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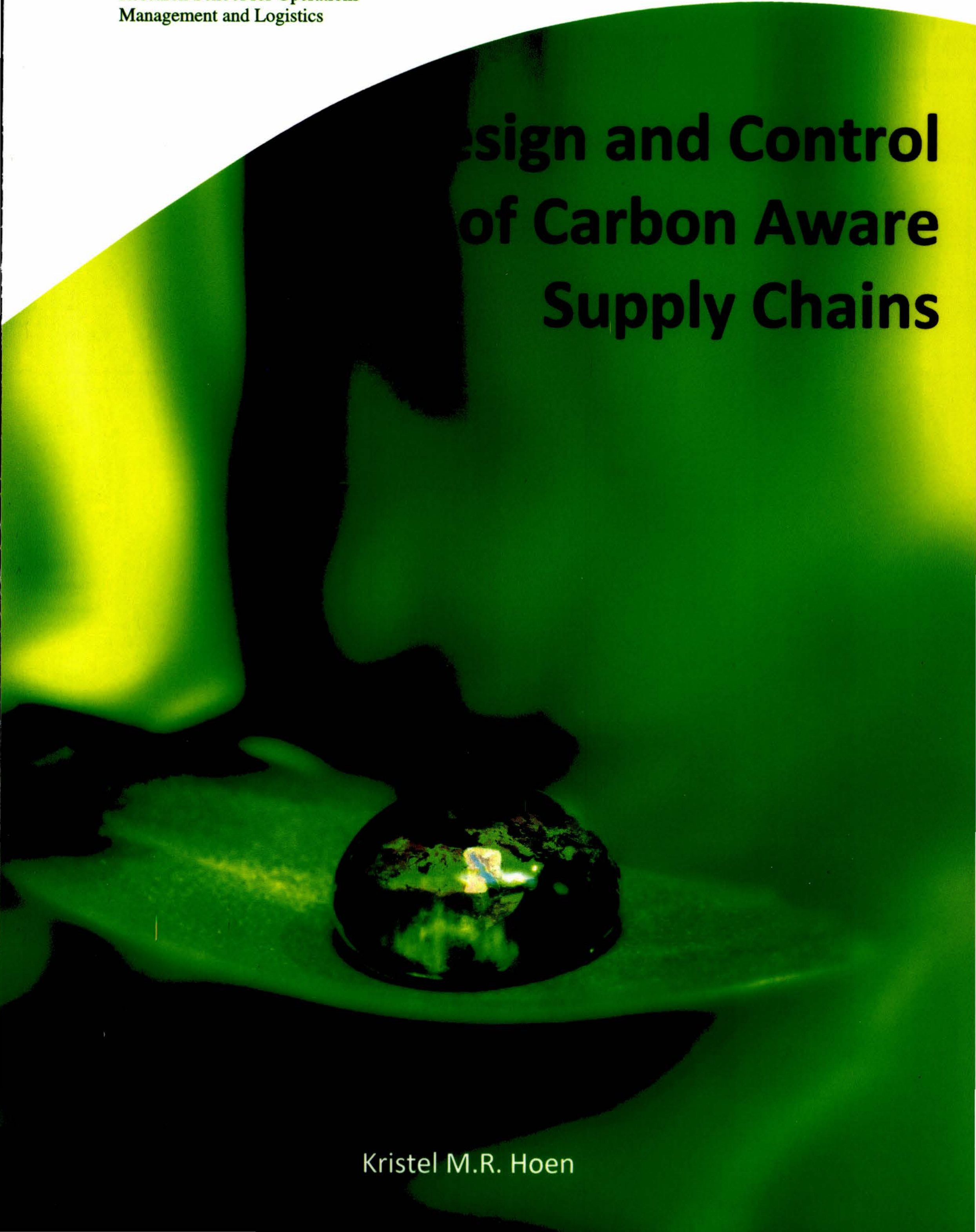

esign and Control of Carbon Aware Supply Chains

Kristel M.R. Hoen

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Design and Control of Carbon Aware Supply Chains

PROEFSCHRIFT

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To me, being a PhD student for the last four years has been like climbing a mountain, say Everest: The start is slow, you are trying to find your way up the slopes and the summit seems to be infinitely far away. After a while you get the hang of it, passing several base camps on the way. But sometimes it can get foggy out of nowhere and you are feeling completely lost but after some time the fog clears and the summit is visible again. Then it gets tricky and you enter the 'death zone': the summit seems within reach but the last part is the hardest. And now ... I have conquered these obstacles and reached the summit of my very own Everest. This would not have been possible without the help of sherpas and fellow mountaineers, who I want to acknowledge here.

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Eindhoven
September 2012

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1

INTRODUCTION

In recent years awareness of the impact of human activity on the environment has risen and will become more important in the future as natural resources are becoming more scarce. In production processes input materials are converted into final products that are sold to customers. Besides raw materials and components, labor, knowledge and capital, natural resources, such as clean air and water are required. The costs of these resources are usually not considered, i.e. the societal cost is external to the company. Concerns related to the impact of greenhouse gas concentrations in the atmosphere resulting in global warming have been growing. It is therefore important that the (societal) cost of emissions is internalized in companies' decision making to reduce global emissions. In this dissertation, we reexamine several decisions in the field of operations management, related to transportation and production, in the light of carbon emission concerns.

Over the last few decades global warming has received increasing attention. In 1995 the Intergovernmental Panel on Climate Change (IPCC) published an assessment that the increase in greenhouse gas concentrations tends to warm the surface of the earth and leads to other climate changes (IPCC, 1995). Due to human activity, causing the so-called *anthropogenic* emissions, concentrations of greenhouse gases in the atmosphere have been increasing steadily and as a result caused global warming. The term "Greenhouse gases" refers to a collection of gases among which are carbon dioxide (or carbon) (CO_2), and methane. A greenhouse gas absorbs and emits radiation from the earth's surface, the atmosphere, and clouds (IPCC, 2007). In Figure 1.1 an assessment of global emissions by the IPCC in 2004 is presented. The term CO_2-eq. refers to carbon dioxide equivalent units, a measure that allows for aggregating all greenhouse gas emissions into one measure. Observe that emissions had increased by 24% in 2004 compared to 1990 levels and had almost doubled compared to 1970 levels, the majority of which is attributable to carbon dioxide. In this dissertation the focus is solely on carbon dioxide because it is an important greenhouse gas and carbon emission regulations impact a wider array of companies than energy companies, as is explained in Section 1.1.

Companies generate carbon emissions as a by-product of several activities, including production processes and indirectly from transportation of goods and from energy generation. In the Greenhouse Gas Protocol (GHG Protocol) three scopes of emissions of a company are distinguished: Scope 1 emissions are direct emissions caused by company-owned assets, Scope 2 emissions are indirect and due to electricity generation, and

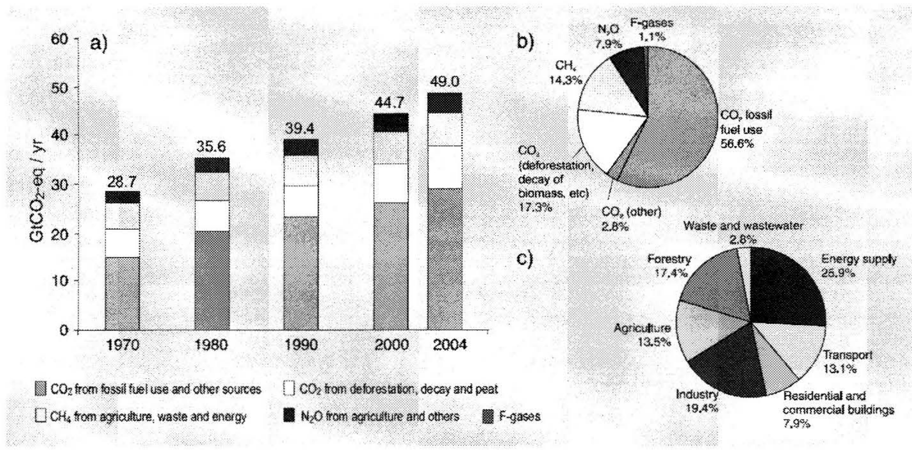

FIGURE 1.1: Global GHG emissions figures for the year 2004 (IPCC, 2007)

Scope 3 encompasses all other sources of emissions (Greenhouse Gas Protocol, 2011). The scopes are ordered in decreasing amount of control of the company. Figure 1.2 is a graphical representation of the three scopes of company emissions. Scope 1 emissions are generated on site during production and by vehicles that are owned by the company. Scope 2 emissions are generated while generating electricity. Using the electricity generally does not result in carbon emissions at the company and are referred to as indirect emissions. A company has only no or limited control over the technology used to generate electricity. All emissions not falling under Scope 1 or 2 fall under Scope 3, which includes emissions from transport if it is executed by a third party and also employee travel.

Figure 1.1 shows that the energy sector is by far the largest contributor of carbon emissions, however transport also accounts for a significant part of emissions, around 13%. In Figure 1.3 an overview of the EU emissions by sector for 2007 is given. Again, the energy sector is the main contributor to carbon emissions, however the share of the transport sector is also considerable, around 25%. In this dissertation the focus is on emissions from logistics operations, transportation, and in Chapter 5 also production, energy producers are therefore outside the scope of this dissertation.

Even though production companies cannot fully influence transport emissions if transport is outsourced, given the scale of emissions, the transport sector cannot be ignored when reducing emissions. It is important to reduce the emissions of the transport sector for two reasons. First, it is one of the largest contributors to carbon emissions. In Europe, in 2006, around 23% of all carbon dioxide emissions were due to the transport sector, and between 30 and 40% of these emissions are due to freight transport (European Commision, 2007). Within the transport sector, road transport is responsible for the largest share, around two thirds. Second, it is expected that emissions from transport continue to increase in the future. Figure 1.4 presents the findings of a study of the European Commission concerning trends in carbon dioxide emissions in the EU for 2030 compared to 1990 levels. It is estimated that the energy demand for freight transport in 2030 will be 60% higher than its 1990 level (currently it is 36% higher), despite the increasing

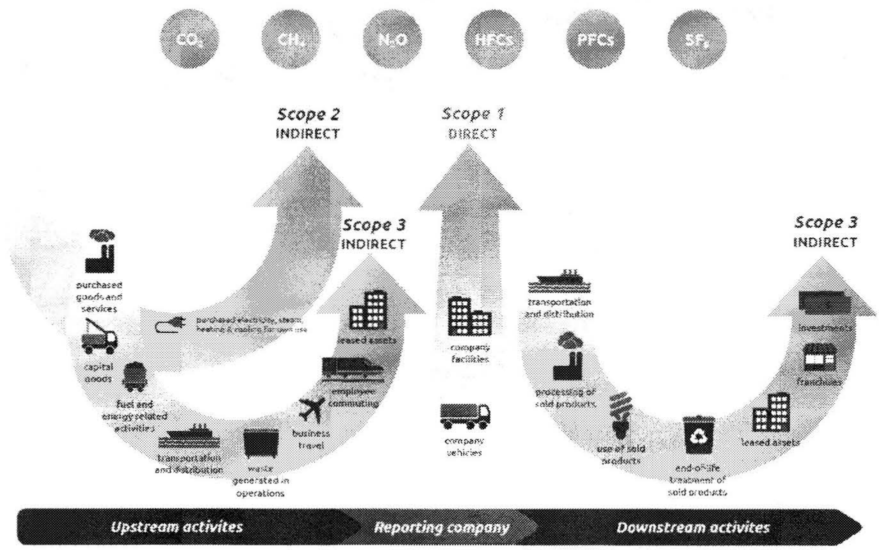

FIGURE 1.2: Graphical representation of the three company emission scopes (World Resources Institute, 2011)

fuel efficiency of vehicles. In a study commissioned by the European Commission (EU Transport GHG, 2011) it is estimated that innovation in vehicles and alternative fuels are not sufficient to meet the emission target levels for 2050 and additional economic and policy instruments are required. It is therefore important to investigate opportunities that reduce demand for high-energy transport modes.

In transportation, a faster transport mode is generally more expensive to use and results in more emissions but requires less inventory and vice versa for a slower mode. When deciding the production location the trade-off to consider is that when production is shifted to another region of the world production costs are lower but transport costs are higher.

The focus of the research presented in this dissertation is on a production company that is reconsidering decisions related to inventory, transportation, and production in the presence of emission considerations, either regulations or self-imposed targets. We assume that transportation is executed by third party logistics service providers, which is a setting commonly used by companies. The study of transport emissions from the perspective of transportation companies is outside the scope of this dissertation but in Chapter 6 we shortly present directions for this type of research. The insights in the trade-offs investigated in this dissertation can however also be applied to transportation companies.

In this dissertation we aim to provide answers to the following questions concerning the impact of carbon emissions on supply chains.

For what type of products should be switched to low-emission transport modes under emission regulation?

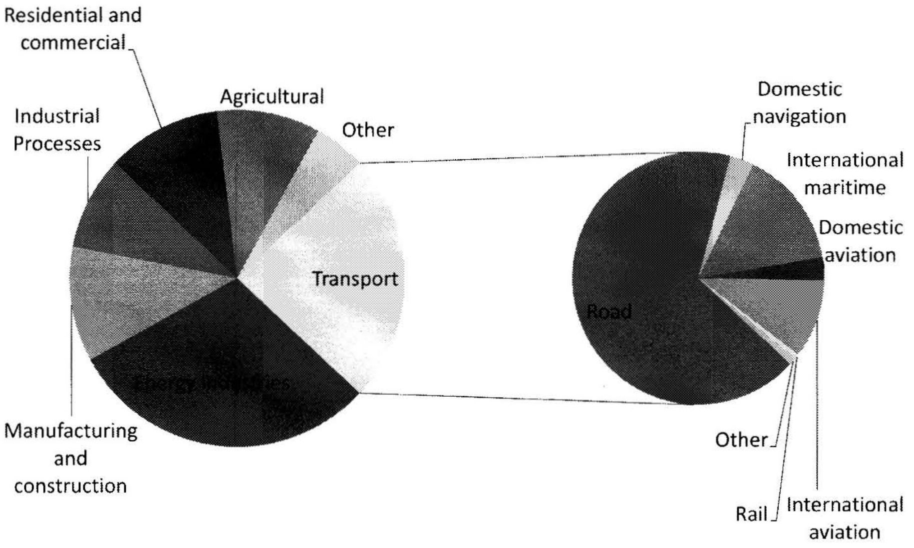

FIGURE 1.3: Overview of EU emissions by sector, adapted from European Commission (2011b)

To what low-emission modes should transport be moved?

What can be gained when considering the emissions for a group of products simultaneously?

When is it beneficial to use an additional transport mode to reduce emissions?

How does uncertainty regarding emission regulation impact investment decisions of companies?

When may emission regulation actually lead to increased emissions?

How do policy measures impact the investment decision?

In the remainder of this chapter, we first present background information on how carbon emissions impact supply chains. First, we discuss self-imposed emission targets and relevant emission regulations to date, both for production and transport emissions, in Section 1.1. Then we describe in Section 1.2 some general issues related to emissions from transport and discuss how transport emissions in supply chains can be reduced. In Section 1.3 we describe briefly how emissions from production can be reduced and an undesirable side-effect of emission regulations: carbon leakage. An overview of available transport emission measurement methodologies is presented in Section 1.4.

Then, we describe the research which is presented in this dissertation. An overview of the research questions investigated in this dissertation is presented in Section 1.5. The contributions of this dissertation to several areas of the literature are presented in Section 1.6. In Section 1.7 we describe recent trends in the literature and how it can develop in the future. Lastly, the outline for the remainder of the dissertation is presented in Section 1.8.

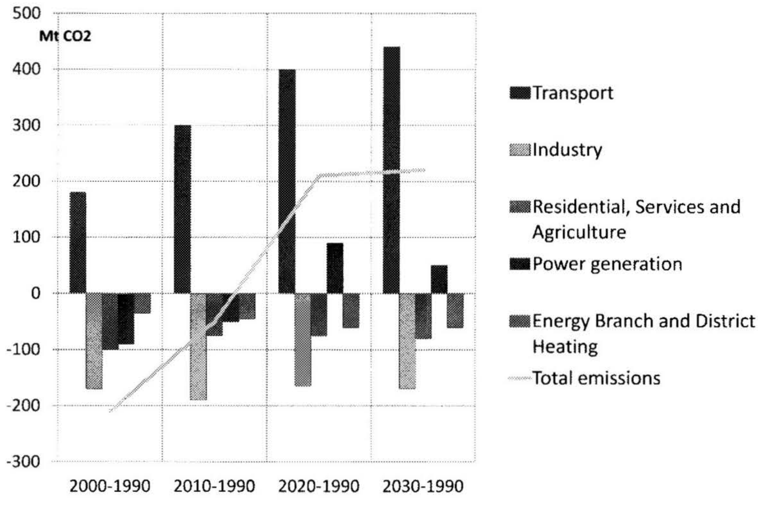

FIGURE 1.4: Carbon emission trends in the EU for several sectors, relative to 1990 levels, (European Commision, 2007)

1.1 Carbon emissions and (self-imposed) regulation

In general, companies reduce their carbon emissions as a result of pressure from one (or more) of three sources: customers, environmental groups, and regulation. As a response to pressure from customers and environmental groups companies may choose to voluntarily restrict their emissions. Usually companies who voluntarily reduce their emissions also want to inform other parties about this: one way to this is to participate in the Carbon Disclosure Project (CDP). The Carbon Disclosure Project allows companies to voluntarily report their emissions, which is publicly available data. The Carbon Disclosure Project reports that 294 of the Global 500 companies have voluntary emission reduction targets (Carbon Disclosure Project, 2011).

Examples of voluntary company emission reduction targets include the following: Alcoa has a target to reduce emissions by 30% in 2030 over 2005 levels (Alcoa, 2010). Boeing aims at 25% emission reduction in 2012 compared to 2007 levels (Boeing, 2011). Cargill has set a goal to improve greenhouse gas intensity by 5% in 2015 from the year 2010 baseline (Cargill, 2012). Dell has set a 15% emission reduction target per dollar of revenue by in 2012 from 2007 (Dell, 2011). Heidelberg cement aims by 2015 to attain a CO_2 reduction of 23% compared to the 1990 level (Heidelberg Cement, 2012). Unilever aims at halving the greenhouse gas impact of products across the life cycle by 2020 against a 2008 baseline (Unilever, 2012). Walmart aims at reducing greenhouse gas emissions from the 2005 base by 20% by 2012 (Walmart, 2011).

Companies can translate these emission reduction targets to department targets by creating a plan with actions to reduce emissions and allocate emission reductions to different departments. We expect that specific emission targets for transportation are set for companies for which transport represents a larger share of the total emissions. Examples of these industries are retail companies and electronics manufacturers for which Scope 1 and Scope 2 emissions account for less than 20% of the total emissions (Huang *et al.*, 2009). Companies can get more insight into the emission reduction potential of transportation by applying our models. Companies may expect that reducing their emissions results in additional benefits, such as improved market share, company image, and value. We have observed that large multi-national companies voluntarily reduce carbon emissions in research projects on mapping and reducing emissions from transport in supply chains, such as Van den Akker (2009), te Loo (2009), Schers (2009), Boere (2010), and Koç (2010).

We next present an overview of carbon emission regulations in place, but first we briefly present the economics behind emission regulations. Before implementation of emission regulations, companies have limited financial incentives to reduce usage of natural resources, e.g. clean air or water, or generation of emissions if it results in a cost increase. Since no cost is charged for this resource, it is external to the company's cost calculation. By implementing emission regulations, the use of this resource is internalized by imposing a cost.

If an emission tax is set, equivalent to e.g. fuel taxes, then in each company emissions will be reduced up to the point at which further emission reductions are more expensive than paying the tax. In reality, companies may not reduce emissions to this point, especially in the case of no emission tax, i.e. companies not always employ emission reduction initiatives that also reduce costs. An explanation for this is that companies may not be aware of reduction opportunities due to lack of information. A map of emissions is required before reduction opportunities can be explored and this is not always present. Moreover, not all reduction opportunities are known to companies. Additionally, companies may not invest in emission reductions because of financial reasons. Emission regulation is subject to uncertainty and the lack of a Kyoto protocol after 2012 may suggest to companies that it will be less important in the future. Or companies may have better investment alternatives with higher returns.

The marginal reduction cost curve is different for all companies and as a result the emission reductions that result from an emission tax differ from company to company. Moreover, the regulator needs to set a correct value for the tax such that desired emission reductions are achieved. A task that is not straightforward at all.

Alternatively, an emissions trading scheme (ETS), also known as a cap-and-trade system, can be implemented to reduce emissions. The regulator sets the cap of emissions for a given year and issues allowances that match the cap. An allowance entails the right to emit one tonne of carbon emissions and allowances can be traded between entities. Initially, companies obtain allowances, either for free or by buying them at an auction. At the end of the period, each company should have sufficient allowances to cover its emissions for that period. Should the company have insufficient allowances, then it can buy allowances from other companies that have excess allowances. Companies again evaluate the cost of reducing emissions and compare this to the price of an allowance in the trading market. By allowing companies to trade allowances emission reductions at the aggregate level can be achieved at a lower overall cost. The mechanism behind it is that companies for which emission reductions are relatively cheap, e.g. due to readily available new technology, will do this and sell the excess allowances. Companies for which emission reductions are more expensive will opt to buy allowances and reduce emissions by a smaller amount.

Another possible type of emission regulation is to impose a cap on emissions without the opportunity for companies to trade allowances. To date, no cap or hard constraint on emissions has been implemented.

The 1995 assessment of the IPCC was used to formulate an important international commitment to reduce greenhouse gas emissions in 1997: the Kyoto protocol. This protocol specified emission reductions targets for individual countries and on average emissions would reduce by 5.2% in 2012 compared to 1990 levels. As a means to ensure that the carbon targets are met in Europe, the European Union has implemented an emissions trading scheme (EU ETS) in 2005 for the energy-intensive industries which currently account for almost 50% of Europe's carbon emissions (European Commission, 2008). Currently, the EU ETS covers CO_2 emissions from over 11,000 installations in 30 countries. The types of installations covered by the EU ETS include "power stations, combustion plants, oil refineries and iron and steel works, as well as factories making cement, glass, lime, bricks, ceramics, pulp, paper and board" (European Commission, 2010).

In Phase I (2005-2007) and II (2008-2012) of the EU ETS, companies obtained the majority of the required emission allowances for free (grandfathering) (European Commission, 2010). In Phase III (2013-2020) an increasing share of allowances is sold at auctions and emission caps will continue to decrease, which is expected to cause the price of carbon emission allowances in the market to increase. Other countries and regions that have adopted (or will adopt) an emissions trading scheme include ten states in North Eastern USA, Tokyo, Australia and New Zealand.

From the start of 2012, aviation is included in the EU ETS as the first transport sector. A cap is set on CO_2 emissions from all international flights, from or to anywhere in the world, that arrive at or depart from an EU airport (European Commission, 2012). A separate emissions trading scheme is operable for the emissions from aviation and around 82% of allowances are currently obtained for free. A lawsuit filed by several American airlines was overruled when the European court ruled in favor of EU legislation and therefore the regulation also impacts non-EU based airlines (European Commission, 2012).

In this dissertation we employ two ways to explicitly incorporate carbon emissions: by imposing a carbon cost, applied in Chapters 2 and 5, and by incorporating a constraint for carbon emissions, Chapters 3 and 4. The emission constraint is applied to a multi-product situation and *Lagrangian relaxation* is used to obtain solutions for these problems. This technique applies a penalty cost for violating the constraint, which implies that at an item level the penalty acts as a carbon cost. In the analysis and numerical study, however, we explicitly measure the impact on all products. As is the case for an ETS, setting a constraint for a group of products allows for taking advantage of the portfolio effect, i.e. reduce emissions where it is cheapest overall.

1.2 Issues concerning transport emissions

In this section, we describe how we model transport and transport emissions in this dissertation, including our assumptions. In general, the following transport modalities can be distinguished: road, rail, air, water, and pipeline. Within water transport we distinguish inland waterway, or barge (using rivers and canals), short-sea shipping (coastal shipping), and deep-see shipping (ocean shipping). *Intermodal transport* refers to the transportation of a good for which at least two transport modes are used, which typically refers to the usage of road transport to ship goods to and from a rail terminal, harbor, or airport, if rail, water or air transport is used. Intermodal transport generally results in lower emissions but additional costs and transport time are associated with changing transport modes.

In all chapters of this dissertation we assume that transport activities are outsourced and executed by a logistics service provider (LSP), which is in line with the real-life situation we have observed at many companies. As mentioned at the beginning of this chapter, this implies that the transport emissions belong to Scope 3 of the GHG protocol, i.e. companies have limited control over the emissions. However, we believe that it is important to reduce these emissions and have observed that companies are becoming more and more aware of Scope 3 emissions and search for ways to reduce them.

When considering emissions from outsourced transport a complicating factor is that the 'ownership' of the emissions is less clear: the shipper, or the logistics service provider. We assume that the shipper is solely responsible for the emissions resulting from transporting the items. This assumption is justified because the shipper creates the demand for transport. Moreover, it is in the best interest of the logistics service provider to make the execution of the transport as efficient as possible, because emissions are aligned with fuel costs. Investments in more fuel-efficient vehicles, such as hybrid or electric trucks, require additional incentives for transport companies. These incentives can be additional regulation targeted at logistics service providers. Moreover, customers, especially large customers, provide the incentive by requiring or selecting logistics service providers that use fuel-efficient vehicles.

For road transport some companies may prefer to send full truckloads, but many companies ship smaller quantities and for non-road transport loads from many customers need to be combined to obtain a moderately high utilization rate. Unless full truckloads are shipped by road transport, a larger shipment quantity of a single customer does not necessarily result in a higher utilization of a vehicle (and lower emissions per product shipped). Therefore, we consider only an incremental cost and unit emissions per unit transported.

The lead time associated with a transport mode is an important factor when deciding which transport mode to use as it impacts pipeline inventory and inventory in stock points. In this dissertation we assume that transport times are deterministic and constant throughout time. This assumption is in line with the tactical decisions we consider, e.g. which mode to use for transportation for the next year. For operational decisions the transportation time is impacted by traffic conditions among others and is dynamic in general. In Chapter 6 we briefly discuss the impact of dynamic transport times.

Let us define the *transport carbon efficiency* of a shipment as the amount of carbon emissions generated while transport 1 $tonne$ of goods over one km, i.e. per $tonne\ km$. We next examine the factors determining the carbon efficiency to determine what actions production companies can take to reduce their emissions from transport.

In a study by McKinnon & Piecyk (2010) the most important factors that determine the carbon emissions from transport operations are presented. Seven factors are distinguished: modal split, average handling factor, average length of the haul, average payload on laden trips, the proportion of empty kilometers, fuel efficiency and carbon intensity of the energy source. Figure 1.5 presents the framework of the factors and their determinants. Observe that the figure is specific for road transport but can be adapted to accommodate other transport modes.

The modal split factor refers to which transport mode and vehicle type are used for what proportion of the trip, which determines the fixed and variable emission component per tonne km. The emission factors associated with a specific vehicle or vessel type might be subject to emission regulations that specify the maximum allowed emission quantity per unit of fuel burnt. For example the EURO standard for cars and trucks limits NO_x emissions in the EU. In the future these regulations may extend to include carbon emissions (EU Transport GHG, 2011).

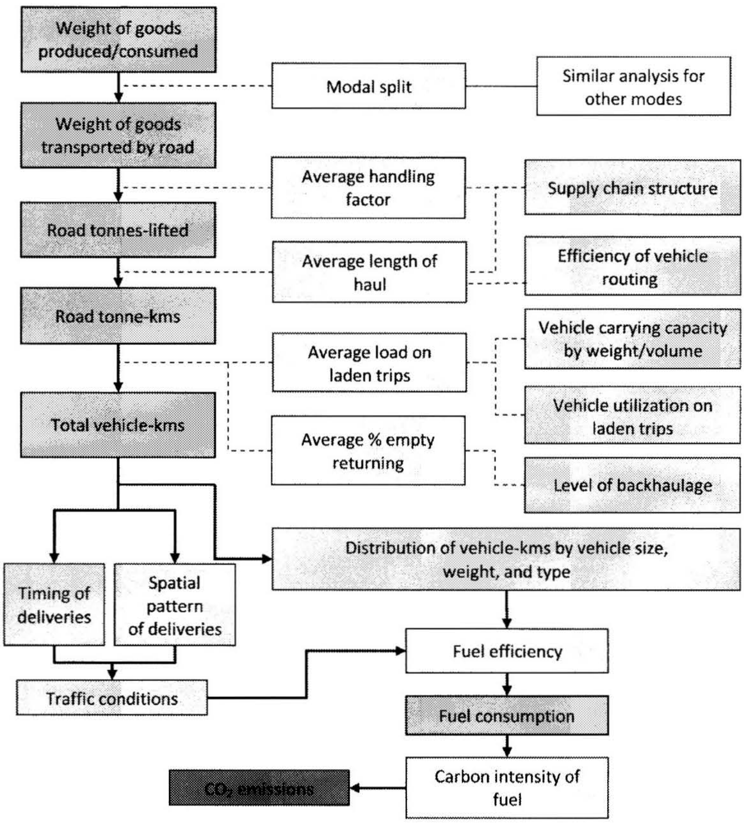

FIGURE 1.5: Framework of transport carbon efficiency, adapted from McKinnon & Piecyk (2010)

The average handling factor and length of the haul refer to the number of transportation links in the supply chain and the distance, a function of the modality type. The transportation carbon efficiency of a given vehicle or vessel is mainly determined by two factors the average payload and the empty kilometers. The payload refers to the amount of cargo shipped in a vehicle or vessel. A related measure is the load factor which measures the weight of the cargo proportional to the maximum load. Figure 1.6 displays the emissions per *tonne km* of a truck as a function of the payload. It is easily observed that the heavier the truck, the lower the emissions per tonne of cargo, e.g. the unit emissions for a payload of 28 *tonne* are 50% lower than for 10 *tonne*.

Empty kilometers are defined as the distance a vehicle has to travel without cargo as part of transporting a certain load, i.e. while traveling to pick up goods at location *A* and after delivering goods at location *B*. Preferably this refers to transport to and from a hub closely located to *A* and *B* but in the worst case it can mean driving back from location *B* to *A* without cargo.

The fuel efficiency of a trip is influenced by vehicle and load characteristics defined before and by traffic conditions, such as congestion and driving behavior. The fuel efficiency combined with the carbon intensity of fuel then determines the total emissions generated during a trip.

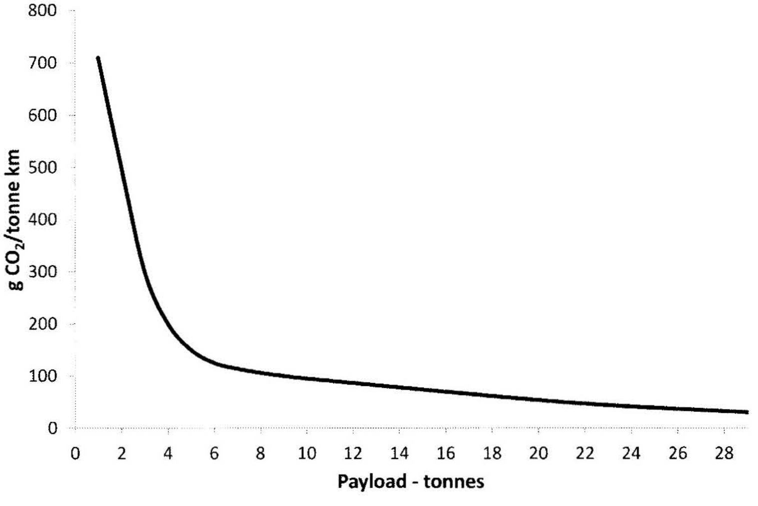

FIGURE 1.6: Emissions per *tonne km* as a function of payload (McKinnon & Piecyk, 2010)

From these factors we derive reduction opportunities for companies to influence the factors impacting carbon emissions from transport. First of all, companies may decide on the transport modality. Companies may indicate specifically what transport mode to use for a certain transportation lane, e.g. road, air or intermodal transport. Or, companies can specify a maximum allowed lead time which typically determines the possible transport modes. This corresponds with the first parameter of the transportation framework.

The problem of deciding which transport mode to use to ship products is an important determinant of transport emissions that needs to be considered in the light of reducing carbon emissions. In Chapters 2, 3, and 4 we consider the situation that a company switches from high-carbon transport modes such as air or road, to low-carbon transport modes such as rail and water, to achieve emission reductions. A mode that generates fewer emissions typically results in lower transport costs but also in higher inventory levels due to longer transportation times. Multiple transport options of the same category, e.g. hybrid and regular trucks, can be compared in addition to modes of different categories.

The company determines indirectly which transport mode to use for transport by specifying a maximum allowed transport time. We have chosen this particular decision because it does not require a change to the supply chain design, which companies are in general more reluctant to do. Moreover, it is a decision that requires little investment and can be implemented on the relative short term. The potential gains in emission reductions are very large for modal shifts, e.g. the emissions (in kg CO_2 per tonne km) are around 0.01 for maritime shipping and 0.50 for shipping with a van (Defra, 2010).

Secondly, the amount of links in the chain and the distance between the locations in the chain also greatly determine the transport emissions, the second and third factor in the framework. Of course, making changes in the supply chain is a medium or long-term decision which impact multiple decision makers within a company, or in multiple companies. In Chapter 5 we consider a situation in which two supply sources are available and the company has to decide where to produce products to deliver them to the market.

Relocating stock points or production facilities may also favorably impact the payload and empty kilometer factors, the fourth and fifth factor in the framework. A production location closely located to a harbor reduces the amount of kilometers traveled by road in case of intermodal water transport. In collaboration with other companies, e.g. suppliers or competitors, it can be ensured that a load is available for shipping back from location B to A.

We consider situations in which a single mode is used per product and a situation in which two modes are used simultaneously to ship products. We investigate the impact of (self-imposed) emission regulations on the transport mode used and expected costs (profits). Moreover, we investigate how the selected mode and costs are affected by product and transport mode properties, such as value, weight, and distance. Lastly, we investigate the advantages of setting an emission constraint for a group of products.

1.3 Issues concerning production emissions

To date, most emission regulations have focused on emissions from production, as discussed in Section 1.1. In general, emission regulations create the desired effect that emissions from production go down. The production emissions can be reduced by investing in a technology with lower energy consumption, using alternative fuels, e.g. biofuels or waste, reduce the material usage (reduce, re-use, recycle), or use alternative materials, e.g. waste or by-products of other processes. Another, undesirable, possibility exists to reduce emissions and that is to relocate production to a location without emission regulations. We take a company perspective and observe how emission regulations impact emission reduction investment decisions.

Carbon emission regulations are currently in effect in several regions of the world, which are mainly developed countries, as described in Section 1.1. As a result, the price of carbon is different (zero or positive) in different regions of the world. This price difference can be explained by examining marginal emission reduction cost curves for different regions in relation to the emissions cap, e.g. the Kyoto target. A positive emissions price is required only when emissions are higher than the target. When the emissions are high in a region, the carbon cost is determined by the availability and cost-efficiency of emission reduction targets, i.e. more cost-efficient reduction opportunities results in a lower cost. The clean development mechanism of the Kyoto protocol allows companies to use this cost difference by investing in emission reduction opportunities in one region and using the carbon allowances in another region.

The fact that emission regulations differ between countries around the world implies that companies face *asymmetric emission regulation*, much like value added tax (VAT) differences between countries. Since carbon emission regulations typically impact developed countries, the price difference between developed and developing countries increases. As a result, global emissions may increase if production (and emissions) is shifted to a region without emission regulations, which is called *carbon leakage*. The emissions increase is due to additional transport emissions and possibly higher production emissions.

Several factors are considered by companies when deciding on the production location, including locations of suppliers, raw materials and customers. Other important factors are the unit production and transportation costs, which are directly impacted by emission regulation. In evaluating to source locally, e.g. in Europe, or in an offshore location, such as the Far East, the decreased production cost needs to be weighed against increased transportation costs. If due to emission regulations the production costs in Europe increase, the trade-off between production and transportation costs needs to be reconsidered. For commodity goods producing offshore has traditionally been too expensive, mainly due to transport costs, but it becomes more attractive as emission regulations become more stringent (Demailly & Quirion, 2006).

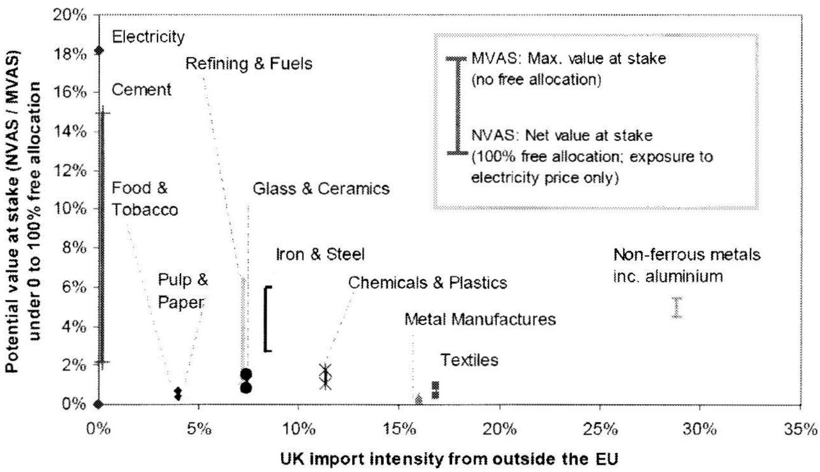

FIGURE 1.7: The impact of the share of free allowances on costs relative to the sector value-added (Grubb & Neuhoff, 2006)

Due to changes in the EU ETS in Phase III, it is expected that the price of allowances will increase, enlarging the risk of carbon leakage. As a result, the European Commission has been investigating which sectors are deemed to be subject to a significant risk of carbon leakage in Phase III of the EU ETS (European Commission, 2011a). Two determinants were distinguished: cost increase as a result of regulation and trade intensity. Figure 1.7 presents for a number of sectors the impact of emission regulations on costs relative to the trade intensity.

Sectors are deemed subject to carbon leakage risk if the additional cost caused by emission regulations (direct and indirect) is at least 5% of the Gross Value Added. The direct costs relate to Scope 1 production emission costs and the indirect costs refer to increased electricity prices. It can be seen in Figure 1.7 that cement has a high score on this factor.

The second risk factor is if the trade intensity (sum of import plus export over annual turnover plus total imports) is more than 10%. If many products are exported to countries without emission regulations, then sales of European companies may decrease due to increased prices. Higher-value commodity goods such as metal and textiles typically have a high score on this factor. In addition, any sector for which either of the two factors are more than 30% are included. In total the sectors subject to carbon leakage risk account for 25% of all emissions covered by ETS and 77% of the emissions of manufacturing industries covered by ETS.

In Chapter 5 we study the decision of a producer where to produce in the supply chain when faced with uncertain emission regulation, which requires significant investment costs and becomes operational in the longer term. In addition, the company can invest in reducing the emissions per unit produced. These decisions are important to reconsider in the light of production emission regulations becoming more stringent, which makes the current production setting unprofitable for some companies. For example, cement is sold for around € 80/tonne and the emission related costs can increase to up to € 20 /tonne of cement (Drake *et al.*, 2010a), (Lafarge, 2010) (for a cost of € 30/tonne and all allowances are purchased).

We firstly investigate in Chapter 5 what investments a production company makes, in terms of capacity in a region without emission regulation and in improving technology in the regulated region, under uncertain and asymmetric emission regulation.

Since the effect of carbon leakage undermines the purpose of emission regulations and it is unlikely that emission regulations will be symmetric across all countries, anti-leakage measures need to be implemented to reduce the effect. A possible measure is a border tax applied to products imported into/or exported from the regulated region, much like import tariffs (Grubb & Neuhoff, 2006). The value of the border tax is based on two variables: the price per unit of emissions and the unit emissions taxed. An important issue with a carbon border tax is that it may not be in line with the rules on international trade as defined by the World Trade Organization (WTO) (see e.g. Rich & Karp (2004)). The trade rules state no distinction can be made between 'like' products, which refers to material use and functionality. The amount of emissions generated during production, the carbon content, may or may not be sufficient to distinguish between two otherwise identical products. Ismer & Neuhoff (2007) conclude in their article that a carbon border tax based on best available technology will most likely not be in conflict with WTO trade rules.

Setting a border tax at the value of the best available technology does not provide incentives for producers in the unregulated market to reduce their emissions from production. This negative effect is compensated for by two reasons that increase the likelihood of being implemented. First, a border tax based on the actual emissions may be in conflict with WTO trade rules. In addition, a border tax based on best available technology is easier to implement than one based on actual emissions because it requires fewer data from producers abroad (Ismer & Neuhoff, 2007).

Alternatively, the regulator may decide to give a certain amount of allowances for free to companies in industries subject to carbon leakage risk. If the amount of allocated allowances is based on historic production figures, this is called partial grandfathering and if it based on current production figures, then it is called output-based allocation (Demailly & Quirion, 2006). By giving an amount of allowances for free the total emission related expenses decrease, thereby making production outside the regulated region less attractive.

The second objective of the research presented in Chapter 5 is to investigate how the technology and capacity investment decisions of a company are impacted by these anti-leakage policies and what the impact is on emissions.

1.4 Accurate measurement of transport emissions

The accurate measurement of carbon emissions is an essential requirement to ensure that the emission targets are met and for companies to reduce their carbon emissions. Information is required on the total emissions associated with the vehicle and allocation of emissions to a single product is required if non-dedicated vehicles are used. Emissions due to transport activities are directly linked to fuel consumption and the emissions of the vehicle are determined straightforwardly if the actual fuel consumption is known. In this dissertation we assume that transportation is outsourced to logistics service providers and we have observed that logistics service providers typically do not share fuel usage information with customers as this regarded as sensitive information. For producers to get insight into the emissions associated with transportation an approximate emission measurement methodology has to be used. The accuracy of the emission estimates obtained is dependent on the quality of the input data. Although fuel consumption is sensitive information, producers might be able to obtain information on vehicle types and thereby making the emission estimates more accurate. The allocation of emissions to a single product is always to a certain extent approximate.

The Greenhouse Gas Protocol (2011) offers, besides guidelines on how to report emissions, calculation tools to measure emissions of many activities ranging from production to transport, and specific tools are developed for certain sectors. The protocol was initiated by World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The scope of the tool is not restricted but the focus is on the US. The approach is very high-level and restricts the number of parameters that can be influenced. Several other calculation methodologies exist, an overview is given in Table 1.1.

TABLE 1.1: Overview of transport emission measurement tools

Method	Scope	Level of Detail	Date	Developer
ARTEMIS	Europe	Very high	2007	Consortium
EcoTransIT	World	Medium	Ongoing	IFEU, RMCon
GHG Protocol	World, US focus	Low	Ongoing	WRI, WBCSD
NTM	Europe	High	Ongoing	NTM
STREAM	Europe	Medium	2011	CE Delft

Artemis is a study executed by a consortium of 36 European organizations involved in research in transport emissions and was funded by the EU TRL Ltd (2004). The focus of the project was to develop a very detailed methodology of transport emissions. As a result, very detailed information on the transport is required to be able to get accurate estimates.

EcoTransIT was originally developed for European railway companies by the Institute for Energy and Environmental Research (IFEU), Heidelberg, and the Rail Management Consultants GmbH (RMCon). It has since extended to include other modalities and its scope has extended to transport around the globe (including ocean shipping) (ECOTransIT, 2011). The methodology can be used in an online calculation tool and it has a relatively low level detail, i.e. few parameters to set.

The Network for Transport and Environment (NTM) method is developed by a Swedish non-profit organization NTM (2011). It provides a moderately high level of detail and is aimed particularly at buyers and sellers of transport services. The calculation methodology provides estimates for parameter values for transport in Europe that are unknown. NTM is also involved with the European Committee for Standardization (CEN) in developing the European standard for emission calculation

The STREAM methodology (Study on the Transport Emissions of all Modalities) is developed by CE Delft for the Dutch Ministry of Transport (Den Boer *et al.*, 2008). Initially it was focused only on transport within the Netherlands but the latest version incorporates international transport. Lastly, STREAM provides a medium level of detail and CE Delft provides an emission scan based on the methodology.

For the research in this dissertation we require estimates for transport emissions. We use the NTM methodology for transport within Europe because it provides estimates for parameters if the real values are unknown. If intercontinental transport is considered, then the EcoTransIT web based tool is used to estimate emissions and distances.

1.5 Research questions

In the research presented in this dissertation we consider well-known problems from the Operations Management field in the light of carbon emission restrictions. We focus on two types of related decisions in this dissertation. Firstly, we consider the transport mode selection decision, i.e. which transport mode to use for (all) shipments to or from a given location in Chapters 2, 3, and 4. Moreover, we consider the decision to offshore production and/or invest in emission reduction technology in Chapter 5.

The well-studied trade-off between inventory related costs, overage and underage costs, and transportation costs, or ordering costs is considered. We extend this framework by bringing in carbon emissions as a third component. We focus on a single stockpoint and the transportation of goods, being components or finished goods, from a supplier, or to a customer.

In Chapter 2 we consider the setting of a single product for which all shipments from a supplier are executed by the same transport mode. Demand is stochastic and the objective is to minimize the expected total logistics cost consisting of transport, inventory and emission costs. The company decides which transport mode to use from a set of available modes and then sets the order up-to level to minimize average period costs. We consider this setting because we want to focus on the impact of emission regulations on transport decisions for a particular product.

We model the product and transport emissions in detail to obtain insights in the impact of product factors, such as weight and volume, on the selected mode. The NTM methodology is used to obtain accurate estimates for the transport emissions. Moreover, we investigate the impact of different types of emission regulations and how this is influenced by the product characteristics. We answer the following research question:

How is the transport mode selection decision impacted by emission regulations?

In Chapter 3 we consider a multi-product setting of goods which are shipped to customers and a single transport mode is used for all shipments to a customer. Demand is deterministic and the company has set a voluntary emission target for the group of products. The company incorporates the transport cost in the sales price quoted to the customer. Hence the company optimizes the sales price for a given transport. This setting is studied to investigate the impact of deciding on the sales price and transport mode simultaneously on emissions and moreover the advantage of setting an emission target for a group of items.

We consider costs for inventory in the pipeline and transportation costs. The analysis can be repeated for each product-customer combination, as a logistics service provider is in charge of transportation and hence there is no significant set-up cost that triggers joint transportation for the shipper. The objective is to maximize the period cost over all products subject to the emission constraint. The first research question we investigate in Chapter 3 is:

How can the transport mode selection and sales prices jointly be optimized to meet an emission target efficiently for a group of customers?

Moreover, we apply our model to a real-life data set of Cargill which contains information on a large numbers of lanes within Europe. We are specifically interested in the portfolio effect, i.e. to compensate costly emission reductions on one lane with less costly reductions on another lane to achieve emission reductions at an overall lower cost. We therefore additionally investigate:

What is the advantage of setting an emission constraint for a group of items?

In Chapter 4 we combine aspects of the first two models to a setting in which two transport modes can be used simultaneously for a given product: a fast (and emitting) mode and a slow (and less-emitting) mode. The fast mode is currently used and the slow mode can be used in addition to reduce emissions. Again, we consider a voluntary emission target for a group of items. Demand is stochastic and we use a so-called single-index policy. This class of policies may not contain the policy resulting in lowest cost but its simple structure makes it more appropriate to use in practice. The single-index policy allows for a direct link between the inventory policy parameters and the expected emissions. We employ dual sourcing to be able to meet emission targets more closely by using a low-emitting mode to a certain extent and we moreover determine the impact of a target for multiple products. The objective is to minimize the expected total costs for all products subject to the emission constraint.

Compared to the situation in which 100% or 0% of the shipments are done with a certain mode, as we assume in Chapters 2 and 3, any distribution between the two modes can be achieved by applying dual sourcing. This allows for a more balanced distribution of emissions over modes. In this research, we are interested in the effect of an emission constraint for a group of items on the distribution between the modes. Moreover, we investigate the benefit of using two supply modes per item as opposed to only one to achieve emission reduction targets. In Chapter 4 we therefore investigate the following research questions:

When is it more profitable to use both the fast and slow mode for a product?

What is the advantage of using fast and slow modes for a group of products?

In Chapter 5 we consider a company that is currently manufacturing a product in a region subject to emission regulation, such as Europe. In the light of uncertainty regarding increasing emission regulations and as a result emission cost, the producer is considering alternatives how to reduce the total carbon related costs. The total emission related expense is determined by the emission price, the quantity produced, and the amount of emissions to produce one product (the emission intensity). Investing in cleaner technology reduces the emission intensity and creating off-shore capacity reduces the quantity produced, and as a consequence, the emission related costs decrease. We consider this setting to investigate what investments are made when faced with uncertain and more stringent emission regulation.

An investment in technology and in building new capacity is a long-term, strategic decision and in the time lapse between the decision and implementation new emission regulations can be implemented or the value of the emission cost can change. The uncertainty regarding emission regulation is first of all reflected in uncertainty regarding the emission cost value in the future. Additionally, a policy measure that aims at reducing carbon leakage can be implemented. We consider a two-stage problem. In Stage 1 the investment decisions are taken: the emission abatement and the offshore capacity. In Stage 2 the investments become operational and the production quantity has to be decided in the two locations. Demand is deterministic and price-dependent. The objective is to decide on the investments in emission abatement and the offshore capacity such that the profit is maximized, while producing the optimal quantity in Stage 2. We have therefore formulated the following research questions we investigate in Chapter 5:

What investments should a company, facing uncertain and asymmetric emission regulation, make in technology and capacity to remain profitable on the long term?

How are these company investment decisions impacted by an anti-leakage policy?

What is the impact of an anti-leakage policy on the emissions?

1.6 Contributions

In this section we describe the main contributions of this thesis to the most related areas of the literature: (i) inventory management, (ii) transportation, (iii) investment, and (iv) environmental economics.

Within operations management, (green) inventory management is related to the research presented in this thesis. The contributions of Chapter 2 to this field are that we

develop an inventory model that incorporates the modality choice. Moreover, we show the impact of product characteristics on the modality choice and inventory. Lastly, our model studies the impact of emission regulations on operational decisions.
Our research in Chapter 4 contributes to the literature on dual sourcing, a specific domain of inventory management. Contributions to this field are that we develop a multi-item dual sourcing model with an aggregate emission constraint. Moreover, we derive structural results on the optimal policy parameters for a special case, with exponentially distributed demand. In a numerical study, we show under what conditions dual sourcing is a cost-effective way to reduce emissions from transport.

The area of transportation research that takes into account environmental considerations is another field that is related to our research. Specifically, we contribute to the transport mode selection literature in Chapters 2, 3, and 4. In Chapter 2 we develop a model which studies the impact of emission regulation, moderated by product characteristics, on transport mode selection. Using convexity arguments, structural conditions are derived that determined whether a mode is selected, or not. We show that the product characteristics highly determine which mode is selected and the effect of the emission price is moderate.
In Chapter 3 we contribute to this field by optimizing for the mode choice and sales price simultaneously under emission considerations. Secondly, we derive structural properties for the transport modes to ensure that they are selected. Moreover, in a real-life case study we show that the portfolio effect can result in significant savings when reducing emissions by switching modes and setting prices simultaneously. Lastly, we observe that a large share of emissions reductions are achieved with virtually no cost increase.
In Chapter 2 we consider unimodal transport and observe that for transport a high emission cost is required to result in transport switches. In Chapter 3 we consider intermodal transport and observe that emissions can be reduced to a certain extent without impacting profits too much. These results are explained by the fact that intermodal transport is relatively more expensive and has relatively more emissions than only unimodal transport, e.g. rail or water, and the impact of an emission cost or constraint is therefore stronger.
To the transport literature with carbon considerations we contribute in Chapter 4 by developing a model in which two transport modes are used simultaneously to study the emission reduction potential of dual sourcing. We show that under certain conditions dual sourcing is not beneficial in terms of costs and emissions.

Within operations management the literature on investment is related. To the literature on off-shoring we contribute in Chapter 5 by specifying a model that studies technology investments and the off-shoring decision simultaneously. Moreover, we develop several models that study the off-shoring decision under asymmetric emission regulations for three anti-leakage policies. In a numerical study based on an European cement manufacturer we observe that the Grandfathering policy is preferred from both the company's and regulator's perspective but care should be taken to determine the amount of grandfathering.

Within environmental economics articles that study the impact of asymmetric emission regulation are related. There are articles that focus on technology investment decisions under asymmetric emission regulation. To this field we contribute in Chapter 5 by considering a model with technology and capacity investments simultaneously under uncertain and asymmetric emission regulation. To this field and the field that examines the impact of anti-leakage policies we contribute by taking explicitly modeling several anti-leakage policies and examining the impact on investments in technology and off-shore capacity.

1.7 Recent and prospective developments in literature

The area of literature related to how environmental (carbon) considerations impact companies' decisions and operations has been extending rapidly over the last few years, partly motivated by the increasing share of industries and regions that are subject to carbon emission regulations. In general, three different areas of research are of interest for the research presented in this dissertation: First of all, research that investigates what type of *emission regulation policy* is preferred. Secondly, research that investigates additional *benefits* companies can gain from *complying with (self-imposed) emission regulation.* Lastly, articles that focus on one (or more) companies and their *best response to given emission regulation* are of interest. The first two areas are of interest to our research because it provides motivation and a basis for comparison of the implications for our models. The third area represents literature that studies problems similar to the work presented in this dissertation. Below we describe typical problems studied in each of the fields, and we refer to typical or well-known papers.

In the first category, the regulator's perspective is taken and in a macro setting the response of companies to regulation is considered, from which conclusions can be made on what type of policy is best (under what conditions). Articles that focus on carbon emission regulations for production companies are Grubb & Neuhoff (2006), and Grubb *et al.* (2011). Also regulations for the transport industry are being investigated, by among others Abrell (2010).

In the second category, articles investigate positive side-effects companies experience from imposing self-regulation or from being subject to, or moving beyond, emission regulations. Corbett & Klassen (2006) investigate what they refer to as "law of the expected unexpected side benefits", i.e. adopting an environmental perspective yields benefits beyond what is expected beforehand. Jacobs *et al.* (2010) empirically investigate the impact of environmental performance on the shareholder value of the company, as another benefit of environmental awareness. Short & Toffel (2010) investigate companies' self-regulation and when it is actually implemented by companies.

The last category that takes the perspective of one company and how the imposed regulations impact operational decisions is most related to our work. Srivastava (2007) provides a comprehensive overview of the literature on green supply chain management. More recently, Dekker *et al.* (2012) provide an overview of articles that incorporate environmental considerations in logistics. We distinguish within this field articles that mainly focus on production and articles that mainly focus on transportation. To reduce the emissions from production one can change the production process or focus on the policy and supply chain. Articles on transportation that are most related to our research either focus on a transportation network (a logistics provider perspective) or on a single company which requires products to be shipped.

When focusing on the impact of emission regulations on the production process one can consider the production technology or the input materials. In the first case, one typically investigates the technology investment decisions of companies under emission regulations, as in done in e.g. Drake *et al.* (2010b). In the second case, reverse logistics is an important field. In this extensive research area a return flow of used products is, after one or more processing steps, used as input in the production process. The re-use of products reduces the usage of new input materials and may also result in fewer emissions. An overview of research in this field is given by Atasu *et al.* (2008).

Alternatively, one can investigate the impact of emission regulations on decisions related to when, where, and how much to order and how to design the supply chain. For example, Rosič & Jammernegg (2010) investigate the impact of emission regulations on the use of an off-shore and on-shore supply source. Cachon (2011) investigates the problem of a retailer that has to decide how many stores to open, while taking into account emissions generated while supplying products to the store and the customers emissions while traveling to the nearest store. Extending the focus beyond a single company while investigating the benefit of collaboration is another interesting area to focus on. Pan *et al.* (2010) for example investigate the possibility of merging supply chains by pooling transportation activities.

Articles that focus on the impact of emissions on transport, besides the technical improvements of vehicles, are related to our research. One stream of articles takes the view of a logistic network operator and investigates how focusing on minimizing emissions instead of minimizing costs impacts the logistics network, see e.g. Neto *et al.* (2008) and Bauer *et al.* (2009). Alternatively, some articles focus on the emissions associated with transportation of a single company. For example, Cholette & Venkat (2009) investigate different options of delivering wine to customers and investigate the impact on emissions. Leal Jr. & D'Agosto (2011) also investigate different modal choices for exporting bio-ethanol.

We believe that future research should concentrate on extending the focus of the model which reveals other trade-offs related to carbon emissions. Firstly, one can extend the horizon vertically in the supply chain by considering the emissions of multiple links in the chain and how investments of one link that reduce emissions further down the chain can be distributed among the links. Secondly, one can extend the horizon horizontally by considering collaboration in sharing the transport network between competitors to reduce emissions from transportation.

Another promising line of research is to focus on a single company and combine two of the fields just described. A first combination should involve production and transport decisions with emission considerations. A second topic of research is to focus on the supply chain network and transportation with emission considerations. By changing the layout of the network emission reductions can be realized without compromising service to customers. Additionally, research should consider the product (design) and the supply chain simultaneously by considering supplier selection and product source. Possible research considers different supply sources, new and refurbished, and the trade-off in production costs and emissions. Another opportunity is to investigate supplier selection with emission considerations: taking into account the location of the supplier in addition to the embedded emissions.

Emission regulations are extending and may likely impact transportation companies in the future. To date regulations impacting transportation companies include time windows for delivery in city centers and allowing only clean vehicles to enter certain areas. Research should focus on the impact of regulations on investments of service providers in more environmentally friendly vehicles, vehicle fleet mix, the layout of the network, and the use of alternative fuels.

1.8 Outline

The research questions presented in the Section 1.5 are investigated in the remainder of this dissertation. An overview of the different problem is given in Table 1.2. The transport mode selection problem in a situation with stochastic demand and emission regulations is described in Chapter 2. The joint pricing and transport selection problem in a deterministic multi-item setting subject to an overall emission target is given in Chapter 3. Next, we consider the possibility to use two transport modes per product in a stochastic multi-item setting with an overall emission target in Chapter 4. Finally, we extend our scope to production emissions and consider the impact of emission regulation on the offshoring and technology investment decision in Chapter 5. The conclusions are presented in Chapter 6.

The research presented in Chapters 2 to 5 have resulted in the following publications: Hoen *et al.* (2012c), Hoen *et al.* (2011), Hoen *et al.* (2012a), and Hoen *et al.* (2012b).

TABLE 1.2: Research summary

Chapter	Products		Transport modes		Emissions	
	One	Multiple	Single	Dual	Transport	Production
2	x		x		x	
3		x	x		x	
4		x		x	x	
5	x		x		x	x

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SUMMARY

Design and Control of Carbon Aware Supply Chains

In this dissertation the impact of carbon emissions on the design and control of supply chains is studied. Increasing awareness for global warming and the role of greenhouse gasses in this has made companies more aware of carbon dioxide emissions caused by supply chains. As a result of this awareness, carbon emission regulations have been developed enforcing companies to incorporate a carbon cost (for certain activities in certain regions). Moreover, companies are voluntarily restricting their carbon emissions by specifying emission reduction targets, as a response to pressure from customers and stakeholders. In this dissertation we develop models with emission regulation and also with voluntary emission targets.

We study well-known trade-offs in the field of Operations Management, such as between inventory and transport costs, by incorporating a carbon emission component, historically often neglected, and investigate the impact of the emissions on decisions. It is important for companies to take carbon emissions explicitly into account in decision making as carbon related costs are expected to increase in the future. Carbon emissions can be reduced to a certain extent by taking efficiency measures that both reduce emissions and costs. As companies can also invest in these measures from a pure cost perspective, we do not consider them in this dissertation. Moreover, it is likely that these measures yield insufficient emission reductions to achieve global emission targets. Hence, to achieve substantial emission reductions, measures that require investments, or increase operational costs, might be necessary. We explore several strategies for companies to reduce carbon emissions and investigate when a certain strategy is cost-effective. Examples of emission reduction strategies are to switch transportation to a mode with lower emissions, or to invest in production technology or off-shore production capacity.

The focus of the research is on production companies and their carbon emissions generated during production and transportation activities, either to facilities of the same company or from suppliers or to customers. When considering emissions from transportation, we assume that transport is executed by a third party logistics service provider, as is often seen in practice. As a result, the control of the production company over the transport (emissions) is limited. The optimization of the load of the vehicle, and the traveled route is outside the control of the production company. However, the production company can decide which transport mode, or combination of modes be used, which determines the emissions to a large extent. In Chapters 2, 3, and 4, this emission reduction opportunity is studied in settings with one or multiple products and imposing the use of one or two modes. Then, in Chapter 5, the focus is extended to include emissions

from production. We consider a company facing emission regulation for production and consider the possibility to invest in cleaner technology or to offshore production to a location without emission regulation. We next present a summary of the models and results presented in Chapters 2 through 5.

First, in Chapter 2, we study the transport mode selection decision for a single product subject to emission regulation. We investigate the impact of different types of emission regulations and investigate under what circumstances a transport mode switch may occur. A transport switch implies that the selected transport mode in a setting with emission regulation differs from the selected mode in absence of emission regulation. The trade-off under consideration is that a fast mode results in low inventory costs but in high transportation costs and emissions (costs), and vice versa. In a setting with stochastic demand we consider an order-up-to inventory policy including an emission cost. To accurately estimate the carbon emissions from transportation, we use a carbon emission measurement methodology based on real-life data and incorporate it into an inventory model. We observe that not the emission cost but the product characteristics, such as weight, density, and value, mainly determine which transport mode is selected. Consequently, a switch to a less polluting transport mode only results for a very high emission cost or if a product has a low weight or density or a high value. We find that even though large emission reductions can be obtained by switching to a different mode, the actual decision depends on the regulation and non-monetary considerations, such as lead time variability.

Then, in Chapter 3, we consider a multi-item setting in which a self-imposed emission reduction target is set for a group of items. One item represents a combination of a particular product and a particular customer for which regular shipments occur, which determines the demand, product characteristics and the distance to be traveled. As the choice of transport mode (and corresponding transport costs) is up to the production company, the quoted price to the customer is also a decision variable. Since a single emission constraint is set for a group of items, the model is a constrained multi-item deterministic problem which can be solved using Lagrangian relaxation. Setting an emission target for a group of items allows for taking advantage of the portfolio effect: reducing emissions first where it is overall less costly. For a fixed emission target the transport mode that minimizes the total logistics cost is selected. If a range of emission targets are considered and we compare the cost-minimizing solutions, then it appears that two opportunities exist for the producer to reduce emissions: first of all, to select a mode that results in lower emissions per product shipped, and secondly to select a slightly higher sales price which results in lower demand and hence lower emissions.

In a case study, we apply our model (with fixed sales price) to a business unit of Cargill and observe that emissions can be reduced by 10% at virtually no cost increase. Emissions can be reduced by at most 27% which results in a 30% cost increase. In an extension in which the sales price can be set, we observe that the portfolio effect results in at most 20% profit savings, a value which is relatively robust to price-sensitivity of demand. As in this case study road transport is the most polluting mode, larger emission reductions can be expected when air transport is used for shipments.

Next, in Chapter 4 we examine the possibility to use two supply modes for a given product simultaneously, which is referred to as dual sourcing in inventory literature, in a multi-item emission-constrained setting with stochastic demand. By using two supply modes, a fast and a slow, one can combine the low transport costs and emissions (the slow mode) with being highly responsive (the fast mode) when required, i.e. in case of a stock out situation. As has been investigated in the literature using dual sourcing may result in lower expected period costs than using only a single mode. From an emission perspective using dual sourcing is beneficial compared to single sourcing since emission reductions can be achieved on a continuous scale. In some situations switching all shipments to a less polluting mode is too costly. Dual sourcing may then provide a large part of the emission reduction at a lower cost than using only the slow mode. We assume that a so-called single-index policy is used, which specifies two order-up-to levels: one for each mode. As a result of this policy, the fast mode is used when the demand in a certain period exceeds a certain value. Making use of a special case with exponentially distributed demand, we provide structural insights for a single product model. Then we extend these results to a model with two products and an aggregate emission constraint which provides insight into the more general situation with n products. In a numerical study we observe that if dual sourcing results in a cost decrease, then emissions can be reduced to a large extent without increasing the costs compared to using only a single mode. For a two-product setting we study if setting an emission constraint for a group of items is more or less beneficial if the products are more similar with respect to the value for one variable. We observe that the demand variability, and not so much for product weight and the penalty cost factor, has a large impact on how beneficial dual sourcing is, i.e. less similar products benefit less from dual sourcing.

Lastly, we study the investments of a production company in production technology and capacity under asymmetric and uncertain emission regulation in Chapter 5. Asymmetric emission regulation refers to the fact that in different regions of the world different, or no, emission regulations exist and as result the emission price differs from region to region. We consider a producer of an energy-intensive good which incurs an emission cost for emissions generated during production. The company is deciding how much to invest in production technology in the regulated market, and how much capacity to build in a location with no emission regulation, the unregulated market. As emission regulation may result in off-shoring production and an increase in total emissions, regulators can implement measures to combat this undesirable effect. We refer to these measures as anti-leakage policies and study for each policy how it affects the company's investment decisions and ultimately global emissions. We consider three different anti-leakage policies: Border Tax, which imposes a cost for products imported into the regulated region, Output-based allocation, which reimburses a certain emission cost per product produced in the regulated market, and Grandfathering, which reimburses a lump sum of emission cost, provided actual emissions exceed the amount.

We consider four scenarios, one without an anti-leakage policy (baseline scenario) and three for the anti-leakage policies just described, and determine the optimal investment strategy and also the production strategy, which specifies how much to produce in each location given an emission cost realization, and the global emissions. We have observed that four possible strategies exist, two of which are to invest and produce only in one market (either the regulated or the unregulated) and two involve investment in both markets. When an anti-leakage policy is implemented and we compare the investments to the baseline scenario two effects may occur. First of all, less capacity may be built in the unregulated market, while not changing the production strategy. Secondly, it may result in the selection of a strategy with more production in the regulated market. We have applied our model to a data set based on a European-based cement producer and conducted a full factorial study for several important parameters. Overall we have observed that the grandfathering policy is preferred from both the company's and regulator's perspective. It is however, important to set the reimbursement not too low or too high.

Finally, in Chapter 6 we present the conclusions of the research presented in this dissertation and provide directions for future research.

Curriculum Vitae

Kristel Hoen was born in Geldrop, the Netherlands, on August 10, 1984. In June 2002, she completed secondary eduction at the Jacob Roelandslyceum in Boxtel, after which she started her bachelor studies in Industrial Engineering and Management Science at the Eindhoven University of Technology (TU/e). After obtaining her BSc degree in August 2005, she continued with a master in Operations Management & Logistics at TU/e. During this program she spent a year as a board member of E.S.M.G. Quadrivium, a student music association for classical music, focusing on organizing concerts for the wind orchestra Auletes. In the fall of 2007 she conducted her (internal) master thesis research project at Boğaziçi University, Istanbul, under the supervision of Refik Güllü and Geert-Jan van Houtum, which resulted in a publication in an ISI journal.

In March 2008 she obtained her MSc degree and in July 2008 she started her PhD project under the supervision of Tarkan Tan, Geert-Jan van Houtum, and Jan Fransoo. In the fall of 2010 she conducted research at the Georgia Institute of Technology, Atlanta, United States of America, under the supervision of Beril Toktay. The results of the research conducted in this period are presented in this dissertation. On November 26, 2012 Kristel defends her PhD thesis at TU/e. As of September 2012, Kristel is working as a consultant at Quintiq Applications in 's-Hertogenbosch.

Beta

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