the second to validation. Moreover, the scenario analysis results are also used for the decision impact analysis of a certain type of decision, namely mode selection. In Chapter 6, the scenario analysis will be discussed, and this method will be explained in more detail.

3.2.4 Sensitivity analysis

A sensitivity analysis is performed to analyse how sensitive certain parameters or variables in the model may be. In sensitivity analysis, these parameters and variables are increased and decreased by 10% at a time to test the sensitivity on the output of the model. Before carrying out this analysis, expectations are given as to what the changes will mean for the output to test whether the model behaves as predicted. This sensitivity analysis is, therefore, part of the verification process of the model. In addition, the sensitivity analysis is carried out to test the impact of uncertainty in emission factors, which will answer sub-question number 7. In Chapter 6, the method of conducting the sensitivity analysis will be explained in more detail.

3.2.5 Decision impact analysis

The decision impact analysis is carried out to analyse the impact of decisions on emissions, costs and time. As the overall method is a case study, relevant decisions for the case, the supply chain of company L, were analysed. This analysis can only take place when all previous steps have been completed, see Figure 3.1. The verified and validated model can be used to perform this decision impact analysis. To this end, it was first determined which types of SCD/C decisions will be analysed, which is also the answer to sub-question number 8. Next, the analysis was carried out for each type of decision. As it concerns a quantitative model, the impact will become clear by comparing different model outcomes. By entering different data, such as different modes, vehicle types, fuel types and routing or locations of facilities, logically different outputs emerged that can be compared. This method is applied on the one hand to ultimately answer the main research question, namely what impact these types of decisions can have on emission costs and time, but on the other hand also to make the decision-makers aware of this impact. The model that has been developed functions as a tool to make this decision impact analysis possible. To this end, the developed model should capture all outputs of the criteria emissions, costs and time to enable the analysis to be carried out.

3.2.6 Analysis method

In this research, an interpretive and impressionistic method of analysis was used. In the interpretative research approach, concrete wholes are the research's starting point, where the concrete whole is initially analysed. Then several concrete wholes are compared with each other, according to 't Hart et al. [2005]. In this research, first, the supply chain of L is analysed, after which the emission model is created, then generated results of the model are analysed with a verification and validation step. Finally, the impact of different SCD/C decisions on emissions, costs and time are compared with each other by using the emission model, which is therefore in line with what 't Hart et al. [2005] states. They also state that in interpretative research, one is interested in the variation within the subject of study, i.e. the variation between the different analysed wholes, in this case, the variation between the impact of different SCD/C decisions on emissions, costs and time. The analysis of interpretive research is done by explaining the situation encountered with the help of concepts and categories derived from the research field. In this way, an attempt is made to arrive at an appropriate, theoretical coverage for the phenomenon under investigation ['t Hart et al., 2005]. In this study, the decision impact analysis also attempts to explain the variation found in this way.

Another characteristic of the interpretative approach is conducting interviews, after which the events are interpreted from the point of view of those involved ['t Hart et al., 2005]. In this study, too, meetings were held, not structured interviews, but more open conversations from which findings were drawn. The impressionistic way of analysis, next to interpretative analysis, is also very apparent here, especially in the validation step of the research. This is because, during the validation of the model, the opinions of the case experts about the model were sought to gain insights into the usefulness of the emission model for the company. This corresponds with the focus on subjectivity instead of objectivity in the impressionistic analysis method. The set-up of the case expert validation meeting that took place gives room to express opinions. This is because it was not a structured interview but because the model and certain outcomes were shown. The reactions to these were asked concerning how realistic certain outcomes were (concerning the time of transport, for example), the usefulness of the model as a whole, the usability of the model in practice and the added value. This ensures an open approach with plenty of room for the subjectivity of the case experts. In this way, the case experts did not have to agree, but there was room for everyone's opinion.

3.2.7 Data gathering methods

For each of the eight sub-question, the data collection methods are described.

1. How are transport-related emissions of global supply chains previously modelled?

To answer this sub-question, a desk and literature study and review was conducted to collect data. Academic literature was searched in the scientific databases Scopus and Web of Science. The purpose of this literature search is to determine how emissions are modelled in the past.

2. What are the causes of emissions within the supply chain of the case study?

To answer this sub-question, a desk and literature study was conducted to collect data for defining a general conceptual model. For the literature study, Scopus and Web of Science were again used as databases. This conceptual model includes where in general, emissions occur in supply chains. After this general conceptual model, the model could be specified to the SC of the case study. For this case-specific conceptual model, data were collected by asking the case experts about their supply chain process. By consulting the case experts, the case-specific conceptual model was validated.

3. Which emissions and criteria should be taken into account in the emission model? 4. Which parameters and variables influence the criteria in the emission model?

To answer these sub-questions number 3 and 4, a desk and literature study was carried out to collect data on which emissions and criteria to include in the emission model on the one hand and to gain insight on the parameters and variables that influence the criteria on the other hand. The criteria were validated by consulting the case experts. For the literature study, Scopus and Web of Science were used as databases. With this knowledge, the model was ready to be developed in the tool Excel.

5. What is the base-case scenario of the case study? 6. What do the alternative scenarios entail with regards to the scenario analysis for verification means?

The next step was to verify and validate the emission model. To this means these sub-questions arise that support the scenario analysis that functions as part of the verification of the model. For these sub-questions, the case experts were consulted to collect data and validate and verify the scenarios. When business data appeared to be unavailable, academic literature was used, or assumptions were made based on literature. Again, Scopus and Web of Science were used as databases.

7. What is the impact of uncertainty in terms of emission factors?

This sub-question is part of the sensitivity analysis carried out to determine the effect of uncertainty of emission factors for different modes, vehicles and fuels of transport used in the model. Therefore, the emission model needed to be used. The data gathering process of the emission factors took place by conducting desk and literature research.

8. Which SCD/C decisions' impact are relevant to the case to model and analyse?

To gather the data needed to answer this sub-question, a case-expert meeting was set up to determine which type of decisions were most relevant to the case. When this final sub-question is answered, everything is set to carry out the decision impact analysis.

4 CONCEPTUAL MODEL

In this chapter a conceptual model is given. First, the type of emissions and the sources of all SC processes in general are conceptually visualised. Then this general model is specified for the case study. The question to be answered with the conceptual model is where, in the supply chains, emissions occur and where can measures therefore intervene?.

4.1 THEORETICAL CONCEPTUAL MODEL

The general conceptualisation is given in Figure 4.1. At the beginning of the SC, raw materials are produced that need to be processed. During these processes, emissions are created. These can be from heating, cooling, transport equipment, storage, packaging materials, etc. These raw materials are usually transported to the production facilities. This transport is generally done by road or inland waterway. For road transport, a number of aspects that determine emissions are outlined. For road transport, the emissions per tonne of cargo depend on the truck load, the distance and the vehicle technology. As far as vehicle technology is concerned, diesel and petrol trucks emit direct emissions (thank to wheel (TTW) emissions), but electric trucks do not emit direct emissions. However, when electric trucks are used, there are emissions from the electricity production needed to run the trucks (well to thank (WTT) emissions). The same type of emissions, emissions due to the production of fuel (WTT emissions), also count for diesel and gasoline trucks. These two types of emissions are categorised as TTW emissions and WTT emissions. Emissions that occur during the transport process are both GHG emissions and air polluting emissions.

Direct production emissions occur during production processes within a SC of a company, depending on the type of production process. This can be during heating, cooling, melting, painting, transport of equipment, storage, packaging of products, etc. After production, transport takes place again. The first part of the transport process involves pre-haulage. This type of transport usually takes place again by road or by inland waterway. This means the same as described above. When the goods from the pre-haulage transport process arrive at terminals, transshipment takes place. During transshipment, loading and unloading activities take place that cause emissions. These emissions are determined by the types and sizes of logistics units handled at the terminal; box sizes (TEU, FEU) or pallet sizes (standard pallet, half pallet), as well as the weight of the goods (heavy, light). The specific way the units are moved and stored is important (type of equipment, duration of storage), as well as whether the cargo is refrigerated or non-refrigerated. Another aspect is whether the terminal is illuminated or based on motion sensors that save light and thus electricity.

The transshipment process is followed by the main haulage of the transport. This main haulage can take place by different modes: road, rail, sea or air. These modes of transport all have different emissions, which can be subdivided into TTW- and WTT emissions. After the main haulage, transshipment takes place at a transport terminal. The same applies to the end-haulage; the emissions are similar to those from pre-haulage because road transport or inland waterway is usually used as the mode of transport.

The transport processes are followed by warehouse activities. As with the transshipment process, emissions depend on the type of logistics unit, the weight of the goods, specific characteristics of the equipment used, the duration of storage, heating/cooling and lighting in the warehouse. From the warehouse the goods are generally transported to the buyer of the goods by road or inland waterway. At the buyer's premises, direct emissions may occur if the goods require energy for their use. Finally, at the end of the life cycle of the good, emissions occur during processing at the end of the life treatment, in the recycling process.

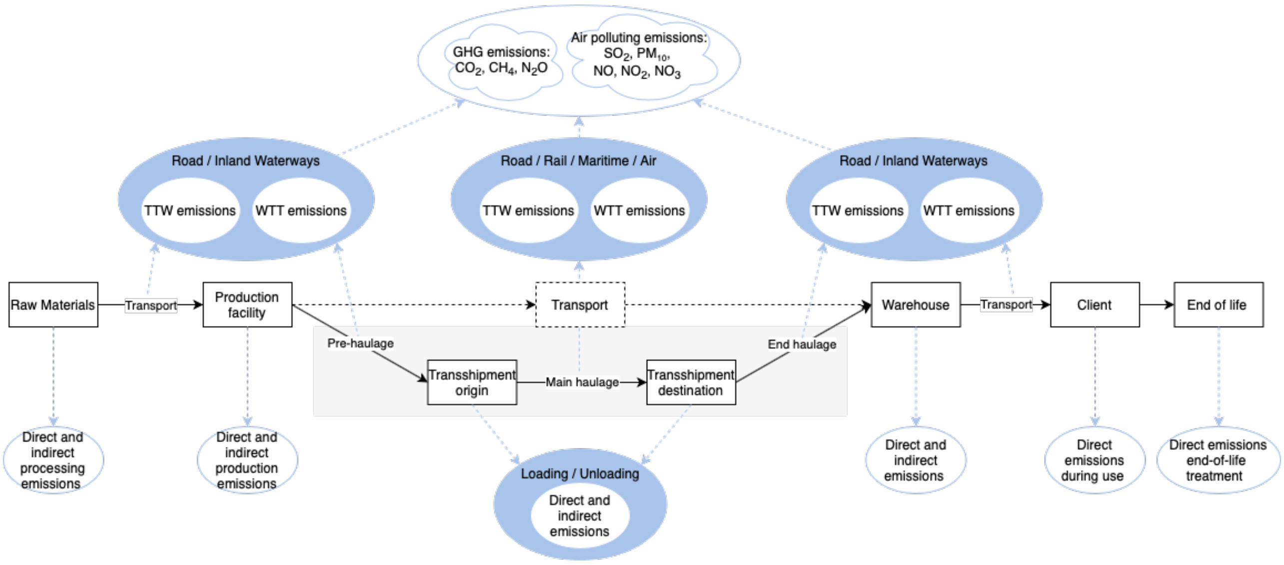

Figure 4.1: Theoretical supply chain emissions

4.2 CASE-SPECIFIC CONCEPTUAL MODEL

For this study, it is important to convert the general conceptual model into a case-specific conceptual model. An important aspect here is to determine which parts of the processes are in the hands of the company. In which parts do they have insight and in which parts can they control or change the way processes are executed. After discussions with case experts, the following conceptual model and scope was determined, Figure 4.2.

The core business of L's SC includes ordering consumer products, receiving these products and shipping them to the customers (the supermarkets). For this reason, the raw material process and the production process were too far away from the core business of L. The green line indicates the scope of the SC to be taken into account when designing and developing the model. The processes of the SC after the process of origin from transshipment to transportation to the customer are considered. This scope has been agreed and validated with the case experts. This scope also seems feasible when looking at the average duration of a master thesis project. First, the focus will be on modelling transport-related emissions and then the emissions from the transshipment and warehouse will be modelled.

It should be noted that the SC of the case study is a fairly simple and straightforward SC. For this very reason it is extremely suitable to develop an emission model from scratch based on this supply chain, as it is a manageable SC. This does not mean that the emission model would not be suitable to be applied to more complex supply chains. Also for more complex supply chains, the emission model can be applied to investigate the impact of different SCD/C decisions on emissions, costs and time. This is because as many transport legs and transshipment points can be added as one would like and it is therefore a general model that can be applied to any SC.

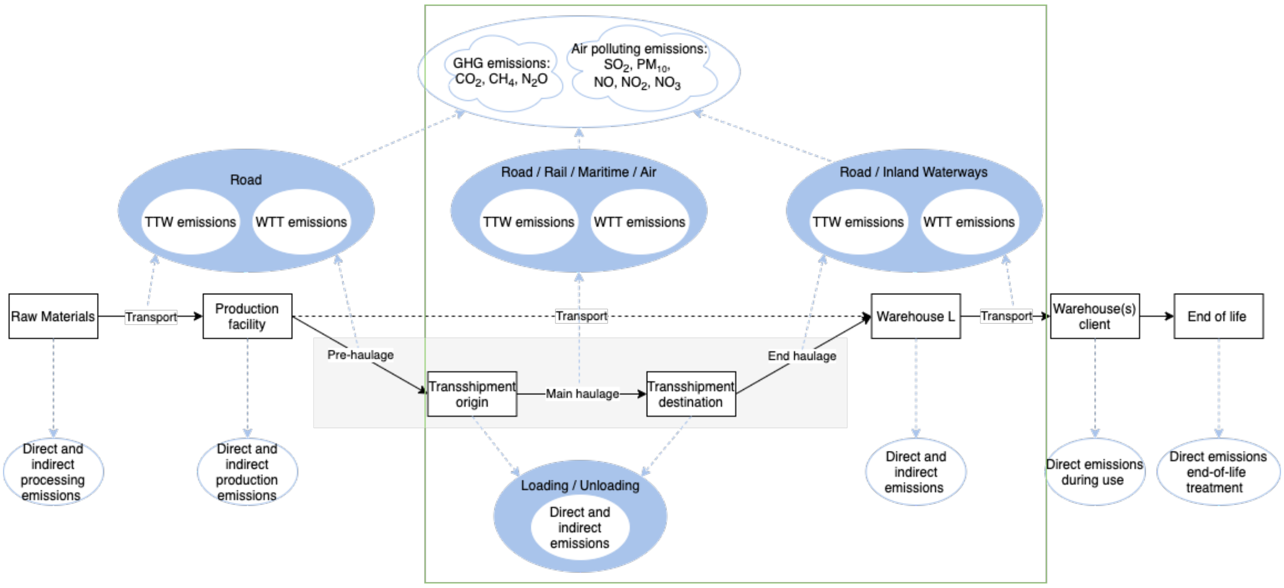

Figure 4.2: Case specific supply chain emissions

5 EMISSION MODEL DESIGN

Based on the conceptual model, the emission model can be designed and developed. This chapter first describes the criteria (emissions, costs and travel time) included in the model. Then the data input is presented; required data per transport leg, product data, emission data and cost and time data. In addition, the structure of the model is explained and finally the calculations used in the model are shown.

5.1 CRITERIA

The criteria included in the model are based on the dual main research question. On the one hand, the effect on emissions needs to be measured, and on the other hand, the effect on costs and travel times needs to be included. Emissions as a criteria concern sustainability performance, while the other part of the main research question, costs and travel times, represent business performance. Therefore, both emissions and costs and travel times are included in the model as measurable criteria. This section examines the criteria in more detail.

5.1.1 Emissions

Type of emissions

Table 5.1 gives an overview of the emissions included in the emissions model. The last row indicates the effects that the emissions have, which increases the importance of the emissions to be included in the model. The choice of these emissions was made based on the relevance of the effect the emissions have, the suitability for quantitative calculations, the significance of the contribution of freight transport to these emissions compared to all other effects, and data availability.

As shown in Table 5.1, the emissions of CO_2, CH_4 and N_2O are collectively referred to as CO_2 equivalents (CO_2e). In Table 5.2, the ratios of CO_2, CH_4 and N_2O are shown in the all-encompassing term CO_2e. The number GWP stands for the global warming potential of 1 kilogram of gas over 100 years as a factor of 1 kilogram of CO_2, whereby the GWP of CO_2 is standardised to 1. Thus, the numbers in the table represent the ratios of CO_2, CH_4 and N_2O to the term CO_2e used in this research. In addition to CO_2, CH_4 and N_2O, three more emissions constitute the total of six greenhouse gas emissions. Hydrofluorcarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SFs) comprise these three other emissions. These three are not included in the model as these are the products of industrial processes [Schmied et al., 2012]. Such emissions are not released during the combustion of oil, gases or other fuels, which is the case for transport or transshipment.

Table 5.1: Selected emissions

Emission	Name	Selection reason
CO_2	Carbon dioxide	Main greenhouse gas emission
CO_2e	CO_2-equivalents Next to CO_2, also CH_4, N_2O	Greenhouse gas emissions
SO_2	Sulphur dioxide	Acidification, eco-toxicity, human toxicity
NO_x	Nitrogen oxide	Acidification, eutrophication, eco-toxicity, human toxicity, summer smog
PM_v	Particle matter during combustion	Human toxicity, summer smog
PM_{sl}	Particle matter during wear and tear	Human toxicity, summer smog

Table 5.2: GWP-factors [IPCC, 2014; Muñoz and Schmidt, 2016]

GHG	Global Warming Potential (100 years)
CO_2	1
CH_4	30,5
N_2O	265

When calculating emissions, a distinction is commonly made between WTT, TTW and WTW emissions. The difference has already been introduced in Section 4.1, but a brief explanation follows here. The difference is visualised in Figure 5.1. WTT emissions refer to the indirect emissions from the extraction, production and transport of fuels and energy. TTW emissions refer to the direct emissions released during the combustion of fuels or the energy consumption during the use of the vehicle. WTW emissions are the total of WTT and TTW emissions combined. In this research, the total, i.e. the WTW emissions, are presented when discussing the results of the model. However, this total is constructed by combining WTT and TTW emissions. The TTW emissions will be presented separately in the calculations section of the emission model.

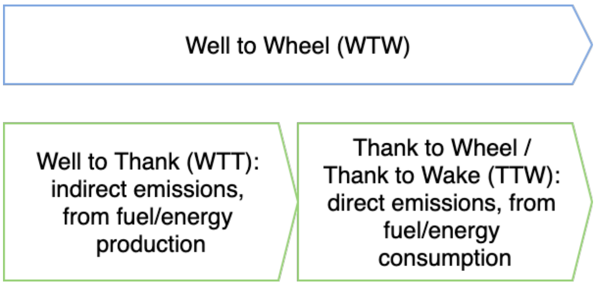

Figure 5.1: Emissions distinction

Emission calculation methods

There are various methods for calculating these emissions. The fuel method, the distance method and the expenditure method are three commonly used methods, all of which are in line with the greenhouse gases protocol [WRI and WBCSD, 2011]. The fuel method involves determining the amount of fuel consumed and applying appropriate emission factors to that amount. The distance-based method involves determining the mass, distance and mode of transport of each shipment and then applying the appropriate mass-distance emission factors for the vehicle used. The expenditure-based method identifies the amount of money spent on each mode of transport and applies secondary emission factors. To identify the most appropriate method in each case, the available data should be considered. The fuel-based method is the most feasible method when it comes to estimating CO_2, but the distance-based method is preferable when it comes to estimating CH_4 and N_2O. All methods have their advantages and disadvantages, but it is generally accepted that the fuel-based method is more specific and therefore always preferable to the other methods. However, as data on fuels is often not available, the distance-based method is the second best option [WRI and WBCSD, 2011, 2013; CE Delft, 2021]. The expenditure-based method is only used as a last resort when data is not available.

Upon deciding which method would be most suitable for this case study, it became clear that the fuel-based method would not be possible. The reason is that the company L does not have its own fleet of transport vehicles, but works with logistics service providers. Hence, it is difficult to obtain their fuel data as they have no insight into the amount of fuel used specifically for L's transport. In contrast, data on distances and product-specific data such as mass are available within L and therefore the distance-based method is the most appropriate method for this case study and is applied in the model.

Transshipment emissions

The emissions just discussed occur during the transport of goods or during the fuel/energy production that is used for the transport of goods. However, in addition to this, emissions are also generated during the transshipment of goods. This involves moving goods from one modality to another or storing them in a warehouse. Activities that cause those transshipment emissions are diesel or energy consumption by handling equipment, or consumption of diesel or energy for equipment such as swap body vehicles or forklift trucks. In multi-modal transport, emissions from loading and unloading can have a significant impact on total transport emissions. In particular, when comparing two transport alternatives where one requires more transshipment than the other, it is important to take the transshipment emissions into account.

5.1.2 Cost & Travel time

As this study is a business case, in addition to emissions, costs and travel times are also included as criteria in the model. The data required to calculate these costs and travel times is explained in the next section, Figure 6.1.2.

5.2 DATA INPUT

The development of the emission model requires the collection of data. This chapter describes the types of data needed, where data can be found and what data will ultimately be used in the model. To structure this chapter, a distinction is made between transport leg data, product data, emission data and cost and travel time data. An overview of all input data is shown in Figure 5.2.

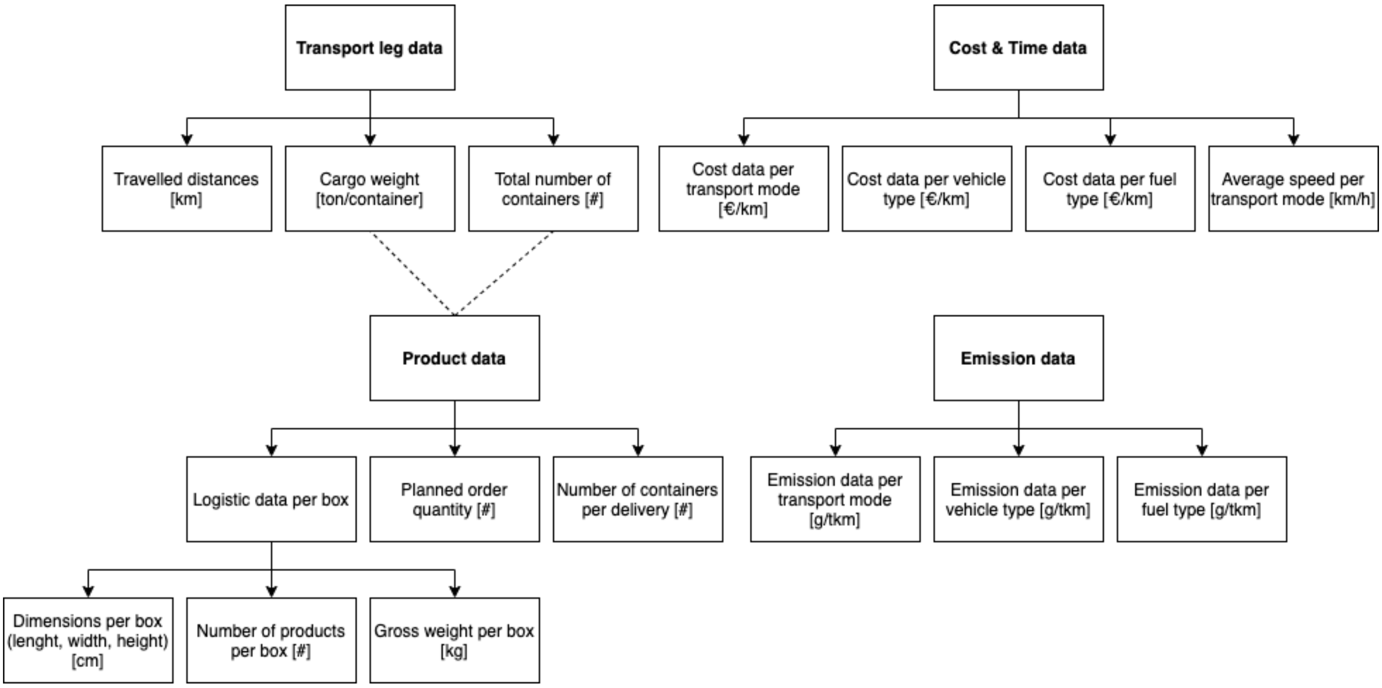

Figure 5.2: Data input overview

5.2.1 Transport leg data

In order to be able to calculate the emissions per transport leg, the following data is required per transport leg: the distance travelled in km and the total cargo weight to be transported along that leg in tonnes. The latter data can be obtained from the total number of containers to be transported over that transport leg, together with the weighted average cargo weight per container. All three of these data inputs will be discussed in this section.

Travelled distance

Firstly, data on the distance travelled per transport leg should be obtained. Since various transport modes are included in the emission model, different distance data for each transport mode should be searched for. In order to automate the emission model as far as possible, data sets per transport mode are ideally needed to be collected. If, during the data collection process, it appears that such data sets do not exist or are not suitable for various reasons, assumptions are made or data is manually retrieved. The different modes included in the model are maritime (and short-sea), inland waterway, road, air and rail transport, and all have different distances to cover. For the air transport mode, the as the bird flies distances can be used. However, for the other modes it is not possible to use the as the bird flies distances and therefore datasets have to be found or distances have to be approximated. After searching for datasets, a choice is made per modality whether a suitable dataset is available, whether certain assumptions have to be made, or whether data has to be manually searched for and entered into the model. Table 5.3 shows per modality where the distance data is collected and which assumptions are made when necessary.

Table 5.3: Distance data sources

Modality	**Distance data sources and assumptions**
Air	Great circle distances are used, calculated with the Haversine formula Dataset with longitude and latitude coordinates of all worldwide airports is used from www.ourairports.com
Inland waterway	Specifically searched per inland waterway route on www.blueroadmap.nl
Maritime	Specifically searched per inland waterway route on www.ports.com
Road	EU Rhomolo model: Road distances between all EU NUTS-2 regions If outside EU, specifically searched per road route on Google Maps road distance
Rail	Specifically searched per railway route on the operators' site If unavailable, road distance is used

In the case of air transport, the great circle distances are used and calculated with the Haversine formula. Section 5.3 presents the formula and explains the calculation, but the input needed for this formula is described here. A data set is retrieved that contains the longitude and latitude coordinates of each airport [OurAirports, 2021]. These coordinates are needed to use the Haversine formula which can subsequently calculate the flight distance between two airports. In the data set of OurAirports [2021], the longitude and latitude coordinates can be looked up per airport. The IACTA code of the airports considered are needed for this task. The IACTA code of the airports considered must therefore be inserted as data input in the emission model (e.g. "PEK" for Beijing Airport and "AMS" for Schiphol Airport).

When searching for data sets with distances between inland ports in Europe, it appeared that such a data set did not exist. Since the routes are limited to waterways, the distances covered are very specific. It is therefore not realistic to use, for instance, road distances. Hence, it was decided to manually retrieve the specific inland navigation distance for each transport leg with the inland navigation modality. This specific distance can be found on the website of Bureau Voorlichting Binnenvaart [2021].

The same applies to the maritime distance data set as to the inland waterways distances, namely that no useful data set could be retrieved. Similarly, the decision was made to manually retrieve the specific maritime distance for each transport leg with the maritime modality. The data from Ports [2021] is used.

In the case of road transport, the EU-Rholomo model is used for road distances within Europe. In a broad sense, Persyn et al. [2019] have created a unique data set of inter-regional transport costs for the EU regions at NUTS-2 level by using the open digitised road network OSM. To calculate these costs they also calculated the road distances between the EU NUTS-2 regions; these distances from their data set [EU Science Hub, 2018] are used in the emissions model. In order to be able to use this data, the start and end locations of each road mode leg in the emissions model needs to be converted to the NUTS-2 code. Therefore data sets are retrieved from European Commission [2020] containing all postcodes of each EU country. However, in these data sets only the postcodes with corresponding NUTS-3 regions were found instead of NUTS-2 regions. For this reason, all data was cleaned and the correct NUTS-3 regions were entered for each postcode. The EU-Rholomo model includes all road distances within the EU. No data set could be found for road distances outside the EU. Therefore, it was decided to manually retrieve the road distance in Google maps when the start or end location of a transport leg is located outside the EU.

Regarding the data collection on rail distances, the same applies as for the inland waterway shipping and maritime shipping distances, namely that no feasible data set could be found. For this reason the decision is made to collect the specific distance data by rail manually for each transport leg with the rail modality. Initially, data from the railway company's website is used as source and when this is missing, an assumption is made to use the road distance data from Google maps. In this research's case study, the railway distance was found at GVT Intermodal Freight Management [2021] and the assumption is applied as well.

Cargo weight per container

Secondly, in addition to the distance data per transport leg, the cargo weight per transport leg must be identified. The cargo weight depends on the type of products being transported. Hence, the product data should be available. This link is visualised in Figure 5.2 by a dotted line. Once the logistical data per box, the planned order quantity of products and the number of containers per delivery are all known, the cargo weight per container can be computed. The specific calculations are given in section Section 5.3.

Total number of containers

Finally, the total number of containers is also linked to the product data, as is the cargo weight. Once the delivery planning is known and so is the number of containers per delivery, the total number of containers can be computed. The cargo weight per container and the total number of containers combined generate the total cargo weight per transport leg. The specific calculations can be found in Section 5.3.

5.2.2 Product data

To be able to calculate the total cargo weight per transport leg, product data must be available, as mentioned earlier. The product data is divided into the logistical data per box in which the products are being transported, the planned order quantity and the number of containers per delivery.

The logistical data per box should be provided by the suppliers of the goods; the dimensions of each box, the number of products in each box and the gross weight per box. The planned order quantity and the number of containers per delivery are to be found in the delivery planning a company creates, which is drawn up in consultation with the suppliers.

5.2.3 Emission data

Transport emission data

Based on the transport leg data as described above, the transport performance per leg can be computed. This transport performance is expressed in tonne-kilometres (tkm). This means that the emission data should be expressed in grams per tonne-kilometre. During the search for emission data, it became apparent that sufficient data on emission factors per tonne-kilometre or per kilometre is available. The decision is made to use data from the CE Delft research institute [CE Delft, 2021]. This institute calculated the emission factors in the year 2020, which means that the data is based on recent findings. Moreover, CE Delft provides a comprehensive set of emissions factors; per transport mode, the emission factors are given for different types of vehicles and different types of fuel or energy sources. For details on the CE Delft emission data used in the emission model, see Appendix B. The data displayed in this appendix shows that road types are also included in the table. Road type namely has an influence on emissions as well. On city roads, more emissions are emitted compared to driving on highways as on highways the speed is more constant versus stopping and starting the vehicle in cities. In this research the average road type is always used, as long distances are covered and the research does not consider specifically city logistics.

Transshipment emission data

Regarding the transshipment emissions, an energy consumption for transshipment of 4.4 kWh/TEU per movement is assumed in the model (TNO). The following emission factors for mobile equipment were used as input for the model to calculate the emissions caused by transshipment, see Table 5.4.

Table 5.4: Emissionfactors transshipment [g/kWh] [TNO, 2016]

	CO_2-eq.	NO_x	PM_v	SO_2
Diesel	779	3.16	0.17	0.005
Electric	549	0.39	0.02	0.164

5.2.4 Cost & Time data

In addition to emissions, data on costs and times is needed to include all three criteria in the emission model.

Cost data per transport mode

For this research, the choice is made to use the cost data from a particular study conducted by research institute Panteia [Panteia, 2020]. Panteia carried out this study on behalf of the KiM (Knowledge Institute for Mobility Policy), which is part of the Dutch Ministry of Infrastructure and Water Management. This study, which examines the cost development of the five most important freight transport modalities, breaks down the costs into: fixed costs, variable costs, personnel costs, modality-specific costs and general operating costs. Panteia's study contains the variable 'total cost per tonne kilometre' for each transport mode and container type of freight. One important note is that these costs do not reflect the freight rates. In fact, freight rates include, in addition to costs, carriers' profit margins and potential subsidies and taxes [Panteia, 2020]. These profit margins of the carriers depend on transport supply and demand and therefore it is difficult to find data on freight rates. For this reason the choice is made to use data on costs instead of freight rates. The costs do reflect the correct proportions of the cost differences between the various transport modes, which is exactly what needs to be known for this emission model. For the modes inland waterway and road transport different vehicle types were consulted by Panteia, which results in a different total cost per tonkm for those different vehicle types. Those differences are taken into account in this study as well. The decision impact analysis of the vehicle type decision in the next chapter will solely focus on the modes inland waterway and road transport, as the cost data for different vehicle types of the modes maritime, railway and air transport were not included in the Panteia research. If assumptions would have been made the output would not be comparable. Table 5.5 shows the cost data included in this model.

Table 5.5: Cost data [Panteia, 2020]

Mode	**Type of vehicle**	**Total cost per tonkm [€]**
Inland waterway	Smal container vessels	0.013
	Medium container vessels	0.033
	Large container vessels	0.023
Road	Tractor+trailer	0.115
	LZV	0.092
Maritime	Container vessel (3000-4999 TEU)	0.0013
Railway	Extra long container train	0.017
Air	Full-freight	0.18

Fuel cost data per fuel/energy type

For each modality, alternative fuel/energy/engine types have been identified. The influence of these different fuel types on fuel costs has been included in the model. To this end, assumptions have been made to reflect the difference in fuel cost of a particular fuel type compared to the base fuel type of that modality, which is currently the most prevalent type. These assumptions are based on collected information regarding costs of alternative fuels. Appendix C shows the ratios found and sources on which the differences from the base fuel type of a given modality are based. These ratio's found compared to the default fuel type are presented in percentages.

Average speed per transport mode

In order to calculate the total travel time per transport leg, data on the transport time per transport mode must be retrieved. Transport times can be computed if the transport speeds are known. In order to estimate the total travel time of a transport leg, it is decided to assume an average speed per transport mode. The total travel time is not only the 'cruising time', but also the time loss which includes the time needed for transshipment, customs controls, etc. Table 5.6 presents the assumptions regarding the average speed per mode to compute the total travel time per transport leg. Both the assumptions before and after a validation step with case-experts are shown, this validation meeting is discussed in Chapter 6. The latter column represents the average speeds that are eventually applied in the model since the output seemed more realistic to the case-experts compared to the first assumed average speeds.

Table 5.6: Assumed average speed per modality pre- and post model validation

Modality	Average speed pre-validation	Average speed post-validation
Air	200 km/h	200 km/h
Inland waterway	7,2 km/h	**8,5 km/h**
Maritime	20 km/h	**25 km/h**
Road	60 km/h	60 km/h
Rail	50 km/h	**35 km/h**

5.3 MODEL STRUCTURE AND CALCULATIONS

Figure 0.1 shows a high-level visualisation of the emissions and criteria (green) included in the model and the parameters (blue) and variables (white) that influence these criteria. On the basis of this diagram the model is created in the tool Excel. The calculations used in the model are presented below.

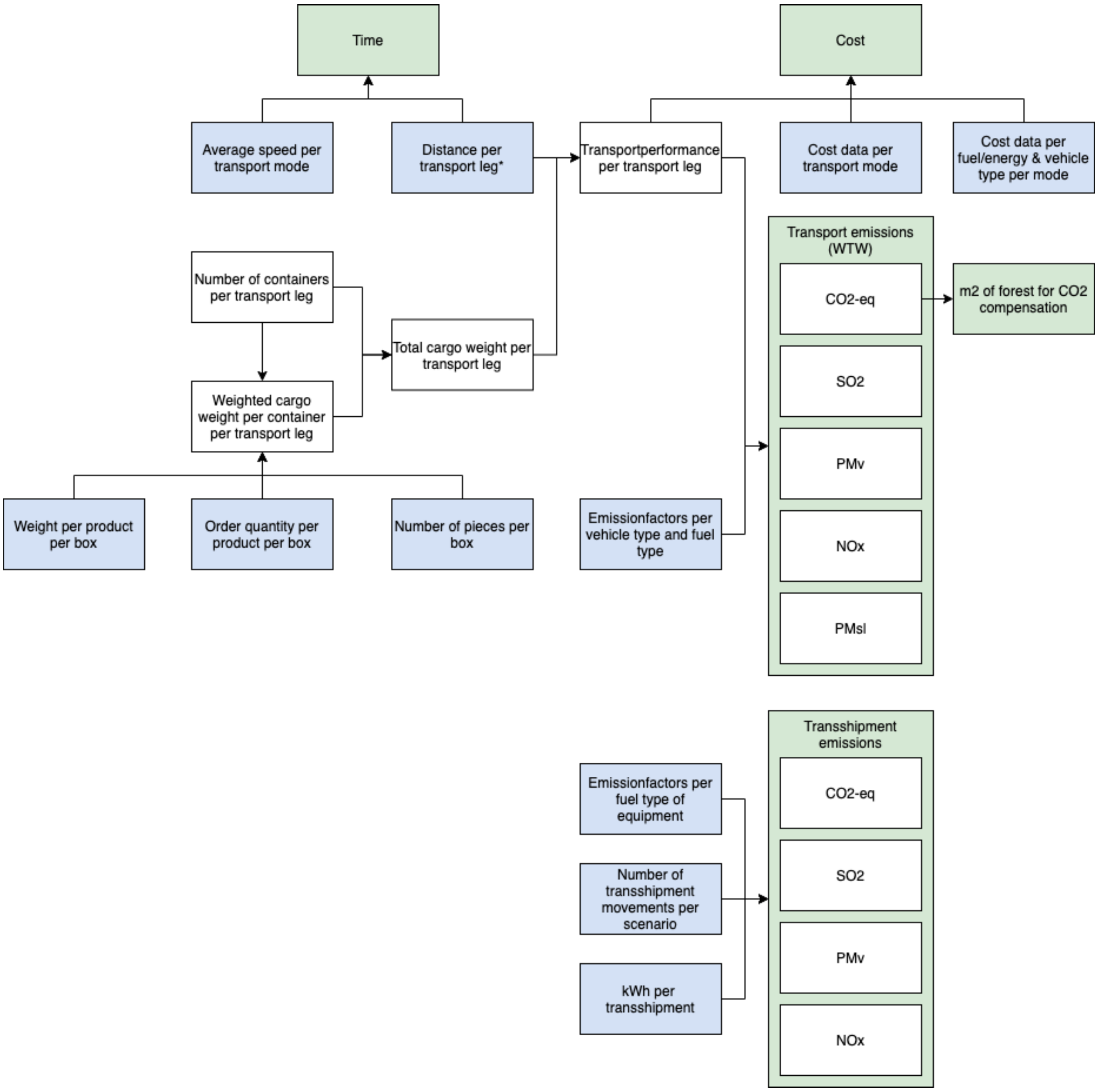

Figure 5.3: Model structure

Per transport leg the total cargo weight and the transport performance need to be calculated.

$$tcw = cwc * nc \tag{5.1}$$

where:

tcw = total cargo weight [ton]
cwc = cargo weight per container [ton/container]
nc = number of containers [#]

$$tp = tcw * d \tag{5.2}$$

where:

tp = transport performance [tkm]
d = distance [km]

Once this is known the CO_2-eq, SO_2, PM_v, NO_x and PM_{sl} transport emissions can be calculated. For each of these emissions counts the following equation. The emission factor needs to correspond to the correct modality, vehicle type and fuel type selected.

$$te = tp * ef \tag{5.3}$$

where:

te = transport emissions [g]
ef = emission factor [g/tkm]

Next to emissions, the transit time can be calculated as a criteria based on the average speed.

$$tt = \frac{d}{as} \tag{5.4}$$

where:

tt = transit time [h]
as = average speed [km/h]

The cost can be calculated by the total cost per tkm and by the fuel cost index from Appendix C. The total cost per tkm and the corresponding default fuel cost per tkm and fuel cost index need to correspond to the correct transport mode and vehicle type.

$$c = (tct - dfc + (dfc * fci)) * tp \tag{5.5}$$

where:

c = cost [euro]
tct = total cost per tkm [euro/tkm]
dfc = default fuel cost [euro/tkm]
fci = fuel cost index [%]

To calculate the transshipment emissions, the transshipment energy consumption needs to be known. In this case study 40ft high cube containers are taken into account, equal to 2 TEU. Regarding the transshipment emission factors, both diesel and electric mobile equipment is considered. It is assumed 80% of the equipment used is diesel and 20% electric.

$$tec = 4.44 * \frac{nc}{2} * nm \tag{5.6}$$

where:

tec = transshipment energy consumption [kWh]
nm = number of movements [#]

$$tshe = tec * tshef \tag{5.7}$$

where:

$tshe$ = transshipment emissions [g]
$tshef$ = trnasshipment emission factor [g/kWh]

To calculate the number of m² of forest area needed for CO_2 compensation in a period of 50 years, the following is assumed: 4.6 tonnes of CO_2/hectare/year is captured in the first 10 years after planting the forest area and 9.1 tonnes of CO_2/hectare/year is captured in the subsequent years, leading to the capturing of 410 CO_2/hectare in a period of 50 years [Boosten et al., 2020].

$$m^2 for = \frac{CO_2te + CO_2tshe}{410} * 10000 \tag{5.8}$$

where:

$m^2 for$ = m² of forest area for CO2 compensation [m²]
CO^2te = CO_2 transport emissions [ton]
CO^2tshe = CO_2 transshipment emissions [ton]

6 EMISSION MODEL VERIFICATION AND VALIDATION

Before the emission model can be used, it has to be verified and validated. This section deals first with the verification, followed by the validation.

6.1 VERIFICATION

First, the verification method applied is explained. Next, the design of the case study scenarios is presented, distinguishing between the base case scenario and the alternative scenarios. Thereafter, the input of the case data is presented. Once the scenarios are drafted and the case data input is obtained, the model can be verified by means of a scenario analysis. Finally, a sensitivity analysis is performed to not only verify the emission model, but also to demonstrate the sensitivity of the model.

6.1.1 Verification method

For the purposes of verifying the emissions model, scenarios should be drawn up to examine whether the model calculates what needs to be calculated. The purpose of the scenario analysis in this case is to check whether the model covers everything that needs to be calculated and whether the model obtains the correct output that is intended. The first goal refers to verification of the model and the second to validation. This section starts with explaining the design of the base case and alternative scenarios, together with providing the case-specific data that is used. This is followed by a section discussing the scenario analysis and the sensitivity analysis. A sensitivity analysis is performed to analyse how sensitive certain parameters or variables in the model may be. In sensitivity analysis, these parameters and variables are increased and decreased by 10% at a time to test the sensitivity on the output of the model. Before carrying out this analysis, expectations are given as to what the changes will mean for the output, in order to test whether the model behaves as predicted, which is part of the verification process of the emission model.

6.1.2 Scenario analysis

Case study scenarios

To carry out the case study, first the base case and alternative scenarios have to be designed. As the case study is conducted within the supply chain of the company L, the approach of the case study is evaluated with the case experts of L. The choice is made for the case of a particular loyalty programme, for a certain customer, that L is developing during the period in which this research is conducted. The programme is assembled by incorporating different products from different suppliers. For the purpose of this programme, two products are produced in China, six in France and one in Portugal. This implies that there are three cargo flows, which are referred to in the emission model as the CHN flow, PRT flow and FRA flow. For each of these flows, there are different possibilities for transporting the goods, routing, different ways of fuel consumption etc., which makes the case so suitable for this research. Based on discussions with case experts within the company, the base case scenario is designed. In the next section, the base case scenario is explained and subsequently the alternative scenarios are presented, as there are various options per cargo flow. At this point, the scenarios will only be used to verify the model, only later in this report the impact of the decisions will be analysed and reported.

Figure 6.1 shows a visualisation of the base case scenario. It represents the scenario that the company applies most often for these cargo flows. For goods coming from Europe, in this case Portugal and France, generally road transport is applied. For goods coming from Asia, in this case China, generally maritime transport is applied combined with road transport. Hence, these modes of transport are considered for the base case scenario, as shown in the figure. Each arrow in the figure depicts a transport leg and each box depicts the location from where the goods depart from, arrive at or pass through. In the diagram all the inbound flows are visualised by a blue square, the outbounds by the green square (from the warehouse in Drunen to all distribution centres of the client) and the returns (the other way around) by the red square and red arrow. For the case study carried out for verification, only the inbound flows are considered. Thus, only for the incoming flows, alternative scenarios are designed to verify the model. The reason behind this is that the underlying data and the manner of calculating the emissions, costs and travel times for the inbound, outbound and return flows are the same and therefore more scenarios are simply not required to accomplish the verification.

In designing the alternative scenarios, the most logical and common modes and routes were applied. An overview of all scenarios combined is given in the appendix Section D.1. As already mentioned in the previous section, only the inbound flows are considered. For the CHN flow, 6 scenarios are designed (C1-C6) and for the FRA and PRT flow, 3 scenarios are designed (F1-F3 and P1-P3). C1, C2 and C3 together form the base case scenario.

Case-data input

For each transport leg of the case study, the city and country of origin and destination must be specified and a transport mode must be selected. With this data, the model can calculate the corresponding travelled distance. Next, the specific vehicle type and fuel/electricity type must be selected, as the model then knows which emission data to use in the calculations. Other input data are the product data, which consist of the logistic data per box,

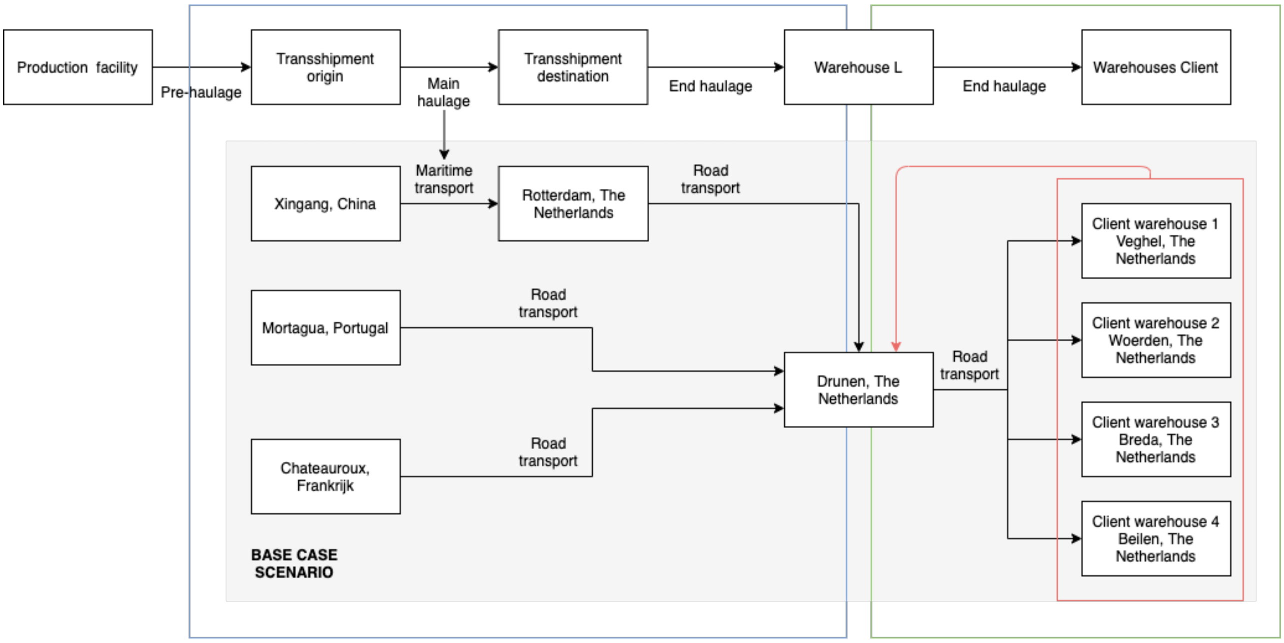

Figure 6.1: Case specific supply chain processes

the planned order quantity per product and the number of containers per delivery. The logistical data per box can be derived from the pallet plans drawn up in cooperation between the company L and the suppliers. The planned order quantity and the number of containers are derived from the delivery planning. The tables in Section D.2 give an overview of the case-input data with regards to origin, destinations, vehicle types, fuel/electricity types per transport stage and the product data of the case, which are used for the verification analysis of this case study.

Scenario analysis output

The output of the emission model according to the above presented input, is shown in this chapter. The output will be analysed for the purpose to verify the emission model. The analysis will be split up into first analysing the output of the transport emissions, followed by the transshipment emissions. Also, the output in the number of m^2 of forest area for CO_2 compensation[1] will be analysed as well. Furthermore, the emissions share per transport leg will be analysed and finally, an analysis of all scenarios of transport emissions combined will be discussed. The purpose of the scenario analysis for verification means is to check whether the model covers everything that needs to be calculated and whether the model obtains the correct output that is intended.

Table 6.1 shows the output of the transport emissions per cargo flow for the different scenarios per flow of goods. The output is coloured, per column per flow of goods, where the colour green indicates a low amount (of the

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[1] in a period of 50 years, where the following is assumed: 4.6 tonnes of CO_2/hectare/year is captured in the first 10 years after planting the forest area and 9.1 tonnes of CO_2/hectare/year is captured in the subsequent years, leading to the capturing of 410 CO_2/hectare in a period of 50 years [Boosten et al., 2020]

criteria emissions, cost and time), red a high amount and yellow an amount in between.

When examining the output of the CHN flow scenarios, scenarios C5 and C6 emit the most emissions, except for PM_{sl} emissions. This makes sense as C5 and C6 are the scenarios where air transport is used for the main part of the transport. It is equally logical that PM_{sl} emissions are not highest because air transport does not involve tyre wear on the road surface, this only occurs on departure and landing. The costs and time of C5 and C6 compared to C1-C4 also make sense, as air transport is considered the most expensive mode of transport, as well as the fastest one. Scenarios C1 and C2 use maritime transport as the main mode of transport. Maritime transport is generally known as the mode that takes the longest and costs the least, which corresponds to the output in the diagram. Rail, the main transport mode for scenarios C3 and C4, is in between the modes sea and air in terms of cost and time, which is consistent with the output in the diagram.

For the FR and PRT flow scenarios, scenarios F1 and P1 are entirely based on road transport, F2 and P2 on rail transport and F3 and P3 on short sea shipping. There is one notable difference in CO_2-eq. emissions between scenarios F2 and F3 and P2 and P3. The difference is that in terms of CO_2-eq. emissions, F3 and P2 are the least polluting flows (compared to F2 and P3), while this seems contradictory. When looking at the different transport route of the two flows, the pre- and end-haulage are also decisive for the emissions. In this case, the pre- and end-haulage transport legs are causing the contradictory difference between the two flows. In scenario F2, the share of road haulage in the pre- and post-haulage is so high that a tipping point is reached so that F2 (rail) causes more CO_2-eq. emissions than F3 (short sea shipping), while the emission factor for rail is 14.6 g/tkm and that for short sea shipping 47.4 g/tkm. It can be concluded that this seemingly contradictory performance is due to the pre- and end-haulage transport legs.

Furthermore, the PRT and FR flows show that the short-sea legs (F3 and P3) involve the least costs but take the longest, and the road legs (F1 and P1) involve the highest costs but take the shortest. The rail options (F2 and P2) fall in between for both criteria.

Table 6.1: Output transport emissions, cost & time per scenario

	Transport emissions (WTW)						
	CO_2-eq [ton]	**SO_2 [kg]**	**PM_v [kg]**	**NO_x [kg]**	**PM_{sl} [kg]**	**Cost [x1000 euro]**	**Time [days]**
C1-**M**Ro	553	1,377	241	10,452	1	€ 55	40
C2-**M**IRo	543	1,366	242	10,447	0	€ 45	41
C3-Ro**Ra**IRo	457	340	25	945	99	€ 492	16
C4-Ro**Ra**Ro	456	338	24	930	99	€ 492	15
C5-Ro**A**IRo	5,078	6,659	427	19,339	5	€ 1,770	5
C6-Ro**A**Ro	5,074	6,655	424	19,287	5	€ 1,768	4
F1-**Ro**	168	172	11	485	8	€ 159	1
F2-Ro**Ra**Ro	154	151	10	425	12	€ 150	3
F3-Ro**M**Ro	141	215	27	1,104	5	€ 91	3
P1-**Ro**	16	16	1	46	1	€ 15	1
P2-Ro**Ra**Ro	9	7	1	21	1	€ 9	4
P3-Ro**M**Ro	9	19	3	126	0	€ 2	5

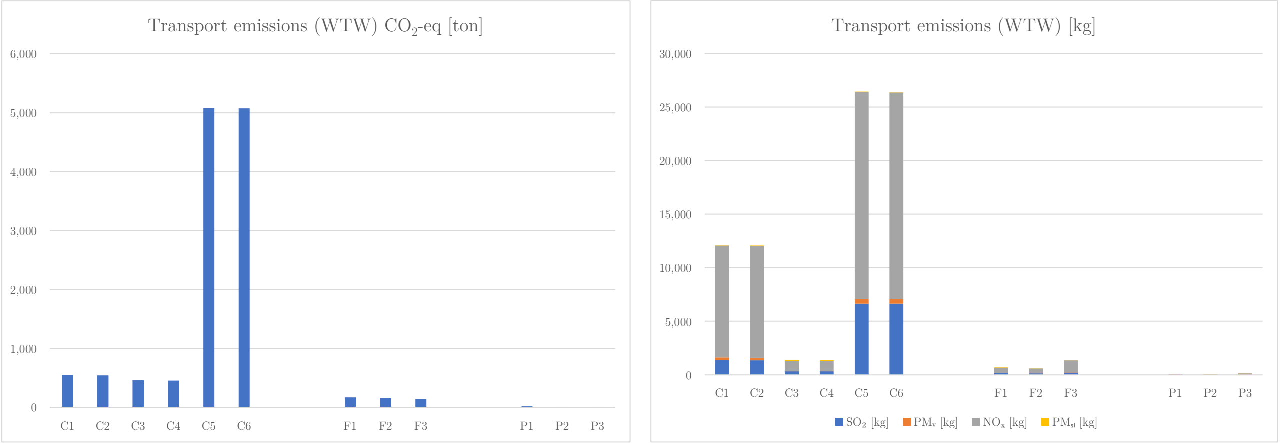

Figure 6.2: Scenario analysis transport emissions output

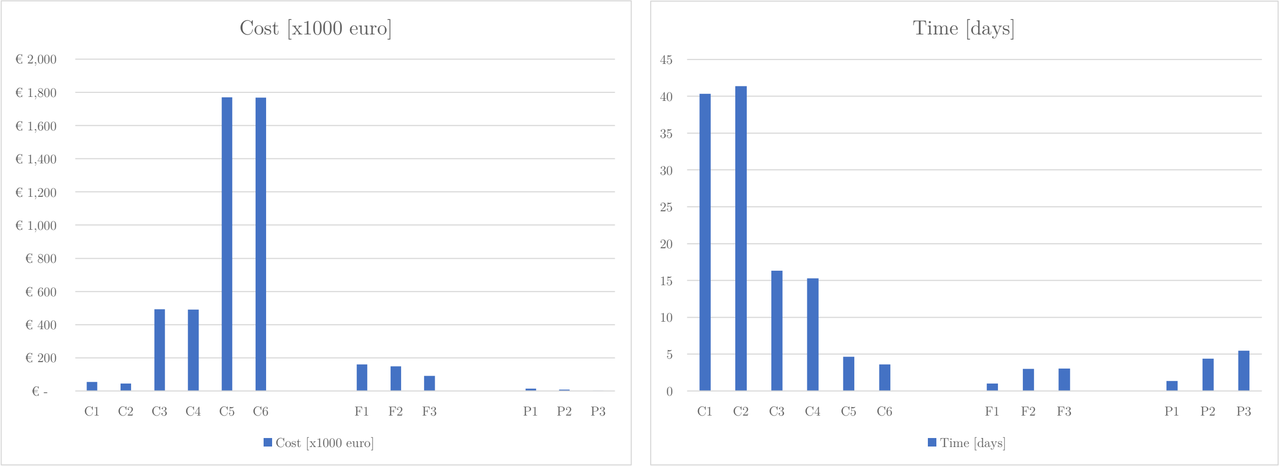

Figure 6.3: Scenario analysis cost and time output

Table 6.2 shows the output of the transshipment emissions per cargo flow for the different scenarios per flow of goods. The same colouring is used for visualisation purposes.

Table 6.2: Output transshipment emissions per scenario

	Transshipment emissions			
	CO_2-eq [kg]	**NO_x [g]**	**PM_v [g]**	**SO_2 [g]**
C1-**M**Ro	2,864	10,182	547	144
C2-**MI**Ro	3,938	14,000	752	198
C3-Ro**RaI**Ro	4,654	16,546	889	234
C4-Ro**Ra**Ro	3,580	12,728	684	180
C5-Ro**AI**Ro	4,654	16,546	889	234
C6-Ro**A**Ro	3,580	12,728	684	180
F1-**Ro**	4,231	15,042	808	212
F2-Ro**Ra**Ro	9,308	33,092	1,778	467
F3-Ro**M**Ro	9,308	33,092	1,778	467
P1-**Ro**	78	278	15	4
P2-Ro**Ra**Ro	195	694	37	10
P3-Ro**M**Ro	195	694	37	10

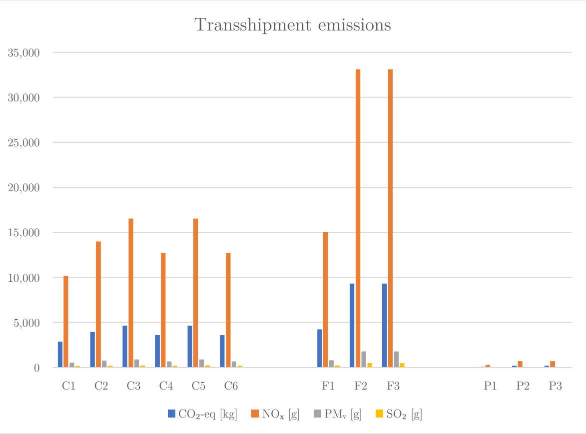

Figure 6.4: Scenario analysis transshipment emissions output

The number of m² of forest area for CO_2 compensation[2] are shown for the different scenarios per flow of goods in Table 6.3. As the number of m² of forest area for CO_2 compensation are based on the transport and transshipment emissions, this table can be compared to Table 6.1 together with Table 6.2. The transshipment emissions compared to the transport emissions are negligible. Therefore, a comparison solely with Table 6.1 is needed for verification analysis. When comparing the two tables exactly the same colours can be found in the CO_2-eq. column of Table 6.1 compared to the number of m² of forest area needed for CO_2 compensation in Table 6.3. The m² of forest area for CO_2 compensation is very useful to implement as an output as it makes the number of CO_2-eq. emissions emitted more imaginable.

Table 6.3: Output m² of forest area for CO_2 compensation

	m² forest area for CO_2 compensation
C1-**M**Ro	13,557
C2-**M**IRo	13,336
C3-Ro**Ra**IRo	11,260
C4-Ro**Ra**Ro	11,203
C5-Ro**A**IRo	123,970
C6-Ro**A**Ro	123,843
F1-**Ro**	4,191
F2-Ro**Ra**Ro	3,984
F3-Ro**M**Ro	3,672
P1-**Ro**	392
P2-Ro**Ra**Ro	214
P3-Ro**M**Ro	221

Table D.12 in the appendix provides a complete overview of the output of all scenarios combined, according to the inputs described in the previous section. This is done because previously the different flows were analysed separately, but L usually operates in the way that a programme is always

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[2] in a period of 50 years, where the following is assumed: 4.6 tonnes of CO_2/hectare/year is captured in the first 10 years after planting the forest area and 9.1 tonnes of CO_2/hectare/year is captured in the subsequent years, leading to the capturing of 410 CO_2/hectare in a period of 50 years [Boosten et al., 2020]

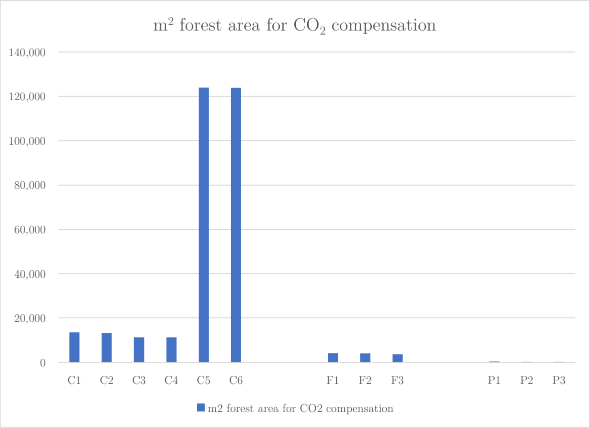

Figure 6.5: Scenario analysis output on m² of forest area for CO_2 compensation

approached as a whole. For this programme, there are three transport flows as the goods come from China, Portugal and France, therefore this table has been drawn up to see the effect when combinations of different scenarios are made. The first row in blue shows the base scenario (C1F1P1), this information is also included in the table below (Table 6.4). The next rows in the appendix show all combinations of the alternative scenarios.

What is striking is that the colours concerning all criteria (emissions, costs and time) correspond to the colours in Table 6.1, the colours of the CHN flow. This would mean that it is almost irrelevant for a decision maker to take the FR and PRT flows into account in such an international programme. In itself, this is an explainable phenomenon since the CHN flow provides the largest transport performance given the larger distances covered. For the base scenario, the share of emissions of each transport leg in relation to the whole is calculated in percentages, see Table 6.5. This also shows that the maritime transport leg of the China flow is responsible for by far the largest part of the emissions. This is why the colours and therefore the proportions in Table D.12 are the same as those of the CHN flow in Table 6.1.

Table 6.4: Output base case scenario combined

			Total emissions (WTW)							
			CO_2-eq [ton]	SO_2 [kg]	PM_v [kg]	NO_x [kg]	PM_{sl} [kg]	Cost [x1000 euro]	Time [days]	m² forest area for CO_2 compensation
C1	F1	P1	737	1,565	253	10,983	10	€ 230	43	17,964

Table 6.5: Emissions share per transport leg base case scenario

	Total emissions (WTW)				
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}
C1.1Maritime	73%	87%	95%	95%	0%
C1.2Road	3%	1%	0%	0%	9%
P1Road	2%	1%	0%	0%	8%
F1Road	23%	11%	4%	4%	83%

6.1.3 Sensitivity analysis

A sensitivity analysis is performed to analyse how sensitive certain parameters or variables in the model may be. In sensitivity analysis, these parameters and variables are increased and decreased by 10% at a time to test the sensitivity on the output of the model. Table 6.6 shows the decreased and increased values of multiple parameters and variables in the model. The sensitivity analysis is carried out for the transport leg of C1, which represents the maritime transport mode for the CHN flow. Per time solely one change is made, the other variables are kept constant (base scenario).

The output of the sensitivity analysis is shown in Appendix E. As the criteria (emissions, cost, time) for C1 are used as output it makes sense that the number of PM_{sl} are zero in all cases as container vessels cause no tyre wear as road or rail modalities do. For the variables distance, number of containers and cargo weight, it is expected that once the values of these variables increase, also an increase will be shown in the output of all emissions. Because a higher amount of containers, cargo weight and distance cause a higher transport performance and the emissions increase with a higher transport performance. This relationship is in line with the output graphs of the sensitivity analysis, as shown in Figure E.1.

The same relationship is expected for these three variables, distance, number of containers and cargo weight, to the cost. It is expected that once these three values increase, cost increase as well. This phenomenona appeared from the sensitivity analysis as well, as can be seen in Figure E.2.

Regarding the output of time it is expected that only the average speed and distance influence this criteria. It is expected once the speed increases, time decreased and once the distance increases, time increases as well. This is in line with the output in Figure E.3.

Considering the transshipment emissions it is expected that the more kWh of energy per movement is needed and the more movements per transshipment are taking place, the more transshipment emissions are emitted. When looking at the graphs in Figure E.4, this is true.

Before carrying out this analysis, expectations are given as to what the changes will mean for the output, in order to test whether the model behaves as predicted. This sensitivity analysis is therefore part of the verification process of the model. In addition, the sensitivity analysis is carried out to test the impact of uncertainty in emission factors, which will answer subquestion number 7.

Table 6.6: Sensitivity analysis input

	Distance	Cargo weight	#containers	Cost/tkm (maritime)	Average speed (maritime)	#transshipment movements	#kWh per movement	Emissionfactor containervessel 3000-5000 TEU, WTW CO_2-eq.	Emissionfactor containervessel 3000-5000 TEU, WTW SO_2
Base (100%)	23609	22,2436	55	0,0013	25	8	4,44	18,5	0,047
90%	21248,1	20,01924	49,5	0,00117	22,5	7,2	3,996	16,65	0,0423
110%	25969,9	24,46796	60,5	0,00143	27,5	8,8	4,884	20,35	0,0517

6.1.4 Verification conclusion

The model verification showed that the model generates logical outcomes. This was demonstrated by means of a scenario analysis of the case study, in which alternative scenarios were set up and tested in addition to the base-case scenario. This showed that the outcomes were as expected. The sensitivity analysis also showed that the model behaves as expected. The change in some variables due to a change in input was measured and nothing remarkable was found as everything behaved as expected.

6.2 VALIDATION

First, the validation method will be shared. This is followed by a discussion of the empirical findings of the validation meeting and the analysis with actual data from transport carriers.

6.2.1 Validation method

To validate the emission model the following steps were taken. First of all, a case-experts validation meeting has been taking place, where multiple points were discussed. There were five case-experts present at the meeting; two supply chain managers, two supply chain engineers and one supply chain director, who all have many years of supply chain experience. The validation meeting was intended to allow the case experts to reflect on the model as a whole, on its usability, on the outcomes and on the overall value of the model. Next to this validation meeting, a meeting was held with the carrier platform that the company uses in order to obtain realistic cost and time data to validate the model. In the next section the empirical findings will be discussed.

6.2.2 Empirical findings - validation meeting

In Appendix F the introduction of the validation meeting can first be found. At the beginning of the meeting this introduction was given to get all case experts well in the material. The output of the model discussed in this validation meeting is the same output used for the scenario analysis. So specifically, the scenarios regarding the inbounds of the loyalty program used for the case study are discussed in this meeting. It is sufficient to only discuss the inbounds as the inbounds are calculated in the same way as the outbounds and returns because the input used in the model is the same. But the assumptions made to calculate the outbounds and returns of the case are validated with the case-experts in the validation meeting. In the appendix in Section G.2 the response of the meeting is summarised. The text highlighted in blue is relevant for the validation process regarding model outcomes and assumptions, the text in green will be used the validation process regarding model usability and overall model value. The key findings regarding the validation of the emission model will be outlined here.

Reflection on model outcomes and assumptions

With regards to the times output the case experts noticed that it does not quite correspond to the transit times they see happening in reality. This especially counts for the time output of the modalities rail and maritime transport. To the case-experts it seemed that the train times are too short and the maritime times are too long. The ratios of the cost output on the other hand did seem realistic and they were aware this data does not consider the freight rates. The case-experts thought that a validation with the data retrieved from the carrier platform they use, the company that books the transports for L and provided a data-set with cost and time data for this research, is very useful, especially for validating the transit times.

The case-experts thought that showing the output on m^2 of forest area for CO_2 compensation in a period of 50 years, is working really well for the imagination of what such a number of tonnes of emissions mean in reality. The case experts stated it makes the numbers more tangible to them.

Finally, some assumptions were validated during the meeting. Regarding the returns it is approved by the case-experts to assume that 10% of the outbounds will be returned, as this is the percentage L often makes calculations with in order to be prepared for the returns. It can also be assumed in this model that those 10% of returns are equally distributed from the four distribution centres of the client to the warehouse of L in Drunen. Regarding the outbounds a similar assumption is approved to equally distribute the inbounds across the four distribution centres of the client, so each outbound flow is 25% of the total inbound flows.

Reflection on model usability and overall model value

The case-experts found several pre- and end-haulage legs redundant, as they think that most of the emissions are caused by the main haulage leg. For research purposed they think it is very useful to gain knowledge of all transport legs, including pre- and end-haulge, but when applying this emission model in practice they prefer a more simplified model where only the main haulage is taken into account in designing scenarios and making calculations.

The term 'utility-model' is devised during this meeting. The current model was called the 'technical-model' by the case-experts, which is very useful for research and to gain relevant insights. But a more user-friendly model is preferred to have next to the technical model, this model is called the 'utility model'. This model should contain some simplifications such as the excluding some pre- and end-haulage legs. Also, instead of seeing all emissions separately they would prefer a certain 'sustainability-ranking' in the utility model. The case-experts think this would improve the usability and lowers the boundary to use the model for decision-makers. Considering the cost, the case experts are aware of the fact that the cost ratio's are applied in the model in such a way that those cost do not show the current freight rates. However, the case-experts are interested in the supply and demand principle behind the transport prices and propose to make use of such scenarios in the outputs in the utility model.

The case experts believe that the model would be suitable to implement in their business process when the sales teams are at an advanced stage with customers. At that point, a scenario analysis with the various SCD/C and its outcomes on emissions, cost and time can be set up and communicated to the sales team. The output can be provided to make the sales team aware of the fact that when a certain arrival date is set with the customer it has a certain effect on emissions, costs and time. But to establish this, the model should be user-friendly otherwise it might be possible that the incentive to use the model is getting lower each time the model is used.

Regarding the overall model value the case experts stated it fulfils its purpose. The purpose was to create a model that shows the impact of SCD/C decisions on emissions, costs and time in a clear manner. The beginning of the purpose is already fulfilled, but regarding the 'clear manner' a few improvements can be made as already explained above. The case experts plan to use the model for every program that is at an advanced stage within the sales process. At that point the different SCD/C decisions and its outcomes on emissions, cost and time can be communicated within the company.

For each transport leg, the model user has to enter the weight per container, number of containers, origin and destination and then the model's 'dials', namely modality, vehicle type and fuel type. Once this is entered, all emissions, costs and time are calculated. The case experts were pleased with this way of gaining insight into the emissions in particular. In terms of costs and time, they were already familiar with the proportions of various modalities. The added value of this model for them is therefore mainly the insight into the emissions. The m^2 of forest for CO_2 compensation was added to the model in order to gain more insight into the order of magnitude of the emissions, at least for CO_2.

6.2.3 Empirical findings - realistic data

Both outputs in cost and time should be validated with the data received from Caroz. Starting of with time, Table 6.7 shows in the second column the time outputs for some of the scenarios from the scenario analysis, in this case executed pre-validation. The third column provides the corresponding time (or time frame) according to the data received from Caroz, if available. The fourth column gives the same data but then retrieved from Cargorouter.com, if available. If one of both validation data from the sources Caroz or Cargorouter.com is not available, another source is conducted, this is showed in the last column. This table can be used, in combination with the knowledge of the case-experts, to validate the time output.

From the empirical findings of the validation meeting it already appeared that the output time for maritime transport was a bit too long and for rail transport too short. This corresponds to the data from Caroz, Cargorouter and other sources as can be seen in Table 6.7. The output times for air transport do correspond to a sufficient level with the Caroz and Cargorouter data, but the output times for inland waterway and road do not match optimally. Therefore, it is preferred to change the input data that is the foundation of the calculation of the travel times for these modalities in order to obtain more realistic times.

Table 6.7: Time output validation

	Time [days] emission model pre-validation	Time [days] from Caroz data	Time [days] from Cargorouter data	Time [days] from other sources
C1/C2 (maritime CHN-NL)	50/51	27-47	27.5	
C3/C4 (rail CHN-NL)	11/12	-	24	15-18
C5/C6 (air CHN-NL)	4/5	1-8	4.5	
C5.3 (inland Amsterdam-Waalwijk)	21h	-	-	14h
P1 (road PRT-NL)	1	3-5	5	
P2 (rail PRT-NL)	4	7	9	
P3 (short-sea PRT-NL)	6	-	7	3-6
F1 (road FR-NL)	1	1-2	2	
F2 (rail FR-NL)	3	-	6	
F3 (short-sea FR-NL)	3	-	5	1-4

Therefore, the decision is made to change the average speed input for the modalities inland waterway, maritime and rail. Table 6.8 shows the changes made and Table 6.9 shows the impact these changes have on the same transport legs used for the validation process of the output criteria time.

Table 6.8: Input average speed per modality pre- and post-validation

Modality	Average speed pre-validation	Average speed post-validation
Air	200 km/h	200 km/h
Inland waterway	7,2 km/h	**8,5 km/h**
Maritime	20 km/h	**25 km/h**
Road	60 km/h	60 km/h
Rail	50 km/h	**35 km/h**

Table 6.9: Time output pre- and post-validation

	Time [days] pre-validation	Time [days] post-validation
C1	**50**	**40**
C2	**51**	**41**
C3	**12**	**16**
C4	**11**	**15**
C5	**5**	**5**
C6	**4**	**4**
F1	**1**	**1**
F2	**3**	**3**
F3	**3**	**3**
P1	**1**	**1**
P2	**4**	**4**
P3	**6**	**5**
C5.3	21h	17h

6.2.4 Validation conclusion

Regarding the validation of the model, a validation meeting was set up to validate the model with the case experts. In general, based on the findings of this meeting, an adjustment was made to the assumption regarding the average speed per transport mode because the transport times did not correspond to reality. This also appeared from a comparison with other data, from Caroz and from other sources. However, the costs between the various modes appeared to be in proportion for the case experts. Regarding the model usability some improvements to the model can still be made, but the overall value of the model is present. The model fulfills its purpose and the case experts plan to use the model for every program that is at an advanced stage within the sales process. At that point the different SCD/C decisions and its outcomes on emissions, cost and time can be communicated within the company.

7 DECISION IMPACT ANALYSIS

7.1 IMPACT ANALYSIS METHOD

First, it was discussed with the case experts of the company which type of SCD/C decisions would be most relevant for this case study to analyse the impact of these decisions. The case experts first of all wished to observe the impact of the use of different modes of transport. Therefore, the scenario analysis already used for the verification of the model can also be used within this decision impact analysis, since for the different flows in the case study different modes of transport are used in the scenario analysis. Besides the choice of transport mode, the case experts were also curious about the effect of using different engines or fuels, especially for road transport. They wonder whether the difference in emissions of, for example, 'Euro VI' engines compared to 'Euro V' engines is big enough to make Caroz decide to only book carriers with trucks that have a certain type of engine. The third type of decision that interested the case-experts is the choice of vehicle type. They wondered whether it is worthwhile to influence carriers to use a certain type of vehicle and whether it is realistic to do so. In order to check whether it is realistic to influence carriers to use a certain type of vehicle and to examine other relevant aspects related to carriers, a meeting is held with Caroz, the company that books the transports for L.

7.2 TRANSPORT MODE SELECTION IMPACT ANALYSIS

The emission model can be used for deciding which mode of transport should be used for a particular goods flow. From the beginning of this study, this type of decision emerged as the first objective that the emission model should meet, to assist in making decisions regarding the choice of transport mode. To estimate the impact in terms of emissions, costs and time, of choosing a particular type of transport mode, the case study was consulted. The scenarios already used to verify the model could be used again to see the impact on all criteria, which could help decision-makers get a clear picture of the situation and weigh up the different modes of transport.

7.2.1 Mode selection impact China-flow goods

From the scenario analysis the scenarios C1 and C2 emerge with maritime transport as the main mode of transport, C3 and C4 rail transport as the main mode of transport and C5 and C6 air transport as the main mode of transport, in Section D.2 in the appendix all the inputs for the scenarios can be reviewed.

As far as transport emissions are concerned, Table 6.1, it can be stated that rail transport (C3 and C4) would be the best option, with the lowest amount of emissions, followed by maritime transport (C1 and C2), whose emissions are very close to those of rail transport. Air transport (C5 and C6) would be the least preferable option, as its emissions are considerably higher compared to the other two modes. Only for the amount of PM_{sl} emissions is rail the least option, then comes air transport and the best option is maritime transport.

In terms of cost, which are displayed in Table 6.1, the maritime option is the least expensive, followed by rail and air transport is considerably the most expensive. This is exactly reversed when it comes to time, as the maritime option takes the longest in terms of time, followed by rail and air is the fastest option.

The maritime transport variant is included in the scenario analysis as the base case scenario since this is the option that the company normally applies when products need to be transported from China to Europe, provided that there is enough time, since this is also the option that takes the longest time. The reaction of the case-experts during the validation meeting (Appendix F), was that they found that the option they usually apply is not too bad in terms of emissions compared to the other options. When looking at Table 6.1, this reaction is understandable, because the emissions of the maritime options (C1 and C2) do not seem that much more than the emissions of the rail options (C3 and C4).

Regarding transshipment emissions, Table 6.2, C1 causes the least amount, followed by C4 and C6 and most transshipment emissions are caused by C3 and C5. The more modalities are used in a scenario, the more the goods have to be moved and thus the more mobile equipment is needed, which results in more transshipment emissions for a scenario. When comparing the amount of transshipment emissions with transport emissions, it turns out that transshipment emissions are almost negligible. The CO_2-eq. emissions for transshipment are shown in the table in kg and the other transshipment emissions in grams, while the transport emissions are shown in Table 6.1 of CO_2-eq. in tonnes and the other transport emissions in kg.

When making a decision, it depends on which criteria are more important than others at a given moment. For example, when time is scarce, air travel may be the only option for a company, even though it is the most polluting and costly option. Showing the effect on emissions when air transport is used can still help in deciding whether there is indeed limited time or whether there might still be an option to use other modes, as both sea and rail transport are significantly less harmful in terms of emissions and less expensive compared to air transport.

The impact of the SCD/C decisions within the type of transport mode selection, i.e. to use rail or air transport instead of maritime transport for the CHN cargo flow which would normally be applied in the case study, is shown in Figure 7.1, the input values for this figure can be found in Appendix H in Table H.1. In Figure 7.1, the change in criteria (emissions, costs and time) when deciding to use rail or air transport instead of maritime transport is presented in percentages. In the base case, the maritime transport mode, all criteria are set to 100%. Therefore, this figure shows the effect that a decision-maker has on all three criteria. This means that a decision-maker has a major influence on both sustainability performance and business performance, this can be both positive and negative.

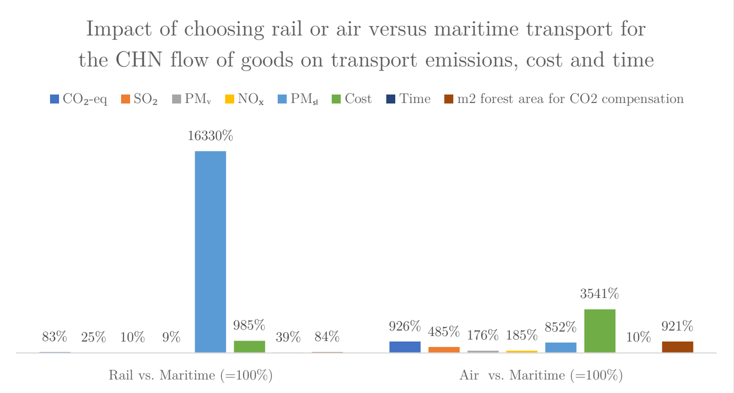

Figure 7.1: Impact of choosing rail or air versus maritime transport for the CHN flow of goods on transport emissions, cost and time

7.2.2 Mode selection impact France-flow goods

From the scenario analysis the scenarios F1 emerges with road transport as the main mode of transport, F2 rail transport as the main mode of transport and F3 short-sea transport as the main mode of transport, in Section D.2 in the appendix all the inputs for the scenarios can be reviewed.

With regard to transport emissions, different conclusions can be drawn for each emission, as can be seen in Table 6.1. For CO_2-eq. emissions, the short sea shipping option (F3) causes the fewest emissions, followed by rail (F2) and road transport (F1) the most. For SO_2, PM_v and NO_x emissions, rail causes the least emissions, followed by road and short-sea the most. For the amount of PM_{sl} emissions, rail is the least option, then comes road transport and the best option is short-sea transport. In terms of costs, the short-sea option is the least expensive, followed by rail and road transport the most expensive. In terms of time, this is exactly the opposite as the short sea shipping option takes the longest time, followed by rail and road transport is the fastest option.

To gain a clearer understanding of the order of magnitude of CO_2-eq. emissions, the number of m_2 of forest area for CO_2 compensation is used as a criteria, as already explained in the previous chapter. For the FR flow of goods, 519 m_2 of forest area for CO_2 compensation can be saved if short-sea is used, versus road transport. So even though the numbers in Table 6.1 seem to make little difference, when it is converted into m_2 of forest area for CO_2 compensation the impact is visible. Because in this way, the decision-makers can visualise the number of trees needed for compensation.

Regarding transshipment emissions, Table 6.2, F1 causes the least amount, followed by F2 and F3 which cause the most amount of emissions. The more modalities are used in a scenario, the more the goods have to be moved and thus the more mobile equipment is needed, which results in more transshipment emissions for a scenario. In scenario F1 only one modality is used, namely road transport, and therefore this makes sense. The decision-maker can keep this in mind, but when comparing the amount of transshipment emissions with transport emissions, it turns out that transshipment emissions are almost negligible. The CO_2-eq. emissions for transshipment are shown in the table in kg and the other transshipment emissions in grams, while the transport emissions are shown in Table 6.1 in tonnes for CO_2-eq. emissions and the other transport emissions in kg.

The impact of the SCD/C decisions within the type of transport mode selection, i.e. to use rail or short-sea transport instead of road transport for the FR cargo flow which would normally be applied in the case study, is shown in Figure 7.2, the input values for this figure can be found in Appendix H in Table H.2. In Figure 7.2, the change in criteria (emissions, costs and time) when deciding to use rail or short-sea instead of road transport is presented in percentages. In the base case, the road transport mode, all criteria are set to 100%. Therefore, this figure shows the effect that a decision-maker has on all three criteria. This means that a decision-maker has a major influence on both sustainability performance and business performance, this can be both positive and negative.

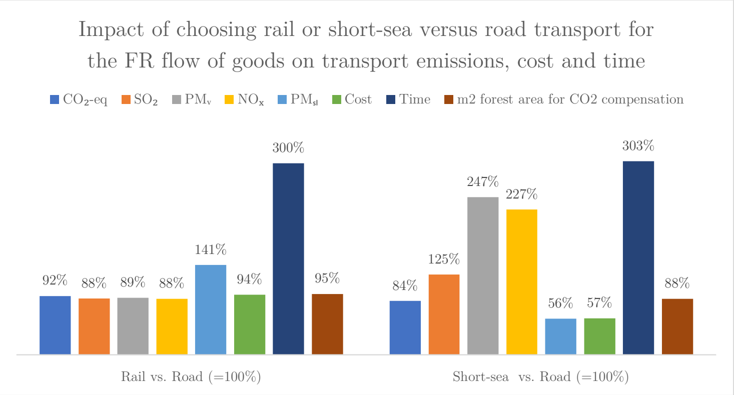

Figure 7.2: Impact of choosing rail or short-sea versus road transport for the FR flow of goods on transport emissions, cost and time

7.2.3 Mode selection impact Portugal-flow goods

From the scenario analysis the scenarios are set up similarly to the FR flow scenarios, which means P1 emerges with road transport as the main mode of transport, P2 with rail transport and P3 with short-sea transport as the main mode of transport, in Section D.2 in the appendix all the inputs for the scenarios can be reviewed.

With regard to transport emissions, different conclusions can be drawn for each emission, as can be seen in Table 6.1. For CO_2-eq. emissions, the rail option (F2) causes the fewest emissions, followed by short-sea (F2) and road transport (F1) the most. But the difference between the rail and short-sea options regarding CO_2-eq. emissions is very small. For SO_2, PM_v and NO_x emissions, rail causes the least emissions, followed by road and short-sea the most. For the amount of PM_{sl} emissions, rail is the least option, then comes road transport and the best option is short-sea transport. In terms of costs and time the same counts for the PRT flow scenarios as for the FR flow scenarios, namely that the short-sea option is the least expensive, followed by rail and road transport the most expensive. And in terms of time, exactly the opposite counts, as the short sea shipping option takes the longest time, followed by rail and road transport is the fastest option.

To gain a clearer understanding of the order of magnitude of CO_2-eq. emissions, the number of m_2 of forest area for CO_2 compensation is used as a criteria, as already explained in the previous chapter. For the PRT flow of goods, 178 m_2 of forest area for CO_2 compensation can be saved if rail is used, versus road transport. So even though the numbers in Table 6.1 seem to make little difference, when it is converted into m_2 of forest area for CO_2 compensation the impact is visible. Because in this way, the decision-makers can visualise the number of trees needed for compensation.

Regarding transshipment emissions, Table 6.2, the same counts as for the FR flow of goods. Namely that, P1 causes the least amount, followed by P2 and P3 which cause the most amount of emissions. The more modalities are used in a scenario, the more the goods have to be moved and thus the more mobile equipment is needed, which results in more transshipment emissions for a scenario. In scenario P1 only one modality is used, namely road transport, and therefore this makes sense. The decision-maker can keep this in mind, but when comparing the amount of transshipment emissions with transport emissions, it turns out that transshipment emissions are almost negligible. The CO_2-eq. emissions for transshipment are shown in the table in kg and the other transshipment emissions in grams, while the transport emissions are shown in Table 6.1 in tonnes for CO_2-eq. emissions and the other transport emissions in kg.

The impact of the SCD/C decisions within the type of transport mode selection, i.e. to use rail or short-sea transport instead of road transport for the PRT cargo flow which would normally be applied in the case study, is shown in Figure 7.3,the input values for this figure can be found in Appendix H in Table H.3. In Figure 7.3, the change in criteria (emissions, costs and time) when deciding to use rail or short-sea transport instead of road transport is presented in percentages. In the base case, the road transport mode, all criteria are set to 100%. Therefore, this figure shows the effect that a decision-maker has on all three criteria. This means that a decision-maker has a major influence on both sustainability performance and business performance, this can be both positive and negative.

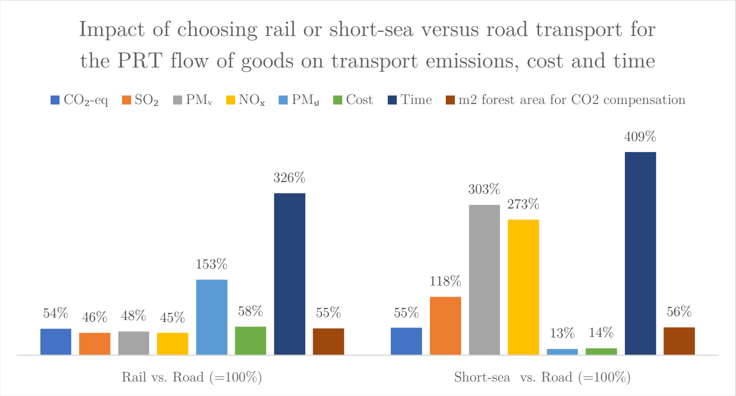

Figure 7.3: Impact of choosing rail or short-sea versus road transport for the PRT flow of goods on transport emissions, cost and time

7.3 FUEL/ENERGY SELECTION IMPACT ANALYSIS

In addition to analysing the effect of decisions on the choice of a certain modality, the model can also be applied to analyse the effect of the choice of a specific engine or fuel type per modality. As mentioned, the case experts were curious to know the impact of such a choice, as in this way it can be determined whether the difference in emissions of, for example, 'Euro VI' engines compared to 'Euro V' engines is large enough to make Caroz (the platform that books L's transports) decide to only book transporters with trucks that have a certain type of engine. The importance of this impact applies especially to road transport, as the case experts believe that for other modes it might be very difficult to influence the fuel/engine type (see Caroz meeting).

For this case study, first the road option for the FR flow is analysed for the impact of using vehicles with a different fuel type or engine. The impact of the SCD/C decisions within the type of fuel/energy selection for the road option of the FR flow is shown in Figure 7.4, the input values for this figure can be found in Appendix H in Table H.4 and Table H.5. In Figure 7.4, the change in criteria (emissions, costs and time) when deciding to use a different type of fuel/energy type instead of Diesel Euro VI is presented in percentages. In the base case, the Diesel Euro VI fuel type, all criteria are set to 100%. Therefore, this figure shows the effect that a decision-maker has on all three criteria. The impact table, Table H.5, shows that the impact on emissions that can be made by choosing a different fuel/engine type is greater in percentages than the additional costs.

Secondly, also the maritime transport option for the CHN flow is analysed for the impact of using vessels with a different fuel type or engine. The impact of the SCD/C decisions within the type of fuel/energy selection for the maritime option of the CHN flow is shown in Figure 7.5, the input values for this figure can be found in Appendix H in Table H.6 and Table H.7. PM_{sl} is not taking into account in the table as maritime transport does not emit such emissions as there is no tyre wear taking place. In Figure 7.5, the change in criteria (emissions, costs and time) when deciding to use a different type of fuel/energy type instead of HFO/MDO Tier II is presented in percentages.

In the base case, the HFO/MDO Tier II fuel type, all criteria are set to 100%. Therefore, this figure shows the effect that a decision-maker has on all three criteria. The impact figure, Figure 7.5 shows that BioLNG emits the least amount of CO_2-eq. emissions and also for all other emissions it scores really well. The cost compared to the base case fuel/engine type is also the lowest. This is due to the advantageous fuel cost associated with BioLNG.

Finally, also the air transport option for the CHN flow is analysed for the impact of using air crafts with a different fuel type. In this case, only kerosine versus biokerosine are compared as these are the only two available options in the airline industry. The impact of the SCD/C decisions within the type of fuel/energy selection for the air option of the CHN flow is shown in Figure 7.6, the input values for this figure can be found in Appendix H in Table H.8 and Table H.9. In Figure 7.6, the change in criteria (emissions, costs and time) when deciding to use a different type of fuel/energy type instead of Kerosine is presented in percentages. In the base case, the Kerosine fuel type, all criteria are set to 100%. Therefore, this figure shows the effect that a decision-maker has on all three criteria. The impact figure, Figure 7.6, shows that bio-kerosine is causing less emissions compared to kerosine, except from the PM_{sl} emissions, but the cost are 163% higher.

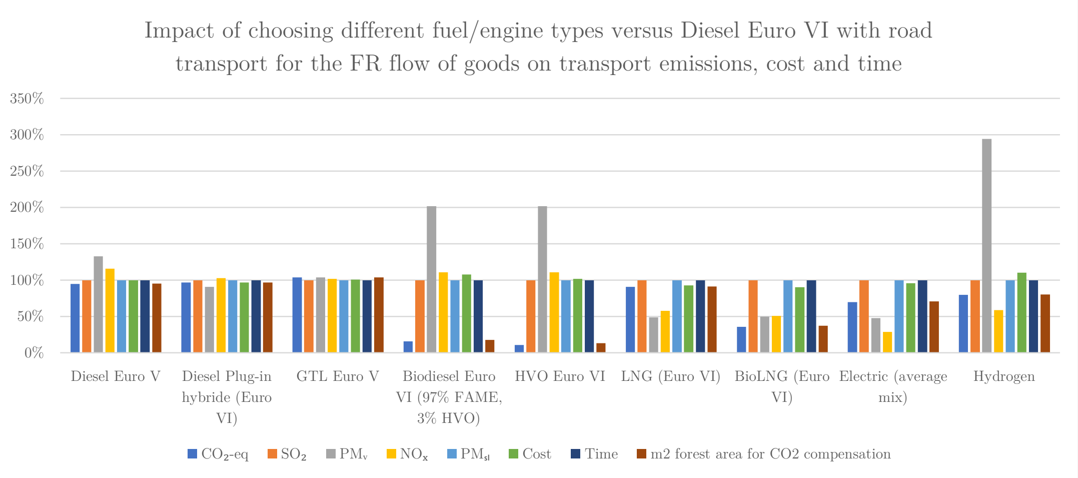

Figure 7.4: Impact of choosing different fuel/engine types with road transport for the FR flow of goods on transport emissions, cost and time

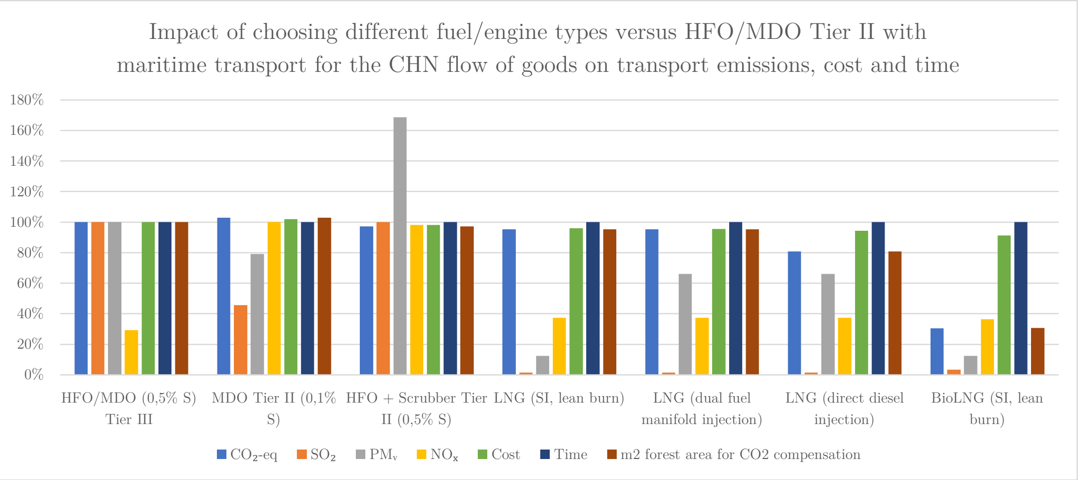

Figure 7.5: Impact of choosing different fuel/engine types with maritime transport for the CHN flow of goods on transport emissions, cost and time

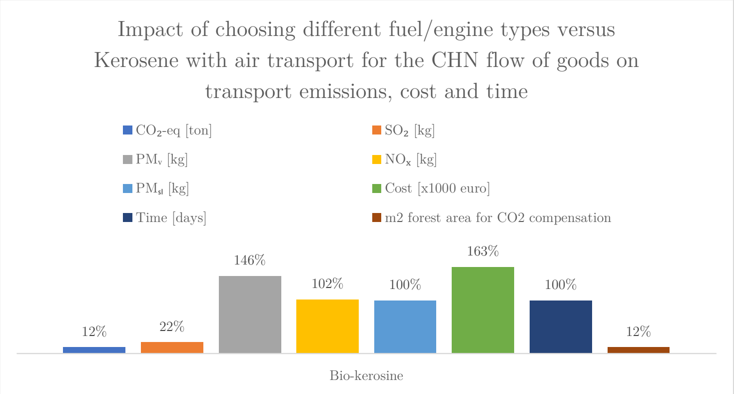

Figure 7.6: Impact of choosing different fuel/engine types with air transport for the CHN flow of goods on transport emissions, cost and time

7.4 VEHICLE TYPE SELECTION IMPACT ANALYSIS

In addition to analysing the effect of decisions on the choice of a certain modality and the effect of the choice of a specific engine or fuel type per modality, also the impact of the decision for a certain vehicle type is analysed. As already mentioned the case-experts wonder whether it is worthwhile to influence carriers to use a certain type of vehicle and whether it is realistic to do so. In order to execute the analysis, first the vehicle type is changed with the road option for the FR flow of goods. Secondly, the vessel type is changed with the inland waterway end-haulage leg for the CHN flow of goods.

For this case study, first the road option for the FR flow is analysed for the impact of using different types of vehicles. The impact of the SCD/C decisions within the type of vehicle selection for the road option of the FR flow is shown in Figure 7.7, the input values for this figure can be found in Appendix H in Table H.10 and Table H.11. In Figure 7.7, the change in criteria (emissions, costs and time) when deciding to use a different type of vehicle type instead of tractor+trailer is presented in percentages. In the base case, the tractor+trailer vehicle type, all criteria are set to 100%. Therefore, this figure shows the effect that a decision-maker has on all three criteria. The impact table, Figure 7.7, shows that LZV is causing less emissions and less cost overall compared to the tractor+trailer vehicle type for road transport.

Secondly, also the inland waterway transport option for the end-haulage leg for the CHN flow is analysed for the impact of using different vessel types. The impact of the SCD/C decisions within the type of vehicle selection for the inland waterway option of the end-haulage leg of the CHN flow is shown in Figure 7.8, the input values for this figure can be found in Appendix H in Table H.13 and Table H.13. PM$_{sl}$ is not taking into account in the table as inland waterway transport does not emit such emissions as there is no tyre wear taking place. In Figure 7.8, the change in criteria (emissions, costs and time) when deciding to use a different type of vehicle instead of Neo-Kemp is presented in percentages. In the base case, the Neo-Kemp vehicle type, all criteria are set to 100%. Therefore, this figure shows the effect that a decision-maker has on all three criteria. The impact figure, Figure 7.5 shows that Groot Rijnschip emits the least amount of emissions. However, the cost are higher.

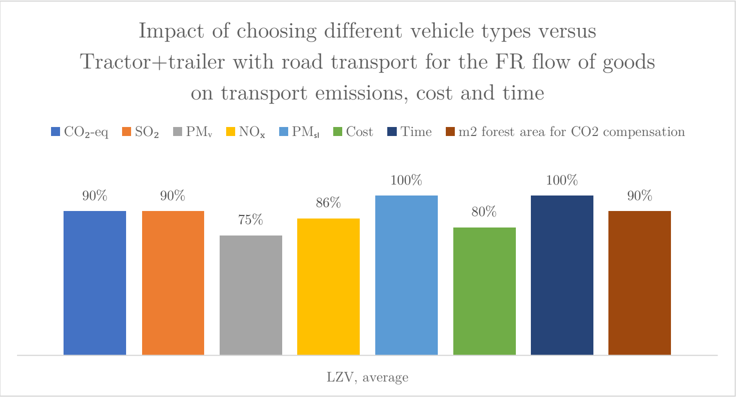

Figure 7.7: Impact of choosing different vehicle types with road transport for the FR flow of goods on transport emissions, cost and time

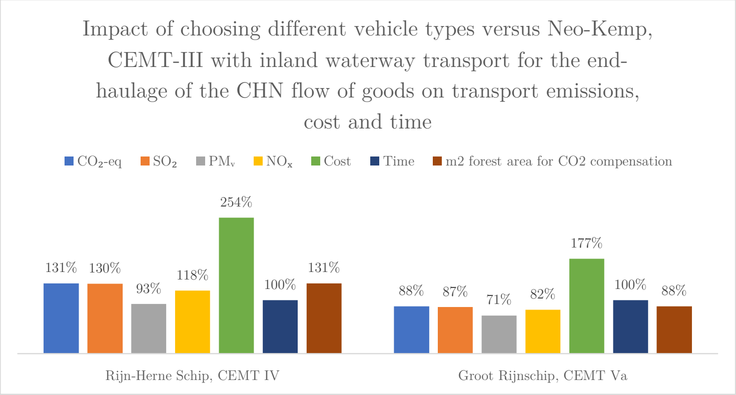

Figure 7.8: Impact of choosing different vehicle types with inland waterway transport for the end-haulage of the CHN flow of goods on transport emissions, cost and time

8 CONCLUSION, DISCUSSION AND RECOMMENDATIONS

8.1 CONCLUSION

Companies are pushed to rethink their existing SC to contribute to the environmental challenges. To do so, companies have to balance their business performance measures with environmental performance measures. This appears to be difficult. This thesis aimed to investigate the impact of SCD/C decisions on supply chain emissions, costs, and transport times. Therefore an answer to the following main research question had to be found:

> *what impact do supply chain design and coordination (SCD/C) decisions in a global supply chain have on the supply chain's emissions, costs and transport times?*

It was decided to use a case study method in this research. The steps of model exploration, conceptualisation, design and testing were followed to find an answer to the main research question. The answers to all subquestions that were found in this process are outlined inTable 8.2.

In the model testing phase, verification and validation of the model were carried out. The model verification showed that the model generates logical outcomes. This was demonstrated through a scenario analysis of the case study, in which alternative scenarios were set up and tested in addition to the base-case scenario. The outcomes of the scenario analysis showed that the outcomes were as expected. This was confirmed by the sensitivity analysis, which also showed that the model behaved as expected. The change in some variables due to a change in input was measured, and nothing remarkable was found as everything behaved as expected. From the scenario analysis it appeared that the transshipment emissions in comparison with the transport emissions were negligible, see Section 6.1.2. Regarding the validation of the model, a validation meeting was set up to validate the model with the case experts. In general, based on the findings of this meeting, an adjustment was made to the assumption regarding the average speed per transport mode because the transport times did not correspond to reality. This also appeared from a comparison with other data. However, the costs between the various modes appeared to be in proportion for the case experts.

Once the emission model was verified and validated, the decision impact analysis could be performed. The model's main function is to calculate the emissions, costs, and times based on the input given. The main dials of the model, which also represent the types of decisions to be made and therefore the different options per type of decision, are the transport mode, the fuel/engine type and the vehicle type. These three main dials represent the three SCD/C taken into account in this research as those decisions were most relevant to the case study. For each transport leg, the model user has to enter a.o. the weight per container, number of containers, origin and destination and the model's 'dials', namely modality type, vehicle type and fuel/engine type. Once this information is entered, all emissions, costs and times are calculated. Because of these functions of the model, a clear overview of results can be gathered as the output changes when a different input is given (when one of the dials has turned).

By performing the decision impact analysis, the following findings were made. The three types of decisions that were most relevant for the case were analysed; these are mode selection decisions, fuel/energy/engine type decisions and vehicle type decisions. Table 8.1 shows a short overview of the results from the decision impact analysis. It shows the ranges in which the impact percentages vary for that particular type of decision in that particular flow. So, for the first row, the percentages for the impact on emissions vary between 9-16330%. This means that in some alternative mode options for the CHN flow, the alternative options impact the emissions between 9-16330% compared to the base case option, which is a massive impact. When overlooking this overview of results, it can be concluded that the decision mode selection impacts all three criteria, emissions, cost and time. The fuel type and vehicle type decisions have no impact on the criteria time. Secondly, it can be concluded that the most crucial decision from this specific case analysis is the mode selection decision. Not only because it impacts all three criteria but also because the emission range, especially in the analysis for the CHN flow, is extensive. On the other hand, it must also be stated that the other two decisions also make an undeniable impact on emissions and cost and must therefore not be neglected but should, on the contrary, also be taken into account. Fuel type selection can make the biggest positive impact on emissions from these two decision types, looking at the smallest percentages of the two decision types. At the same time, the changes in costs for road and maritime transport are not that big. This indicates a feasible outcome; fewer emissions with minimum extra cost. Finally, it can be concluded that all three decision types have an impact and therefore matter and that it is recommended for the case to take all three types of decisions into account. Mode selection is the decision type that is most commonly considered within companies. However, if companies influenced carriers to select a specific fuel or vehicle type, the transportation sector as a whole would be activated to change to using more sustainable fuel or vehicle options. Imagine what positive change this would bring to the transportation sector if companies start imposing fuel/vehicle requirements on carriers. This would bring more incentives to the transportation sector to act more sustainably and offer more sustainable transportation options.

Table 8.1: Results overview table - impact ranges per SCD/C decision type

	Emissions	Cost	Time
Mode selection CHN flow	9-16330%	985-3541%	10-39%
Mode selection FR flow	56-247%	57-94%	300-303%
Mode selection PRT flow	13-303%	14-58%	326-400%
Fuel/engine type selection FR flow (road)	49-294%	93-110%	no impact
Fuel/engine type selection CHN flow (maritime)	2-196%	91-102%	no impact
Fuel/engine type selection CHN flor (air)	12-146%	163%	no impact
Vehicle type selection FR flow (road)	75-100%	80%	no impact
Vehicle type selection (inland waterway)	71-254%	177-254%	no impact

Regarding the added value of the model, the following can be concluded. As the mode selection decision is already commonly considered in companies, decision-makers are already familiar with especially the cost and time differences of the different modalities. Nevertheless, from the case study, it appeared that this knowledge is not present concerning the cost differences of the different fuel and vehicle types. This leads to the first added value point of the model, the added value of getting insight into the cost differences when using different fuel/engine types or vehicle types in transporting goods. The second added value point is that it first appeared from the case study that concerning emissions knowledge was only present on a general level. The value of the emission model is that it contributes to a much more accurate view of the impact on emissions among decision-makers. Because of this accurate overview, the model outcomes can function as a handle for the decision-makers to see the impact of their decisions. The model can compare different possibilities for transporting goods; it can compare different modalities, vehicle types per modality and fuel/engine types per modality and express its impact in terms of emissions, costs and time. As a result, the model can identify not only sustainability measures but also business measures. Consequently, the impact (positive/negative) of certain decisions within the supply chain on emissions, costs, and time can be made clear at a glance. If the company starts using this model, conscious choices may be made more often if the business measures allow it. The model also provides a handle for communication about different options (in terms of modalities, type of fuels and type of vehicles) within different company departments. The model and the results provide a tool for making decisions and an overview in a table of this impact, which can be communicated to relevant departments. As a result, it can make stakeholders more aware of their impact when making a certain decision.

The case experts confirmed the above outlined added value conclusions. From the validation, it became apparent that the case experts were pleased to see the emission model has fulfilled its purpose to create a model that shows the impact of their SCD/C decisions. The case experts plan to use the model for every program at an advanced stage within the sales process. At that point, the case experts want to apply the model to the specific program and show the outcomes of all different decisions to the rest of the company. On the one hand, it can help the supply chain team to make decisions based on numbers and on the other hand, the outcomes of the model can also be used to back their decisions with numbers. Regarding the model's overall value to the case experts, they were very pleased to gain insight into the criteria emissions in particular. Regarding the mode selection decisions, they were already familiar because of their experiences of the cost and time ratios between the different modalities. However, for the fuel type and vehicle type decisions, they were interested in the changes in the costs. Specifically, the insight the model gives into the impact on emissions provides the added value of the model to the case experts. But in the end, the model as a whole, with all its functions, so the insight into the combination of emissions, costs and times is what gives the total package. As solely in this way, once all information is known, well-thought decisions can be made. It can be concluded that the model fitted the knowledge gap for L and has therefore contributed to their decision-making process regarding the transport of goods. Recommendations for L can be found in Section 8.3.2.

Regarding the added value of the research from a scientific point of view, it can first of all be concluded that all knowledge gaps found in the literature review are filled, see Section 8.2.6. Besides this, this research can be used to further research. Recommendations for further research can be found in Section 8.3.1.

Table 8.2: Answers on sub-questions

Sub-question	Answer
1. How are transport-related emissions from global supply chains previously modelled?	Previously, in the literature, different modelling techniques were used depending on the primary focus of a research project. In this research, an emission model was created, not an optimisation model, which consists of a system of equations.
2. What are the causes of emissions within the supply chain of the case study?	As the core business of L's supply chain includes ordering consumer products, receiving these products and shipping them to the customers (the retailers), the scope of the supply chain included in this research is from the transhipment origin right after the production facility up until the transport to the client's warehouse. Within that scope, namely, the loading and unloading activities of the transhipment processes and the WTT and TTW emissions for the transport processes are the main causes of emissions.
3. Which emissions and criteria should be taken into account in the emission model?	Emissions as a criteria concern sustainability performance, while the other part of the main research question, costs and travel times, represent business performance. CO_2, NH_4, and N_2O are included as CO_2-eq emissions; these emissions are the main greenhouse gasses. SO_2 and NO_x are included, which can cause acidification, ecotoxicity and human toxicity. In addition, NO_x can also cause eutrophication and summer smog. Finally, PM_v (during combustion) and PM_{sl} (during wear & tear) are included, that cause human toxicity and summer smog.
4. Which parameters and variables influence the criteria in the emission model?	Distance, cargo weight per container, number of containers, mode type, vehicle/vessel type, road/waterway type, fuel/technique type, emission factors transport, number of movements for transhipment, mobile equipment type for transhipment, emission factors mobile equipment for transhipment, cost data per transport mode, cost data per fuel type, cost data per vehicle/vessel type, average speed per transport mode.
5. What is the base case scenario of the case study?	For the selected program of the case, there are three flows of goods, goods that originate from China, France and Portugal. Regarding the inbounds in the base case scenario, the goods from China are shipped by maritime transport to the port of Rotterdam and transported by road to L's warehouse in Drunen. The goods from France and Portugal are transported by road to Drunen. Regarding the outbounds of the base case scenario, solely road transport is used to transport the goods to the four warehouses of the client.
6. What do the alternative scenarios entail with regards to the scenario analysis for verification means?	For all three flows of goods (CHN flow, FR flow and PRT flow), multiple different scenarios are created. For the CHN flow, in total, six different scenarios are created where the main and end-haulage legs of transport differ from each other; next to the base case, the scenarios maritime-inland-road, road-rail-inland-road, road-rail-road, road-air-inland-road and road-air-road are created. For the FR and PRT flow, in total, three different scenarios are created; next to the base case, the scenarios road-maritime-road and road-rail-road are created.
7. What impact has uncertainty in emission factors?	From the sensitivity analysis, it appeared that changing a certain corresponding emission factor affects the outcome of that certain emission. So, if uncertainty exists around emission factors used, it does impact the outcomes if calculations are executed with those emission factors.
8. Which scdc decisions' impact are relevant to the case to model and analyse?	The case experts, first of all, wished to observe the impact of the use of different modes of transport. Therefore, the scenario analysis already used to verify the model could also be used within the decision impact analysis since different modes of transport are used in the scenario analysis for the different flows in the case study. Besides the choice of transport mode, the case experts were also curious about the effect of using different engines or fuels, especially for road transport. They wonder whether the difference in emissions of, for example, 'Euro VI' engines compared to 'Euro V' engines is big enough to make the carrier platform they use to only book carriers with trucks that have a certain type of engine. The third type of decision that interested the case experts is the choice of vehicle type.

8.2 DISCUSSION

8.2.1 Reflection on the research approach

This study decided to create a model based on a system of equations to gain insight into the output in terms of emissions, costs, and time for each transport leg. The idea was to use this model to investigate the impact of certain scdc decisions on emissions, costs and time. The choice was made to investigate this through a case study. Because of this choice, only the SCD/C decisions that were considered relevant for this case were investigated. Decisions such as routing decisions and facility location selection have thus been left out of consideration. Still, it was beneficial to conduct this research through a case study since real data of real products and real transports to be booked were used. Also, a case study made it possible to create insights into how this model can be optimally adjusted to actually be used in making SCD/C decisions in business execution.

In creating the model, the choice was made to include certain criteria. These are several types of emissions: CO_2-eq. (CO_2, CH_4 and N_2O), SO_2, PM_v, NO_x and PM_{sl}. In addition to these emissions, cost and time were also used as criteria in the model. Concerning costs, a conscious decision was made to include costs in the model as opposed to prices. The idea behind this is that prices depend strongly on supply and demand for transport and that this is difficult to include in the model. The validation showed that the costs are in roughly the same proportion as the prices. However, given the large differences in prices that can occur in a tight market, for example, when the Suez Canal is congested, the supply and demand for freight transport and its influence on prices would be an interesting subject for further research.

8.2.2 Reflection on model assumptions

In constructing the model, several assumptions were made. Most of the assumptions concern data used in the model. These include the emission figures used, the assumptions on average speed per mode, the cost figures used per mode and the assumptions on fuel cost data. Nevertheless, assumptions regarding transshipments include the number of trips per transport leg, the number of kWh needed per TEU per transport of goods, and the assumption that 20% of the equipment used for transhipment is electric and 80% of this equipment uses diesel as fuel. These assumptions should be taken into account when interpreting the results and using the model. These assumptions can also be further investigated in follow-up research.

The outbounds and returns were also made transparent for the case, although these were not used for the analysis. The assumption made is that 10% of the goods delivered for the programme are returned. Moreover, for the outbounds, it is assumed that all goods of the inbounds are equally divided over the four warehouses of the customer. For the outbounds and returns, a weighted average of the cargo weight of the inbounds is used, even though it is not known which goods are sent to which warehouses for the outbounds and which goods are returned.

8.2.3 Reflection on model findings

As far as the model findings are concerned, this section reflects the generation of answers to the main question. These answers are taken from the results of the decision impact analysis. For each type of decision, several analyses were carried out based on the case study. These analyses could also have been carried out on other cases with different outcomes. Nevertheless, these analyses have shown that SCD/C decisions impact certain criteria, some decisions on emissions only, some on emissions and costs and others on all three criteria. So even though the numerical outcomes might have been different in another case, the impact would also have been visible. With the results of this study, decision-makers in the business world who are responsible for these kinds of SCD/C decisions can at least see the impact of the choices they are faced with on emissions, costs and time. The results of this research can also be used to substantiate certain decisions.

8.2.4 Implications for the freight transportation sector

In this section, several aspects will be discussed in which action is required from the freight transport sector. For the fuel type decision, all kinds of fuels have been considered in the research. However, the availability of these fuels is not guaranteed or accessible for all of them. The research showed that some fuels that are very favourable for emissions are still costly. This applies, for example, to bio-kerosene as an alternative fuel for kerosene in aircraft. Solutions to this problem lie in the cooperation of the entire transport sector. This means that policymakers, fuel producers, companies and vehicle owners must all work together to make alternative fuels accessible and put them into use.

In terms of vehicle type decisions, it has been shown that this impacts emissions as well. However, it has also become apparent that it is currently not common or possible to influence a shipping company or airline to transport the containers in question on a particular type of ship or aircraft. This would potentially be an option for road transport, as tenders could then be placed with carriers who have certain types of trucks or delivery vehicles. However, this is certainly not possible or common for transport modes such as inland waterway, maritime, rail, and air transport. For this problem, too, all those involved in the freight transport sector must work together to develop solutions that will make it possible and customary for companies to exert influence on a vehicle type.

8.2.5 Societal relevance

This study contributes to the emission reduction that needs to take place in the freight transportation sector. The results of this study help decision-makers within companies to understand the impact they have when making SCD/C decisions. By taking this impact into account and being aware of it, decision-makers can act on this knowledge. If all decision-makers within all companies took emissions into account in addition to costs and time and tried to act as sustainable as possible within the limits of a company's business performance, many emissions could be saved.

8.2.6 Scientific relevance

The following aspects can summarise the knowledge gap that was identified. Current scientific research was lacking:

- research into SCD/C decisions, as compared to TI decisions and OM decisions
- research into the modelling of global SC's as compared to modelling national SC's
- research into specifically SC's within the consumer goods industry within SSCM
- research into other emissions as compared to the prominent GHG emissions

This research contributes to all identified knowledge gaps. First of all, the impact of SCD/C decisions is analysed in this study, namely the decisions regarding mode selection, fuel/energy/engine type and vehicle type. Secondly, the case study within company L considers a global supply chain. In the specific case used, three flows of goods were identified, goods from China, France and Portugal, making it a global case. Thirdly, the case considers goods for loyalty programs of retailers, in this case, a supermarket. So the goods considered are consumer goods as the clients of the supermarkets are consumers. Finally, next to the GHG emissions, SO_2, NO_x and PM_v and PM_{sl} are taken into account in the model and analysis.

8.3 RECOMMENDATIONS

The intention is to expand further the knowledge obtained from this research. Therefore, this section contains several recommendations for further research, an extension of the model, and practical recommendations for the freight transportation sector.

8.3.1 Recommendations for further research and improving the model

Firstly, there are several recommendations related to additional functions in the model. The choice has been made to include costs in the model as business criteria, but an addition to the model could be to include prices in the model. This will be complex, as prices depend strongly on the market, so certain scenarios will have to be used. Furthermore, the model could be automated so that less manual data entry is required. In particular, inserting all distances separately requires much work. For this, company-specific data sets should be compiled with the most common transport legs per modality.

Secondly, in general, the model could be made more usable so that companies can use it as a tool to gain insight into the impact of certain decisions they are about to make. This has already been discussed with the case experts in the modal usability meeting. The recommendations that emerged to make the model more user-friendly are implementing a 'sustainability ranking', which would be based on all emissions so that all emissions are no longer shown separately. It is difficult for decision-makers to interpret the emissions, so it would be desirable that the model has already taken this interpretation step. In addition, it was noted that all possible options, including options for pre-and end-haulage legs, are now shown for the case. However, given the little impact these pre-and end-haulage legs have, it is recommended to design the model so that only the main-haulage legs are included in the analysis. Furthermore, in addition to the 'technical dashboard' which currently shows the inputs and outputs, a 'user dashboard', which is presented more quickly, i.e. without all emissions separately, but including a 'sustainability ranking', would be recommended to make the model more usable in practice for decision-makers. If the results are shown more user-friendly, these results can also be communicated internally within companies. Namely, towards other teams to serve as argumentation for making the relevant decisions.

Third, it is recommended when the model is put into use by companies to initiate a continuous improvement of the input portfolio concerning vehicle types and fuel types as the freight transport sector continues to develop. The input parameters concerning the emission rates should be updated annually, using the most recent data.

Finally, other SCD/C decisions can be investigated with the model. Only the decisions considered relevant for the case study were analysed in this study, but the model is also suitable for analysing routing or facility location decisions.

8.3.2 Recommendations for the case-study

Specifically for this case study, it is recommended to consider the outcomes regarding the impact of the different analysed decisions when deciding upon transport of the goods. For this case, the outcomes are interpreted in Chapter 7. Within the boundaries of cost and time, the most sustainable decisions should be made to contribute to society positively. The outcomes can function as a handle to making these decisions. Therefore it is recommended to use them in general when deciding upon the transport for this specific program. If it appears imposing certain fuel types or vehicle types as a requirement at carriers seems difficult, then first focus on the mode selection decision. This decision turned out to be most crucial when it comes to impact on emissions cost and time.

Besides this, it is recommended to apply this model to every program. This research shows massive impact can be made on emissions, cost and time. When the model becomes part of the business process of deciding upon transportation of goods for every program, the impact on emissions can be big. In this way, a big contribution to society can be made by making sustainable decisions within the business boundaries. If all companies started doing this, a big movement in the whole sector could be started.

Finally, it is recommended to keep on updating the model on the latest emission factors. It could also be an option to back-test the model at some point. The emissions are calculated based on the distance-based method in this model, as fuel data was unknown. However, if back-testing of the model outcomes is desirable, fuel data should be collected. In this way, after a period of time, the outcomes from the distance-based method can be compared with the fuel-based method.

8.3.3 Recommendations for decision-makers and the freight transportation sector

It is recommended for decision-makers within companies to generate knowledge about the impact of decisions they make. The knowledge of costs and time is already embedded in their business way of thinking. However, knowledge of emissions and the impact of decisions on them is important to be updated. This knowledge consists of knowledge about different types of fuels that exist per modality and knowledge about the harmfulness of emissions. All decision-makers in supply chains in companies could create a platform to exchange this information.

However, decision-makers alone cannot improve the freight transport market. It requires cooperation in the whole sector. The study showed that some fuels positively impact emissions, for example, bio-kerosene, but sometimes these fuels can be costly. This then makes it impossible for companies and vehicle owners to use these fuels. The whole sector needs to think about solutions to bring these costs down. Policymakers, fuel producers, vehicle owners, companies and researchers must work together to bring about this change. Another example where cooperation in the sector is also needed is the possibility for companies to choose a certain type of vehicle to transport their goods. This applies to the modalities maritime, air, inland waterway and rail. For these modalities, it is currently impossible to influence the type of vehicle/vessel/aircraft on which goods are transported.

In short, it is not only decision-makers who have to make conscious decisions to solve the problem of emissions in the transport sector, but all those involved have to initiate a change to make real steps in the right direction. However, decision-makers can already exert influence by making the most conscious decision possible within the constraints of the business at that time in terms of cost and time.

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A LITERATURE ANALYSIS TABLE

Table A.1: Literature analysis table

	Type of SCD/C decision	Modelling technique
Bauer (2010)	Transport mode selection	Mixed integer non-linear programming (MINLP)
Lam et al.(2010)	Facility location selection	P-median
Harris (2011)	Transport mode selection	Simulation model
Tarek et al. (2011)	Facility location	Mixed integer programming (MIP)
Hoen et al. (2013)	Transport mode selection	Algebraic equation
Hoen et al. (2014)	Transport mode selection	Algebraic equation
Validi et al. (2014)	Routing decision	Multi objective linear programming (MOLP)
Zhu et al. (2014)	Freight management	Algebraic equation
Glock and Kim (2015)	Routing decision	Mixed integer non-linear programming (MINLP)
Huang et al. (2016)	Carbon footprint	Input-Output method
Nouira et al. (2016)	Facility location selection	Mixed integer linear programming (MILP)
Kumar et al. (2016)	Routing decision	Multi objective linear programming (MOLP)
Suzuki (2016)	Routing decision	Mixed integer linear programming (MILP)
Qiu et al. (2017)	Routing decision	Mixed integer linear programming (MILP)
Ameknassi et al. (2016)	Freight management (logistics outsourcing)	Multi objective linear programming (MOLP)
Rudi et al. (2016)	Freight management (freight size)	Non-linear function
Chen and Wang (2016)	Transport mode selection	Algebraic equation
Li et al. (2017)	Freight management (logistics outsourcing)	Algebraic equation
Musavi and Bozorgi-Amiri (2017)	Routing decision (location selection)	Mixed integer linear programming (MILP)

B

EMISSION DATA INPUT

Table B.1: Inland waterway emission data

	TTW emissies [g/tkm]					**WTW-emissies [g/tkm]**				
	CO_2-eq	**SO_2**	**PM_v**	**NO_x**	**PM_{sl}**	**CO_2-eq**	**SO_2**	**PM_v**	**NO_x**	**PM_{sl}**
Neo Kemp, CEMT III (=DEFAULT)	17.04	0.00011	0.014	0.27	0	22.46	0.023	0.014	0.28	0
Rijn-Herne Schip, CEMT IV	22.29	0.00014	0.012	0.32	0	29.38	0.03	0.013	0.33	0
Groot Rijnschip, CEMT Va	15.03	0.00009	0.01	0.22	0	19.81	0.02	0.01	0.23	0
CCR2 (=DEFAULT)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
CCR2 with HVO	1%	100%	80%	90%	100%	11%	100%	99%	91%	100%
CCR2 with GTL	96%	100%	80%	90%	100%	99%	100%	83%	91%	100%
CCR2 with SCR	100%	100%	90%	20%	100%	100%	100%	92%	24%	100%
CCR2 with DPF	100%	100%	10%	100%	100%	100%	100%	25%	100%	100%
CCR2 with SCR & DPF	100%	100%	10%	15%	100%	100%	100%	25%	19%	100%
Stage V kW <300	103%	100%	50%	41%	100%	102%	100%	56%	44%	100%
Stage V kW <300 with HVO	1%	100%	50%	41%	100%	11%	100%	73%	44%	100%
Stage V kW >300	95%	100%	8%	34%	100%	96%	100%	19%	37%	100%
Stage V kW >300 with HVO	1%	100%	8%	34%	100%	10%	100%	34%	37%	100%
LNG pilot <10% Diesel	104%	100%	25%	25%	100%	96%	100%	19%	37%	100%
LNG dual fuel, 20% Diesel	104%	100%	50%	50%	100%	96%	100%	48%	51%	100%
LNG single fuel, SI	104%	100%	10%	25%	100%	96%	100%	13%	27%	100%
BioLNG single fuel, SI	25%	100%	10%	25%	100%	47%	100%	13%	58%	100%

Table B.2: Maritime emission data

	TTW emissies [g/tkm]					WTW-emissies [g/tkm]				
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}
Containervessel 0-999 TEU	38.3	0.072	0.0198	0.82	0	47.4	0.12	0.0214	0.84	0
Containervessel 1000-1999 TEU	25.5	0.048	0.0132	0.57	0	31.5	0.08	0.0142	0.58	0
Containervessel 2000-2999 TEU	19.2	0.036	0.0099	0.44	0	23.7	0.06	0.0107	0.45	0
Containervessel 3000-4999 TEU (=DEFAULT)	14.9	0.028	0.0077	0.36	0	18.5	0.047	0.0083	0.36	0
Containervessel 5000-7999 TEU	11.7	0.022	0.0061	0.29	0	14.5	0.037	0.0065	0.29	0
Containervessel 8000-11999 TEU	9.3	0.018	0.0048	0.23	0	11.5	0.029	0.0052	0.24	0
Containervessel 12000-14499 TEU	6.3	0.012	0.0033	0.16	0	7.8	0.02	0.0035	0.16	0
Containervessel 14500-19999 TEU	5.3	0.01	0.0027	0.13	0	6.5	0.016	0.0029	0.13	0
Containervessel 20000+ TEU	4.7	0.009	0.0024	0.11	0	5.8	0.015	0.0026	0.11	0
HFO/MDO (0,5% S) Tier II (=DEFAULT)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HFO/MDO (0,5% S) Tier III	100%	100%	100%	27%	100%	100%	100%	100%	29%	100%
MDO Tier II (0,1% S)	101%	20%	77%	100%	100%	103%	45%	79%	100%	100%
HFO + Scrubber Tier II (0,5% S)	104%	100%	100%	100%	100%	97%	100%	169%	98%	100%
LNG (SI, lean burn)	98%	0.1%	10%	36%	100%	95%	0.2%	12%	37%	100%
LNG (dual fuel manifold injection)	98%	0.1%	68%	36%	100%	95%	0.2%	66%	37%	100%
LNG (direct diesel injection)	80%	0.1%	68%	36%	100%	80%	0.2%	66%	37%	100%
BioLNG (SI, lean burn)	0%	0.1%	10%	36%	100%	28%	2%	12%	36%	100%

Table B.3: Road emission data

	TTW emissies [g/tkm]					WTW-emissies [g/tkm]				
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}
Tractor+trailer, average (=DEFAULT)	91.9	0.0005	0.003	0.303	0.006	120.9	0.124	0.008	0.35	0.006
Tractor+trailer, city road	185.6	0.0011	0.007	0.63	0.01	244.1	0.25	0.016	0.72	0.01
Tractor+trailer, country road	116.5	0.0007	0.004	0.374	0.005	153.2	0.157	0.009	0.43	0.005
Tractor+trailer, highway	78.1	0.0005	0.002	0.259	0.006	102.8	0.105	0.006	0.3	0.006
LZV, average	82.8	0.0005	0.002	0.259	0.006	108.9	0.112	0.006	0.3	0.006
LZV, city road	167	0.0001	0.005	0.539	0.009	219.6	0.225	0.014	0.62	0.009
LZV, country road	104.8	0.0006	0.003	0.32	0.005	137.9	0.141	0.008	0.37	0.005
LZV, highway	70.3	0.0004	0.002	0.221	0.006	92.5	0.095	0.005	0.25	0.006
Diesel Euro VI (=DEFAULT)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Diesel Euro V	95%	100%	270%	121%	100%	95%	100%	133%	116%	100%
Diesel Plug-in hybride (Euro VI)	80%	100%	80%	100%	100%	97%	100%	91%	103%	100%
GTL Euro V	103%	100%	100%	100%	100%	104%	100%	104%	102%	100%
Biodiesel Euro VI (97% FAME, 3% HVO)	2%	100%	100%	100%	100%	16%	100%	202%	111%	100%
HVO Euro VI	2%	100%	100%	100%	100%	11%	100%	202%	111%	100%
LNG (Euro VI)	97%	100%	100%	50%	100%	91%	100%	49%	58%	100%
BioLNG (Euro VI)	6%	100%	100%	50%	100%	36%	100%	50%	51%	100%
Electric (average mix)	0%	100%	0%	0%	100%	70%	100%	48%	29%	100%
Electric (wind/solar)	0%	100%	0%	0%	100%	2%	100%	0%	0%	100%
Hydrogen	0%	100%	0%	0%	100%	80%	100%	294%	59%	100%
Hydrogen (from wind/solar/hydroelectric electrolysis)	0%	100%	0%	0%	100%	7%	100%	0%	0%	100%

Table B.4: Air emission data

	TTW emissies [g/tkm]					**WTW-emissies [g/tkm]**				
	CO$_2$-eq	**SO$_2$**	**PM$_v$**	**NO$_x$**	**PM$_{sl}$**	**CO$_2$-eq**	**SO$_2$**	**PM$_v$**	**NO$_x$**	**PM$_{sl}$**
Belly-freight short (<1500km)	712	0.22	0.028	0.0378	0.0184	9.1	0.012	0.078	0.042	0.0184
Belly-freight medium (>1500km, <6000km)	483	0.15	0.018	2.37	0.0008	617	0.82	0.053	2.6	0.0008
Belly-freight long (>6000km)	448	0.14	0.017	2.33	0.0003	572	0.76	0.049	2.6	0.0003
Full-freight short (<1500km)	1095	0.35	0.039	5.86	0.0087	1399	1.85	0.118	6.5	0.0087
Full-freight medium (>1500km, <6000km)	435	0.14	0.016	1.93	0.0005	556	0.73	0.047	2.2	0.0005
Full-freight long (>6000km)	411	0.13	0.014	1.72	0.0003	525	0.69	0.044	2	0.0003
Kerosene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Bio-kerosene	1%	1%	100%	100%	100%	11%	21%	146%	102%	100%

Table B.5: Rail emission data

	TTW emissies [g/tkm]					**WTW-emissies [g/tkm]**				
	CO$_2$-eq	**SO$_2$**	**PM$_v$**	**NO$_x$**	**PM$_{sl}$**	**CO$_2$-eq**	**SO$_2$**	**PM$_v$**	**NO$_x$**	**PM$_{sl}$**
Long train (1.270t GTW) electric (E)					0.007	14.6	0.004	0.0005	0.0104	0.007
Extra long train (1.481t GTW) electric (E)					0.0064	13.3	0.004	0.00045	0.0094	0.0064
Long train (1.270t GTW) diesel (D)	20.3	0.00013	0.0066	0.29	0.0069	26.8	0.028	0.00763	0.2979	0.0069
Extra long train (1.481t GTW) diesel (D)	18.4	0.00012	0.006	0.26	0.0063	24.3	0.025	0.00694	0.2707	0.0063
E Electric average mix (=DEFAULT)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
E Renewable electricity, solely wind and solar	100%	100%	100%	100%	100%	3%	100%	0%	0%	100%
E Renewable electricity, all sources (incl. biomass)	100%	100%	100%	100%	100%	7%	100%	36%	19%	100%
E Overvoltage (3 kV (t.o.v. 1.5 kV)	100%	100%	100%	100%	100%	80%	100%	80%	80%	100%
D Stage IIIb (=DEFAULT)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
D Stage V	100%	100%	100%	95%	100%	100%	100%	100%	96%	100%
D Stage IIIB HVO	1%	100%	80%	90%	100%	11%	100%	163%	94%	100%

C FUEL COST DATA INPUT

Table C.1: Road fuel cost

Road options	**Fuel cost difference compared to default fuel type**	**Source used**
Diesel Euro VI	100,00%	
Diesel Euro V	100,00%	
Diesel Plug-in hybride (Euro VI)	80,14%	[RVO, 2021]
GTL Euro V	106,37%	[ABC Olie, 2021]
Biodiesel Euro VI (97% FAME, 3% HVO)	153,05%	[Statista, 2021]
HVO Euro VI	113,38%	[Fieten, 2021]
LNG (Euro VI)	50,96%	[CBS, 2021]
BioLNG (Euro VI)	34,25%	[Groengas Nederland, 2016] [CBS, 2021]
Electric (average mix)	71,36%	[RVO, 2021]
Electric (wind/solar)	71,36%	[RVO, 2021]
Hydrogen	168,58%	[RVO, 2021]
Hydrogen (from wind/solar /hydroelectric electrolysis)	168,58%	[RVO, 2021]

Table C.2: Inland waterway fuel cost

Inland-waterway options	**Fuel cost difference compared to default fuel type**	**Source used**
CCR2	100,00%	
CCR2 with HVO	331,50%	[TNO, 2020]
CCR2 with GTL	106,37%	[ABC Olie, 2021]
CCR2 with SCR	100,00%	
CCR2 with DPF	100,00%	
CCR2 with SCR & DPF	100,00%	
Stage V kW <300	100,00%	
Stage V kW <300 with HVO	331,50%	[TNO, 2020]
Stage V kW >300	100,00%	
Stage V kW >300 with HVO	331,50%	[TNO, 2020]
LNG pilot <10% Diesel	79,21%	[Pitpoint, 2018]
LNG dual fuel, 20% Diesel	82,86%	[Pitpoint, 2018]
LNG single fuel, SI	78,57%	[Pitpoint, 2018]
BioLNG single fuel, SI	52,81%	[Pitpoint, 2018] [Groengas Nederland, 2016]

Table C.3: Maritime fuel cost

Maritime options	Fuel cost difference compared to default fuel type	Source used
HFO/MDO (0,5% S) Tier II	100,00%	
HFO/MDO (0,5% S) Tier III	100,00%	
MDO Tier II (0,1% S)	109,78%	[TNO, 2011]
HFO + Scrubber Tier II (0,5% S)	90,22%	[TNO, 2011]
LNG (SI, lean burn)	78,57%	[Pitpoint, 2018]
LNG (dual fuel manifold injection)	76,71%	[TNO, 2011]
LNG (direct diesel injection)	69,68%	[TNO, 2011]
BioLNG (SI, lean burn)	52,81%	[Pitpoint, 2018] [Groengas Nederland, 2016]

Table C.4: Rail fuel cost

Rail options	Fuel cost difference compared to default fuel type	Source used
E Electric average mix	100,00%	
E Renewable electricity, solely wind and solar	100,00%	
E Renewable electricity, all sources (incl. biomass)	100,00%	
E Overvoltage (3 kV (t.o.v. 1.5 kV)	100,00%	
D Stage IIIb	140,13%	[RVO, 2021]
D Stage V	140,13%	[RVO, 2021]
D Stage IIIB HVO	158,88%	[RVO, 2021] [Fieten, 2021]

Table C.5: Air fuel cost

Air options	Fuel cost difference compared to default fuel type	Source used
Kerosene	100,00%	
Bio-kerosene	250,00%	[Schiphol, 2021]

D

SCENARIO ANALYSIS

D.1 SCENARIO OVERVIEW

Table D.1: Scenario overview

			CHN flow				FRA flow			PRT flow		
C1	F1	P1	Maritime	Road			Road			Road		
C1	F1	P2	Maritime	Road			Road			Road	Rail	Road
C1	F1	P3	Maritime	Road			Road			Road	Maritime	Road
C1	F2	P1	Maritime	Road			Road	Rail	Road	Road		
C1	F2	P2	Maritime	Road			Road	Rail	Road	Road	Rail	Road
C1	F2	P3	Maritime	Road			Road	Rail	Road	Road	Maritime	Road
C1	F3	P1	Maritime	Road			Road	Maritime	Road	Road		
C1	F3	P2	Maritime	Road			Road	Maritime	Road	Road	Rail	Road
C1	F3	P3	Maritime	Road			Road	Maritime	Road	Road	Maritime	Road
C2	F1	P1	Maritime	Inland	Road		Road			Road		
C2	F1	P2	Maritime	Inland	Road		Road			Road	Rail	Road
C2	F1	P3	Maritime	Inland	Road		Road			Road	Maritime	Road
C2	F2	P1	Maritime	Inland	Road		Road	Rail	Road	Road		
C2	F2	P2	Maritime	Inland	Road		Road	Rail	Road	Road	Rail	Road
C2	F2	P3	Maritime	Inland	Road		Road	Rail	Road	Road	Maritime	Road
C2	F3	P1	Maritime	Inland	Road		Road	Maritime	Road	Road		
C2	F3	P2	Maritime	Inland	Road		Road	Maritime	Road	Road	Rail	Road
C2	F3	P3	Maritime	Inland	Road		Road	Maritime	Road	Road	Maritime	Road
C3	F1	P1	Road	Rail	Inland	Road	Road			Road		
C3	F1	P2	Road	Rail	Inland	Road	Road			Road	Rail	Road
C3	F1	P3	Road	Rail	Inland	Road	Road			Road	Maritime	Road
C3	F2	P1	Road	Rail	Inland	Road	Road	Rail	Road	Road		
C3	F2	P2	Road	Rail	Inland	Road	Road	Rail	Road	Road	Rail	Road
C3	F2	P3	Road	Rail	Inland	Road	Road	Rail	Road	Road	Maritime	Road
C3	F3	P1	Road	Rail	Inland	Road	Road	Maritime	Road	Road		
C3	F3	P2	Road	Rail	Inland	Road	Road	Maritime	Road	Road	Rail	Road
C3	F3	P3	Road	Rail	Inland	Road	Road	Maritime	Road	Road	Maritime	Road
C4	F1	P1	Road	Rail	Road		Road			Road		
C4	F1	P2	Road	Rail	Road		Road			Road	Rail	Road
C4	F1	P3	Road	Rail	Road		Road			Road	Maritime	Road
C4	F2	P1	Road	Rail	Road		Road	Rail	Road	Road		
C4	F2	P2	Road	Rail	Road		Road	Rail	Road	Road	Rail	Road
C4	F2	P3	Road	Rail	Road		Road	Rail	Road	Road	Maritime	Road
C4	F3	P1	Road	Rail	Road		Road	Maritime	Road	Road		
C4	F3	P2	Road	Rail	Road		Road	Maritime	Road	Road	Rail	Road
C4	F3	P3	Road	Rail	Road		Road	Maritime	Road	Road	Maritime	Road

Table D.2: Scenario overview

			CHN flow				**FRA flow**			**PRT flow**		
C5	F1	P1	Road	Air	Inland	Road	Road			Road		
C5	F1	P2	Road	Air	Inland	Road	Road			Road	Rail	Road
C5	F1	P3	Road	Air	Inland	Road	Road			Road	Maritime	Road
C5	F2	P1	Road	Air	Inland	Road	Road	Rail	Road	Road		
C5	F2	P2	Road	Air	Inland	Road	Road	Rail	Road	Road	Rail	Road
C5	F2	P3	Road	Air	Inland	Road	Road	Rail	Road	Road	Maritime	Road
C5	F3	P1	Road	Air	Inland	Road	Road	Maritime	Road	Road		
C5	F3	P2	Road	Air	Inland	Road	Road	Maritime	Road	Road	Rail	Road
C5	F3	P3	Road	Air	Inland	Road	Road	Maritime	Road	Road	Maritime	Road
C6	F1	P1	Road	Air	Road		Road			Road		
C6	F1	P2	Road	Air	Road		Road			Road	Rail	Road
C6	F1	P3	Road	Air	Road		Road			Road	Maritime	Road
C6	F2	P1	Road	Air	Road		Road	Rail	Road	Road		
C6	F2	P2	Road	Air	Road		Road	Rail	Road	Road	Rail	Road
C6	F2	P3	Road	Air	Road		Road	Rail	Road	Road	Maritime	Road
C6	F3	P1	Road	Air	Road		Road	Maritime	Road	Road		
C6	F3	P2	Road	Air	Road		Road	Maritime	Road	Road	Rail	Road
C6	F3	P3	Road	Air	Road		Road	Maritime	Road	Road	Maritime	Road

D.2 CASE INPUT

Table D.3: O/D CHN flow alternatives per transport leg

		Origin		Destination	
Transport leg name	**Mode**	**Place**	**Country**	**Place**	**Country**
C1.1Maritime	Maritime	Xingang	CHN	Rotterdam	NLD
C1.2Road	Road	Rotterdam	NLD	Drunen	NLD
C1					
C2.1Maritime	Maritime	Xingang	CHN	Rotterdam	NLD
C2.2Inland_waterway	Inland_waterway	Rotterdam	NLD	Waalwijk	NLD
C2.3Road	Road	Waalwijk	NLD	Drunen	NLD
C2					
C3.1Road	Road	Xingang	CHN	Chengdu	CHN
C3.2Rail	Rail	Chengdu	CHN	Tilburg	CHN
C3.3Inland_waterway	Inland_waterway	Tilburg	NLD	Waalwijk	NLD
C3.4Road	Road	Waalwijk	NLD	Drunen	NLD
C3					
C4.1Road	Road	Xingang	CHN	Chengdu	CHN
C4.2Rail	Rail	Chengdu	CHN	Tilburg	CHN
C4.3Road	Road	Tilburg	NLD	Drunen	NLD
C4					
C5.1Road	Road	Xingang	CHN	Beijing	CHN
C5.2Air	Air	Beijing	CHN	Amsterdam	NLD
C5.3Inland_waterway	Inland_waterway	Amsterdam	NLD	Waalwijk	NLD
C5.4Road	Road	Waalwijk	NLD	Drunen	NLD
C5					
C6.1Road	Road	Xingang	CHN	Beijing	CHN
C6.2Air	Air	Beijing	CHN	Amsterdam	NLD
C6.3Road	Road	Amsterdam	NLD	Drunen	NLD
C6					

Table D.4: O/D FRA flow alternatives per transport leg

		Origin		Destination	
Transport leg name	**Mode**	**Place**	**Country**	**Place**	**Country**
F1Road	Road	Chateauroux	FRA	Drunen	NLD
F1					
F2.1Road	Road	Chateauroux	FRA	Bonneuil-sur-Marne	FRA
F2.2Rail	Rail	Bonneuil-sur-Marne	FRA	Tilburg	NLD
F2.3Road	Road	Tilburg	NLD	Drunen	NLD
F2					
F3.1Road	Road	Chateauroux	FRA	Le Havre	FRA
F3.2Maritime	Maritime	Le Havre	FRA	Dordrecht	NLD
F3.3Road	Road	Dordrecht	NLD	Drunen	NLD
F3					

Table D.5: O/D PRT flow alternatives per transport leg

		Origin		Destination	
Transport leg name	**Mode**	**Place**	**Country**	**Place**	**Country**
P1Road	Road	Mortagua	PRT	Drunen	NLD
P1					
P2.1Road	Road	Mortagua	PRT	Vigo	ESP
P2.2Rail	Rail	Vigo	ESP	Pernis	NLD
P2.3Road	Road	Pernis	NLD	Drunen	NLD
P2					
P3.1Road	Road	Mortagua	PRT	Aveiro	PRT
P3.2Maritime	Maritime	Aveiro	PRT	Dordrecht	NLD
P3.3Road	Road	Dordrecht	NLD	Drunen	NLD
P3					

Table D.6: Vehicle & fuel type CHN flow alternatives per transport leg

Transport leg name	**Vehicle-type, road/waterway-type**	**Fuel/technique-type**
C1.1Maritime	Containervessel 3000-4999 TEU	HFO/MDO (0,5% S) Tier II
C1.2Road	Tractor+trailer, average	CCR2
C1		
C2.1Maritime	Containervessel 3000-4999 TEU	HFO/MDO (0,5% S) Tier II
C2.2Inland_waterway	Neo Kemp, CEMT III	CCR2
C2.3Road	Tractor+trailer, average	Diesel Euro VI
C2		
C3.1Road	Tractor+trailer, average	Diesel Euro VI
C3.2Rail	Extra long train (1.481t GTW) electric	E Electric average mix
C3.3Inland_waterway	Neo Kemp, CEMT III	CCR2
C3.4Road	Tractor+trailer, average	Diesel Euro VI
C3		
C4.1Road	Tractor+trailer, average	Diesel Euro VI
C4.2Rail	Extra long train (1.481t GTW) electric	E Electric average mix
C4.3Road	Tractor+trailer, average	Diesel Euro VI
C4		
C5.1Road	Tractor+trailer, average	Diesel Euro VI
C5.2Air	Full-freight long (>6000km)	Kerosene
C5.3Inland_waterway	Neo Kemp, CEMT III	CCR2
C5.4Road	Tractor+trailer, average	Diesel Euro VI
C5		
C6.1Road	Tractor+trailer, average	Diesel Euro VI
C6.2Air	Full-freight long (>6000km)	Kerosene
C6.3Road	Tractor+trailer, average	Diesel Euro VI
C6		

Table D.7: Vehicle & fuel type FRA flow alternatives per transport leg

Transport leg name	Vehicle-type, road/waterway-type	Fuel/technique-type
F1Road	Tractor+trailer, average	Diesel Euro VI
F1		
F2.1Road	Tractor+trailer, average	Diesel Euro VI
F2.2Rail	Extra long train (1.481t GTW) electric	E Electric average mix
F2.3Road	Tractor+trailer, average	Diesel Euro VI
F2		
F3.1Road	Tractor+trailer, average	Diesel Euro VI
F3.2Maritime	Containervessel 0-999 TEU	HFO/MDO (0,5% S) Tier II
F3.3Road	Tractor+trailer, average	Diesel Euro VI
F3	Neo Kemp, CEMT III	CCR2

Table D.8: Vehicle & fuel type PRT flow alternatives per transport leg

Transport leg name	Vehicle-type, road/waterway-type	Fuel/technique-type
P1Road	Tractor+trailer, average	Diesel Euro VI
P1		
P2.1Road	Tractor+trailer, average	Diesel Euro VI
P2.2Rail	Extra long train (1.481t GTW) electric	E Electric average mix
P2.3Road	Tractor+trailer, average	Diesel Euro VI
P2		
P3.1Road	Tractor+trailer, average	Diesel Euro VI
P3.2Maritime	Containervessel 0-999 TEU	HFO/MDO (0,5% S) Tier II
P3.3Road	Tractor+trailer, average	Diesel Euro VI
P3	Neo Kemp, CEMT III	CCR2

Table D.9: Product data CHN products

	Product name	Length [cm]	Width [cm]	Height [cm]	CM3	Weight [kg]	Planned OQ	Pieces per box
CHINA	Cast Iron braiser 26 cm	38	35,5	25,5	34399,5	12,5	93312	2
	Cast Iron Casserole 24cm round	35,5	33,2	32	37715,2	12,34	103760	2

Table D.10: Product data PRT products

	Product name	Length [cm]	Width [cm]	Height [cm]	CM3	Weight [kg]	Planned OQ	Pieces per box
PORTUGAL	Mini cocotte	37	26	9	8658	4,5	91302	6

Table D.11: Product data FRA products

	Product name	Length [cm]	Width [cm]	Height [cm]	CM3	Weight [kg]	Planned OQ	Pieces per box
FRANCE	Round storage with lid 0,6L	33,6	26,6	14	12512,64	3,56	126000	8
	Round storage with lid 1.1L	32,6	20,6	6,9	4633,764	2,62	184032	4
	Square storage 2 L	29,9	21,3	21,9	13947,453	4,1	203320	4
	Rectangular storage 2.6L	40	26,3	21,6	22723,2	7,17	242100	5
	Rectangular storage 4L	29,1	24	29,3	20463,12	5,92	203346	3
	Pasta box 0.8L	39,1	26,4	14,2	14657,808	4,2	184086	6
	Rectangular storage with valve 0,8L	35,1	21,7	17,2	13100,724	3,85	184140	6
	Rectangular storage with valve 1.7L	38,3	26,7	21,2	21679,332	5,23	203400	5

D.3 CASE OUTPUT

Table D.12: Output all scenarios combined

			Total emissions (WTW)							
			CO_2-eq [ton]	SO_2 [kg]	PM_v [kg]	NO_x [kg]	PM_{sl} [kg]	Cost [x1000 euro]	Time [days]	m2 forest area for CO_2 compensation[a]
C1	F1	P1	737	1,565	253	10,983	10	€ 230	43	17,964
C1	F1	P2	729	1,556	253	10,958	10	€ 223	46	17,784
C1	F1	P3	729	1,568	255	11,063	9	€ 217	47	17,791
C1	F2	P1	723	1,544	252	10,924	13	€ 220	45	17,634
C1	F2	P2	716	1,535	251	10,898	14	€ 214	48	17,453
C1	F2	P3	716	1,547	254	11,004	13	€ 207	49	17,460
C1	F3	P1	710	1,608	269	11,602	6	€ 162	45	17,322
C1	F3	P2	703	1,600	269	11,576	7	€ 155	48	17,141
C1	F3	P3	703	1,611	272	11,682	6	€ 148	49	17,148
C2	F1	P1	726	1,554	254	10,979	9	€ 219	44	17,717
C2	F1	P2	719	1,546	253	10,953	10	€ 213	47	17,536
C2	F1	P3	719	1,557	256	11,058	9	€ 206	48	17,543
C2	F2	P1	713	1,534	253	10,919	13	€ 209	46	17,386
C2	F2	P2	705	1,525	252	10,893	13	€ 203	49	17,205
C2	F2	P3	706	1,537	255	10,999	12	€ 196	50	17,212
C2	F3	P1	700	1,598	270	11,597	6	€ 151	46	17,074
C2	F3	P2	693	1,589	270	11,572	6	€ 144	49	16,893
C2	F3	P3	693	1,601	272	11,677	5	€ 138	50	16,900
C3	F1	P1	641	528	37	1,477	109	€ 667	19	15,624
C3	F1	P2	633	519	37	1,451	109	€ 661	22	15,443
C3	F1	P3	633	531	39	1,557	108	€ 654	23	15,450
C3	F2	P1	627	507	36	1,417	112	€ 657	21	15,293
C3	F2	P2	620	498	36	1,392	112	€ 651	24	15,112
C3	F2	P3	620	510	38	1,497	111	€ 644	25	15,119
C3	F3	P1	614	571	54	2,095	105	€ 599	21	14,981
C3	F3	P2	607	563	53	2,070	105	€ 592	24	14,800
C3	F3	P3	607	574	56	2,175	104	€ 586	25	14,807
C4	F1	P1	639	527	37	1,461	109	€ 666	18	15,593
C4	F1	P2	632	518	36	1,436	109	€ 660	21	15,412
C4	F1	P3	632	529	39	1,541	108	€ 653	22	15,419
C4	F2	P1	626	506	35	1,401	112	€ 657	20	15,262
C4	F2	P2	618	497	35	1,376	112	€ 650	23	15,082
C4	F2	P3	619	509	37	1,481	111	€ 643	24	15,088
C4	F3	P1	613	570	53	2,079	105	€ 598	20	14,950
C4	F3	P2	606	561	52	2,054	105	€ 592	23	14,770
C4	F3	P3	606	573	55	2,159	104	€ 585	24	14,776
C5	F1	P1	5,262	6,848	439	19,870	14	€ 1,945	7	128,334
C5	F1	P2	5,254	6,839	439	19,845	15	€ 1,939	10	128,153
C5	F1	P3	5,255	6,851	441	19,950	14	€ 1,932	11	128,160
C5	F2	P1	5,248	6,827	438	19,810	18	€ 1,935	9	128,003
C5	F2	P2	5,241	6,818	437	19,785	18	€ 1,929	12	127,823
C5	F2	P3	5,241	6,830	440	19,890	17	€ 1,922	13	127,829
C5	F3	P1	5,235	6,891	455	20,488	11	€ 1,877	9	127,691
C5	F3	P2	5,228	6,882	455	20,463	11	€ 1,870	12	127,511
C5	F3	P3	5,228	6,894	458	20,568	10	€ 1,864	13	127,517
C6	F1	P1	5,258	6,843	437	19,818	14	€ 1,943	6	128,232
C6	F1	P2	5,250	6,835	436	19,793	15	€ 1,936	9	128,052
C6	F1	P3	5,250	6,846	439	19,898	14	€ 1,930	10	128,058
C6	F2	P1	5,244	6,823	435	19,758	18	€ 1,933	8	127,902
C6	F2	P2	5,237	6,814	435	19,733	18	€ 1,926	11	127,721
C6	F2	P3	5,237	6,826	438	19,838	17	€ 1,920	12	127,728
C6	F3	P1	5,231	6,887	453	20,436	11	€ 1,874	8	127,590
C6	F3	P2	5,224	6,878	452	20,411	11	€ 1,868	11	127,409
C6	F3	P3	5,224	6,890	455	20,516	10	€ 1,861	12	127,416

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[a] in a period of 50 years, where the following is assumed: 4.6 tonnes of CO_2/hectare/year is captured in the first 10 years after planting the forest area and 9.1 tonnes of CO_2/hectare/year is captured in the subsequent years, leading to the capturing of 410 CO_2/hectare in a period of 50 years [Boosten et al., 2020]

E SENSITIVITY ANALYSIS OUTPUT

Table E.1: Sensitivity analysis table output on transport emissions, cost and time

	Transport emissions (WTW)						
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	Cost	Time
	[ton]	[kg]	[kg]	[kg]	[kg]	[x1000 euro]	[days]
Base (100%)	553	1,377	241	10,452	1	€ 55	40
Distance 90%	500	1,241	217	9,412	1	€ 52	36
Distance 110%	606	1,512	265	11,492	1	€ 59	44
Cargo weight 90%	500	1,241	217	9,412	1	€ 52	40
Cargo weight 110%	606	1,512	265	11,492	1	€ 59	40
#containers 90%	500	1,241	217	9,412	1	€ 52	40
#containers 110%	606	1,512	265	11,492	1	€ 59	40
Average speed 90%	553	1,377	241	10,452	1	€ 55	45
Average speed 110%	553	1,377	241	10,452	1	€ 55	37
#transshipment movements 90%	553	1,377	241	10,452	1	€ 55	40
#transshipment movements 110%	553	1,377	241	10,452	1	€ 55	40
#kWh per movement 90%	553	1,377	241	10,452	1	€ 55	40
#kWh per movement 110%	553	1,377	241	10,452	1	€ 55	40
Emissionfactor containervessel 3000-5000TEU, WTW CO_2-eq. 90%	500	1,377	241	10,452	1	€ 55	40
Emissionfactor containervessel 3000-5000TEU, WTW CO_2-eq. 110%	606	1,377	241	10,452	1	€ 55	40
Emissionfactor containervessel 3000-5000TEU, WTW SO_2 90%	553	1,241	241	10,452	1	€ 55	40
Emissionfactor containervessel 3000-5000TEU, WTW SO_2. 110%	553	1,512	241	10,452	1	€ 55	40

Figure E.1: Sensitivity analysis output on transport emissions

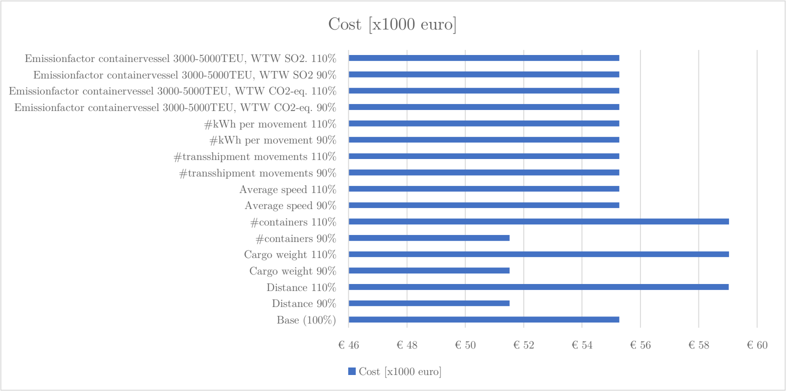

Figure E.2: Sensitivity analysis output on cost

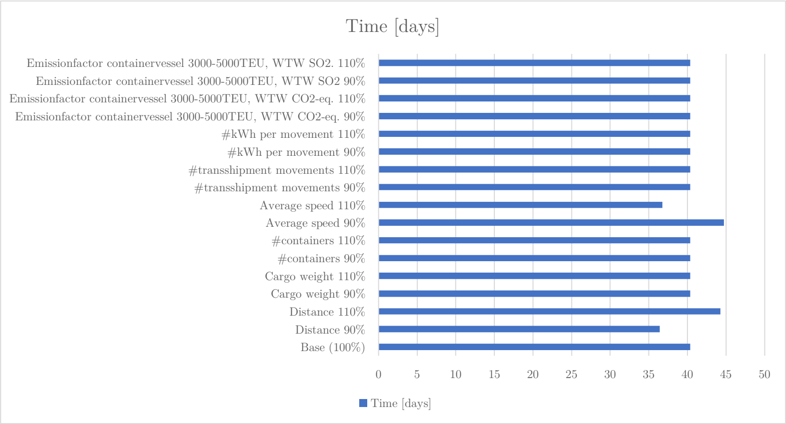

Figure E.3: Sensitivity analysis output on time

Table E.2: Sensitivity analysis table output on transshipment emissions

	Transshipment emissions			
	CO_2-eq [kg]	NO_x [g]	PM_v [g]	SO_2 [g]
Base (100%)	2,864	10,182	547	144
Distance 90%	2,864	10,182	547	144
Distance 110%	2,864	10,182	547	144
Cargo weight 90%	2,864	10,182	547	144
Cargo weight 110%	2,864	10,182	547	144
#containers 90%	2,864	10,182	547	144
#containers 110%	2,864	10,182	547	144
Average speed 90%	2,864	10,182	547	144
Average speed 110%	2,864	10,182	547	144
#transshipment movements 90%	2,578	9,164	492	129
#transshipment movements 110%	3,150	11,200	602	158
#kWh per movement 90%	2,578	9,164	492	129
#kWh per movement 110%	3,150	11,200	602	158
Emissionfactor containervessel 3000-5000TEU, WTW CO_2-eq. 90%	2,864	10,182	547	144
Emissionfactor containervessel 3000-5000TEU, WTW CO_2-eq. 110%	2,864	10,182	547	144
Emissionfactor containervessel 3000-5000TEU, WTW SO_2 90%	2,864	10,182	547	144
Emissionfactor containervessel 3000-5000TEU, WTW SO_2. 110%	2,864	10,182	547	144

Figure E.4: Sensitivity analysis output on transshipment emissions

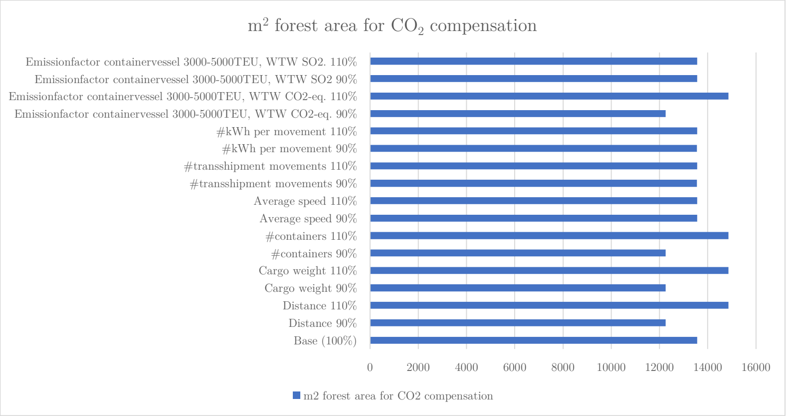

Figure E.5: Sensitivity analysis output on m² of forest area for CO_2 compensation

F VALIDATION AND MODEL-USABILITY MEETING

F.1 MEETING INTRODUCTION

"The emission model is designed to provide insight into the emissions, costs and time for each loyalty programme. As it concerns a scientific research, the idea was to also do a business case study to see how the model works. The specific case has become the programme for retailer x. In the programme for retailer x, there are in fact three flows, because the products come from China, Portugal and France. For this, I created a scenario planning with 6 options for the China flow, 3 for Portugal and 3 for France. I have already heard from the last update that it is not necessary to be as specific, for example, that in the case of the China flow a number of options could be removed if this model were really applied, but we will talk about this in more detail later. The model works in such a way that you get to see the output per scenario and also per combination of the scenarios of the three flows, so that you could view the output of the entire programme. The output consists of the three criteria of the model, namely emissions, costs and time. Per output column there are colours given to visualise what is good (green), less good (yellow) and least good (red), this applies per emission but also for the costs, time and m^2 of forest area for CO_2 compensation.

The emissions are calculated on the basis of the travelled distance, type of vehicle, type of fuel, number of containers, cargo weight and so-called emission factors. The costs are based on a study by Panteia for the national government. The government uses this for all its calculations within the transport domain. However, these are not the transport prices. But the ratios are correct, which I also want to check with you today. The transit times are based on assumptions and today I want to check with you to what extent this corresponds to the truth. I had already heard that for example the train from China to the Netherlands would be 15 days too short. From Caroz I received a dataset to validate the transport times.

In terms of usability, I want to secure all tabs in the future so that only one sheet, the dashboard, is visible. For this, only a few things would need to be entered: the programme data (from the pallet plan), the number of containers per delivery (from the delivery planning) and the information per flow (locations suppliers, locations warehouses client). But I also want to use this meeting to see how you would ideally like the model to look, based on what is already there. Also the question what the dashboard should specifically look like.

The output of the model that we discuss in this validation meeting is the same output used for the scenario analysis. So specifically, the scenarios regarding the inbounds of the loyalty program used for the case study are discussed in this meeting. It is sufficient to only discuss the inbounds as the inbounds are calculated in the same way as the outbounds and returns because the input used in the model is the same. But for the outbounds and returns I do want to make some assumptions, I want to go through these with you and check them."

F.2 MEETING RESPONSE

After the introduction and showing the emission model in Excel, the first reaction was mainly that the dashboard is not clear. After showing all the input that needs to be entered per leg, the reaction was also that they found some pre- and end-haulage legs redundant, for example the legs from Waalwijk to Drunen. But the case-experts thought it would be useful to calculate this and then see the share per leg from the output and develop the final model in such a way that only the main-haulage is considered. To come back to this so-called 'utility model', this idea came about during the validation meeting. The current model was called the 'technical model', which is good for research and the results of which are very useful and helpful to have. But for future use they would prefer a model that is a little more user-friendly and therefore also contains some simplifications compared to the technical model. The biggest simplification is to only calculate the main haulage per scenario (leaving the pre- and end-haulage out of consideration). Another adjustment that was mentioned to make the model more applicable is to visualise the emissions as a whole, for example by means of a kind of sustainability ranking, instead of all individual emissions.

Moving on to the numbers for validation, the case experts noticed that the output regarding times does not quite correspond to the times occuring in reality. They suggest adjusting the assumptions on the input used to calculate the times so that it is more in line with reality. At the moment it seems to them that the train times are too short and the maritime times are too long, the times of the other modalities they find realistic. The input on which these times are calculated for these two modalities (train and maritime) should be adjusted and re-validated with the case experts.

The case-experts find it a correct way to calculate the costs with the data of Panteia. They understand that it does not concern transport prices but costs and are aware of the difference. However, they find the supply and demand principle behind the transport prices interesting and therefore propose to see the output in scenarios in the utility-model, i.e. a scenario with a lot of supply and little demand and vice versa. According to the case-experts, the cost ratios compared for the various modes of transport do seem proportionate. A validation with data from Caroz, the carrier that books the transports for L and has provided a complete dataset with cost and time data, seems useful to the case-experts. This validation step still needs to take place.

What struck the case experts is that all emissions at C5 and C6 are so high, except for PMsl. They wondered why and are curious to know the reason behind this. Furthermore, they find showing the output on m^2 of forest area for CO_2 compensation a the good way for the imagination of what such a number of tonnes of emissions mean in reality. The case experts stated it makes the numbers more tangible to them. They find the difference between maritime, C1 and C2, and rail, C3 and C4, remarkably small and are happy that their base-case scenario is not so bad after all.

Regarding the assumptions for outbounds, returns and transshipments, the case-experts agreed that the returns are normally calculated at 10%. So it can be assumed that 10% of all goods delivered to the customer are returned. The assumption that this is equally distributed from the four locations of the distribution centre of the client is approved by the case-experts. For the outbound flows, a similar assumption is approved by the case-experts. Namely to distribute the inbound flows equally among the four distribution centres of the customer, so that each outbound flow is 25% of the total inbound flows.

Regarding the overall value of the model, the case experts were pleased to get insights in this way of especially emissions. The fact that the outcomes function as one overview of all options per decision, would help them in making well-thought decisions. Once the model is made mode user-friendly the case-experts want to use the model in their business processes.

G CARRIER MEETING

G.1 MEETING INTRODUCTION

As part of my master thesis project, I am developing an emission model that provides insight into the emissions, costs and time of a certain transport, with a certain origin, destination and some other input. I am doing the case study for L in order to test the model in practice and to ultimately investigate what impact scdc decisions, such as mode selection, fuel type selection, routing decisions, have on emissions, costs and time.

Since you are the platform that tenders and books the transports for L, I have a number of questions and topics that I would like to raise to investigate what is possible in the market. This concerns questions about your way of doing business, for example, what criteria you impose on transporters or plan to impose in the future because I have heard that you are also planning to take more account of sustainability. In addition, therefore, I would also like to ask whether you currently impose certain requirements on carriers, for example in terms of fuel type and, if so, whether it is possible that such requirements will be imposed. Furthermore, with regard to the type of vehicle, the question is, for example, when maritime transport is booked, is there a possibility to choose a certain vessel (large vs. small container vessel)? Finally, I have a request regarding data on costs and lead times of transports. If you have a dataset with booked transports and their costs and lead times, so I can validate my model with realistic data.

G.2 MEETING RESPONSE

Firstly, the emission model was received as particularly interesting. In terms of the answers that were sought, the following information passed.

Concerning the inspection of fuel, or requirements for fuel use on the part of carriers, this was considered to be difficult. They can request this information, so in that sense something may be possible, but it is unusual to do so when a transport is about to be booked. But getting insight into the type of propulsion, i.e. the different types of engines, is something that can be achieved in reality. If they deal with a client who wants, for example, only trucks with a certain type of engine to be used, the pool of carriers that they put out a tender for a particular transport is in fact reduced. So it will probably come down to a limitation if you use this requirement, which may also have an effect on the costs. As far as the type of ship is concerned, there are enormous parties active within the maritime shipping industry and it is impossible to exert any influence on them. However, the sector itself is improving through guidelines that are set for vessels or for sailing speeds in certain areas.

As for the data to be used for validation, they can provide some old data from which averages can be drawn. In this data set, the costs and estimated time of departure and arrival will be given, so you can calculate the lead time yourself.

H DECISION ANALYSIS OUTPUT

Table H.1: Impact of choosing rail or air versus maritime transport for the CHN flow of goods on transport emissions, cost and time

	Transport emissions (WTW)							
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	Cost	Time	m^2 forest area for CO_2 compensation
Rail vs. Maritime (=100%)	83%	25%	10%	9%	16330%	985%	39%	84%
Air vs. Maritime (=100%)	926%	485%	176%	185%	852%	3541%	10%	921%

Table H.2: Impact of choosing rail or short-sea versus road transport for the FR flow of goods on transport emissions, cost and time

	Transport emissions (WTW)							
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	Cost	Time	m^2 forest area for CO_2 compensation
Rail vs. Road (=100%)	92%	88%	89%	88%	141%	94%	300%	95%
Short-sea vs. Road (=100%)	84%	125%	247%	227%	56%	57%	303%	88%

Table H.3: Impact of choosing rail or short-sea versus road transport for the PRT flow of goods on transport emissions, cost and time

	Transport emissions (WTW)							
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	Cost	Time	m^2 forest area for CO_2 compensation
Rail vs. Road (=100%)	54%	46%	48%	45%	153%	58%	326%	55%
Short-sea vs. Road (=100%)	55%	118%	303%	273%	13%	14%	409%	56%

Table H.4: Output road transport with different fuel/engine types for the FR flow of goods in transport emissions, cost and time

	Transport emissions (WTW)							
	CO_2-eq [ton]	SO_2 [kg]	PM_v [kg]	NO_x [kg]	PM_{sl} [kg]	Cost [x1000 euro]	Time [days]	m^2 forest area for CO_2 compensation
Diesel Euro VI (=100%)	168	172	11	485	8	€ 159	1	4191
Diesel Euro V	159	172	15	563	8	€ 159	1	3986
Diesel Plug-in hybride (Euro VI)	163	172	10	500	8	€ 155	1	4068
GTL Euro V	174	172	12	495	8	€ 161	1	4354
Biodiesel Euro VI (97% FAME, 3% HVO)	27	172	22	539	8	€ 172	1	757
HVO Euro VI	18	172	22	539	8	€ 163	1	553
LNG (Euro VI)	152	172	5	281	8	€ 148	1	3823
BioLNG (Euro VI)	60	172	6	247	8	€ 144	1	1575
Electric (average mix)	117	172	5	141	8	€ 153	1	2964
Hydrogen	134	172	33	286	8	€ 176	1	3373

Table H.5: Impact of choosing different fuel/engine types with road transport for the FR flow of goods on transport emissions, cost and time

	Transport emissions (WTW)							
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	Cost	Time	m^2 forest area for CO_2 compensation
Diesel Euro V	95%	100%	133%	116%	100%	100%	100%	95%
Diesel Plug-in hybride (Euro VI)	97%	100%	91%	103%	100%	97%	100%	97%
GTL Euro V	104%	100%	104%	102%	100%	101%	100%	104%
Biodiesel Euro VI (97% FAME, 3% HVO)	16%	100%	202%	111%	100%	108%	100%	18%
HVO Euro VI	11%	100%	202%	111%	100%	102%	100%	13%
LNG (Euro VI)	91%	100%	49%	58%	100%	93%	100%	91%
BioLNG (Euro VI)	36%	100%	50%	51%	100%	90%	100%	38%
Electric (average mix)	70%	100%	48%	29%	100%	96%	100%	71%
Hydrogen	80%	100%	294%	59%	100%	110%	100%	80%

Table H.6: Output maritime transport with different fuel/engine types for the CHN flow of goods in transport emissions, cost and time

	Transport emissions (WTW)						
	CO_2-eq [ton]	SO_2 [kg]	PM_v [kg]	NO_x [kg]	Cost [x1000 euro]	Time [days]	m^2 forest area for CO_2 compensation
HFO/MDO (0,5% S) Tier II (=DEFAULT)	553	1377	241	10452	€ 55	40	13557
HFO/MDO (0,5% S) Tier III	553	1377	241	3069	€ 55	40	13557
MDO Tier II (0,1% S)	569	630	191	10452	€ 56	40	13948
HFO + Scrubber Tier II (0,5% S)	537	1377	406	10244	€ 54	40	13166
LNG (SI, lean burn)	526	22	30	3901	€ 53	40	12906
LNG (dual fuel manifold injection)	526	22	159	3901	€ 53	40	12906
LNG (direct diesel injection)	446	22	159	3901	€ 52	40	10951
BioLNG (SI, lean burn)	168	46	30	3797	€ 50	40	4174

Table H.7: Impact of choosing different fuel/engine types with maritime transport for the CHN flow of goods on transport emissions, cost and time

	Transport emissions (WTW)						
	CO_2-eq	SO_2	PM_v	NO_x	Cost	Time	m^2 forest area for CO_2 compensation
HFO/MDO (0,5% S) Tier III	100%	100%	100%	29%	100%	100%	100%
MDO Tier II (0,1% S)	103%	46%	79%	100%	102%	100%	103%
HFO + Scrubber Tier II (0,5% S)	97%	100%	169%	98%	98%	100%	97%
LNG (SI, lean burn)	95%	2%	12%	37%	96%	100%	95%
LNG (dual fuel manifold injection)	95%	2%	66%	37%	96%	100%	95%
LNG (direct diesel injection)	81%	2%	66%	37%	94%	100%	81%
BioLNG (SI, lean burn)	30%	3%	12%	36%	91%	100%	31%

Table H.8: Output air transport with different fuel/engine types for the CHN flow of goods in transport emissions, cost and time

	Transport emissions (WTW)							
	CO_2-eq [ton]	SO_2 [kg]	PM_v [kg]	NO_x [kg]	PM_{sl} [kg]	Cost [x1000 euro]	Time [days]	m^2 forest area for CO_2 compensation
Kerosine	5074	6655	424	19287	5	€ 1,768	4	123843
Bio-kerosine	600	1435	618	19670	5	€ 2,874	4	14715

Table H.9: Impact of choosing different fuel/engine types with air transport for the CHN flow of goods on transport emissions, cost and time

	Transport emissions (WTW)							
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	Cost	Time	m^2 forest area for CO_2 compensation
Bio-kerosine	12%	22%	146%	102%	100%	163%	100%	12%

Table H.10: Output road transport with different vehicle types for the FR flow of goods in transport emissions

	Transport emissions (WTW)							
	CO_2-eq [ton]	SO_2 [kg]	PM_v [kg]	NO_x [kg]	PM_{sl} [kg]	Cost [x1000 euro]	Time [days]	m^2 forest area for CO_2 compensation
Tractor+trailer, average	167.580	171.877	11.089	485.138	8.317	159.402	1.000	4190.521
LZV, average	150.947	155.244	8.317	415.832	8.317	127.522	1.000	3784.831

Table H.11: Impact of choosing different vehicle types with road transport for the FR flow of goods on transport emissions, cost and time

	Transport emissions (WTW)							
	CO_2-eq	SO_2	PM_v	NO_x	PM_{sl}	Cost	Time	m^2 forest area for CO_2 compensation
LZV, average	90%	90%	75%	86%	100%	80%	100%	90%

Table H.12: Output inland waterway transport with different vehicle types for end-haulage of CHN flow of goods in transport emissions

	Transport emissions (WTW)						
	CO_2-eq [kg]	SO_2 [g]	PM_v [g]	NO_x [g]	Cost [euro]	Time [days]	m^2 forest area for CO_2 compensation
Neo Kemp, CEMT III	2557.885	2619.383	1594.407	31888.145	1480.521	1.000	62.387
Rijn-Herne Schip, CEMT IV	3345.977	3416.587	1480.521	37582.456	3758.246	1.000	81.609
Groot Rijnschip, CEMT Va	2256.086	2277.725	1138.862	26193.833	2619.383	1.000	55.026

Table H.13: Impact of choosing different vehicle types with inland waterway transport for the end-haulage of the CHN flow of goods on transport emissions, cost and time

	Transport emissions (WTW)						
	CO_2-eq	SO_2	PM_v	NO_x	Cost	Time	m^2 forest area for CO_2 compensation
Rijn-Herne Schip, CEMT IV	131%	130%	93%	118%	254%	100%	131%
Groot Rijnschip, CEMT Va	88%	87%	71%	82%	177%	100%	88%