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Abstract

The transport sector is the second largest carbon emissions contributor in Europe and its emissions continue to increase. Many shippers are committing themselves to reducing transport emissions voluntarily, possibly in anticipation of increasing transport prices. In this paper we study a shipper that has outsourced transport and has decided to cap its carbon emissions from outbound logistics for a group of products. Setting an emission constraint for a group of products allows taking advantage of reducing emissions substantially where it is less costly and less where it is more costly. We focus on reducing emissions by switching transport modes within an existing network, since this has a large impact on emissions. In addition, the company sets the sales prices for the products, which influences demand. We develop a solution procedure that uses Lagrange relaxation. Conditions on total logistics cost and unit emissions are derived that determine which transport mode is selected for a product. It is observed that a diminishing rate of return applies in reducing emissions by switching transport modes. In a case study we apply our method to a producer of bulk liquids and find that emissions can be reduced by 10% at only a 0.7% increase in total logistics cost. *Keywords*: carbon emissions, green supply chains, sustainability, transport mode selection, Lagrange relaxation, pricing.

1 Introduction

In recent years concern has been growing over the factors contributing to climate change. One of the important contributors to climate change is (freight) transport. In Europe, in 2006, around 23% of all carbon dioxide (CO_2) emissions were due to the transport sector, which makes it the second biggest contributor after the energy sector (European Commission, 2011). More than two thirds of these emissions are due to road transport (European Commision, 2009a). It is estimated (European Commision, 2009b) 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 fuel efficiency of vehicles. The increased demand for transport is mainly due to two trends: increasing global trade and supply chains becoming more spatially dispersed around the globe due to extensive offshoring.

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If transport emissions continue to increase at the current pace, then global emission targets of the United Nations may become unattainable.

In response to the concern of growing carbon emissions from transport, policy makers have started developing emission regulations. In the European Union (EU), emission regulations for transport are currently limited to air transport, for which an emissions trading scheme (EU ETS) has been developed (European Commission, 2010). In a trading scheme, an authority sets a cap that emissions cannot exceed and issues a matching amount of allowances (rights to emit 1 tonne of CO_2), which are either given to companies for free (grandfathering) or auctioned (Tietenberg, 2001). Companies should have enough allowances to cover their emissions for a given period, where the surplus and shortage are traded in a carbon market. How and whether the regulations for transport should be extended in the future is currently being investigated (EU Transport GHG, 2011). Fuel taxes that aim at reducing consumption of fossil fuels are already in place and they have a similar effect as carbon tax on fuel, because each unit of fuel consumed results in a certain amount of carbon emissions. A possible extension of regulations is to increase the already existing fuel taxes. If emission regulation for transport is implemented, then it is most likely applied to transport companies, as is currently the case for air transport, because the regulators then have to deal with fewer parties and the issue of allocating emissions to shippers is circumvented. As a consequence of regulating emissions, prices for transport would increase and shippers would have further incentives to reduce their emissions. Moreover, companies are voluntarily reducing emissions, not only because of corporate responsibility, but also in an attempt to improve their market share, company image and value. For example, the Carbon Disclosure Project reports that 294 of the Global 500 companies have voluntary emission reduction targets (Carbon Disclosure Project, 2011).

In this paper, we consider a company that is committed to reducing emissions from transport with a self-imposed emission target for the outbound transport emissions. To achieve emission reductions, the company switches from high-carbon transport modes such as air or road, to low-carbon transport modes such as rail and water. The company decides which transport mode to use for each product-lane combination (which we refer to as "product" in the remainder of the text) while transport is outsourced to a Third Party Logistics Provider (3PL). Note that the choice of transport mode is one of the most simple emission abatement options in terms of implementation, provided that transport is outsourced. Moreover, it does not require a change in the supply chain, e.g. relocating warehouses. It is generally recognized that the transport mode used is one of the key factors that determine the emissions from transport. The potential gains in emission reductions are very large for modal shifts. Traditionally, the decision as to which mode for which product to use is based on the trade-off between the transport and inventory related costs. We extend this framework by bringing in carbon emissions as a third component. 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 meeting emission reduction targets.

Transport emissions are a part of Scope 3 (indirect) emissions of the Greenhouse Gas Protocol

(Greenhouse Gas Protocol, 2011), unless company-owned vehicles are used. This implies that detailed information such as vehicle type, load factors, followed routes, etc. needs to be acquired externally to calculate the emissions. In order to calculate the emissions accurately, it is essential that the information is as accurate and detailed as possible.

We consider a profit-maximizing firm that is determining the sales price and the transport mode of each product subject to an emission constraint over all products, where demand is assumed to be linearly decreasing in price. Observe that by optimizing the price, the company would influence the demand for different products in such a way that the overall emission target is met. The assignment of transport modes to products is typically a tactical decision, we therefore determine which mode maximizes the profit, based on the average demand figures. The logistics cost consists of a transport cost and a holding cost for the pipeline stock. We develop a solution procedure using Lagrange relaxation. We consider the unit transport costs per mode to be pre-determined, nonetheless our method is also applicable to the case where transport costs increase proportionally to emissions (as a consequence of emission regulation at the 3PL). We decompose the multi-product problem into a number of single-product problems that are solved separately. We derive conditions on the logistics costs and the unit emissions that determine which transport mode maximizes the profit of a product for a given emission target. We find that the optimal sales price increases linearly and the profit decreases quadratically in the emission reduction target.

We apply our solution procedure to a business unit of Cargill company, which is an international producer and marketer of food, agricultural, financial and industrial products and services. We use data from third party logistics providers on transport cost and lead time, and we consider the prices given to us by Cargill as fixed. The transport emissions are calculated by using a tool based on the NTM emission calculation methodology (NTM, 2011). We find that intermodal transport, which is typically less carbon emitting, is more expensive than road transport for 63% of the products, implying that cost and emissions are not aligned (our experience with other companies showed that this observation is not unique to Cargill). We have observed that a diminishing rate of return applies when reducing emissions by switching transport modes. As a result, the solution is increasingly sensitive to the tightness of the emission target. We observe that a 10% emission reduction can be achieved at only a 0.7% cost increase, compared to the minimum-cost solution, and it is possible to reduce emissions by 27%. In an extension of the case study where we compare and contrast different price elasticities in a profit-maximization setting, we find that emissions can be reduced up to 30% at a 1.2% profit loss, which does not appear to be sensitive to price elasticity.

The main contribution of this research is threefold: First, we develop a model to achieve an overall emission target by optimizing transport modes and prices of products simultaneously. Secondly, we develop a solution procedure that takes into account an overall emission constraint on a *group of products*. This allows us to exploit the portfolio effect, which implies that emissions are reduced on lanes for which this is less costly. This way, a certain emission target can be achieved while maintaining higher profit compared to a situation with the same reduction target for each product. Lastly, we apply our analysis to a real-life case study and we develop several managerial

insights.

The remainder of the paper is organized in the following structure. In Section 2 we position our work in the existing body of literature. The model and underlying assumptions are presented in Section 3. In Section 4 the analysis of the model is described. In Section 5, we apply the analysis to a real-life case study. In Section 6, we end with the conclusion.

2 Related literature

The transport mode selection decision has been studied mainly in the fields of Inventory Management and Transport. Within inventory management (or supply chain management) environmental impacts have been internalized by the works in the green supply chain management literature. Articles in this field deal with how much to produce or order from one or more sources taking into account environmental impacts, which can range from (carbon) emissions to waste. The literature review by Srivastava (2007) provides an overview of the research on green supply chain management. Other extensive literature reviews on the topic of green supply chain management are: Corbett & Kleindorfer (2001a), Corbett & Kleindorfer (2001b), Kleindorfer *et al.* (2005), and Sasikumar & Kannan (2009).

The field of models within Inventory Management that specifically take into account carbon emissions, as we do, is rapidly expanding. One of the earlier works in this field that takes into account emissions is Penkuhn *et al.* (1997), which develops a production planning model for the process industry, taking into account environmental constraints. In Hua *et al.* (2011) the order quantity decision is reexamined, taking into account that emissions from transport are subject to an emissions trading scheme. Our model considers a more complex setting with multiple products and transport modes and an overall emission constraint. We assume, moreover, that transport is outsourced for which variable emissions and order/transport costs are more appropriate. Yalabik & Fairchild (2011) determine how much to invest in abatement of production emissions under emission regulation, also in the presence of a competitor offering an identical product. In Hoen *et al.* (2011), a stochastic inventory model is extended to incorporate transport emissions. The transport mode and order-up-to level are jointly optimized in a single product setting, for a company subject to alternative emission regulations for transport. To the best of our knowledge, we are the first to consider a voluntary emission target for a group of items for which transport modes, from possibly more than two available, need to be selected.

Within the transportation literature many articles incorporating emissions can be found. The impact of transport emission regulation in Europe on transport costs is investigated in several articles. Abrell (2010) uses an economic general equilibrium model to determine the impact of several regulation scenarios on the welfare of individual (EU and non-EU) countries. He finds that exempting transport from emission regulation and shifting the reduction burden to other sectors leads to the smallest welfare reduction. Scheelhaase *et al.* (2010) investigate the impact of the inclusion of aviation in the EU ETS on the competition of EU based and non-EU based

airlines. They find that non-EU based airlines gain competitive advantage over EU based airlines. In Cadarso *et al.* (2010), a method is developed to measure emissions from international freight transport and to allocate emissions based on consumer responsibility. According to the consumer responsibility principle, emissions are allocated to the country in which goods are consumed, even when it is produced elsewhere. These models that study the impact of transport emission regulation have in general a high aggregation level and as a result, do not explicitly model the decisions made by the shipper(s).

Another field in the transportation literature is the transport mode selection literature, which is closely related to our work. In this field, the focus is a shipper for which several available transport modes are compared based on several attributes, ranging from cost to lead time and accuracy, to derive which performs best in minimizing total logistics costs. A literature review is of this field is given by Tyworth (1991). Also within this field the transport emissions have been taken into account. In Blauwens *et al.* (2006) the effectiveness of policy measures that aim at moving away from road transport, because of congestion, to other transport modes is investigated. They take the perspective of a policy maker and investigate what policy is preferred. Two articles that study the transport mode selection decision including emissions for a specific case study are Cholette & Venkat (2009) and Leal Jr. & D'Agosto (2011). Cholette & Venkat (2009) determine for a wine supply chain the emissions from transport and warehousing and investigate the impact of different supply chain designs, including transport modes. Several delivery options are considered and evaluated in terms of costs and emissions. One of their findings is find that the transport mode has a large impact on the total emissions of the supply chain. Leal Jr. & D'Agosto (2011) consider the modal choice decision while taking into account socio-environmental considerations for the case of shipping bio-ethanol from a production location to a port from which it is exported. In addition to rail, road and water transport, they consider transportation through a pipeline.

To the best of our knowledge, we are the first to model the transport mode selection decision in a multi-item setting, including a a pricing problem, and in which transport emissions are bound by a constraint. Further, we focus on the shipper and we develop a formal model that takes into account cost and emissions from transport.

3   Model description

We model an overall emission constraint for a group of products in a setting where the firm decides per product which transport mode to use for the shipments and sets the sales price accordingly. Our model focuses on the tactical decision what mode to use for each product, which typically corresponds with the medium term agreements with 3PLs, e.g. a year, on which transport prices are based. Accordingly, we consider deterministic demand which is dependent on the sales price. We assume that the market share and competitiveness of the market are reflected in the demand function parameters. Hence, the price offered by competitors is not taken into account explicitly. Moreover, we assume that the demand function is corrected for the impact of *production* emissions

on demand. In line with our focus on the tactical decision level for given demand figures and lead times, the mode used does not affect the delivery times of the goods at the customer's location, as the production schedule is adjusted accordingly, such that a longer lead time is compensated by producing earlier.

We assume that the transport activity is outsourced and executed by a Third Party Logistics Provider or a carrier. This assumption holds in general in practice (unless company-owned trucks are used). If transport would be executed by company-owned vehicles, a modal shift may in fact be a capital investment decision. Moreover, in that case utilization of vehicles is very important and few transport alternatives may exist. So, reducing emissions by shifting company-owned transport modes is not likely to be the most cost-efficient alternative. The assumption that transport is outsourced has implications for our cost function and emissions structure: we only consider a variable component per product shipped. The 3PL provides for a given product-mode combination the distance of the route, the transportation lead time and the transport cost.

We assume that the shipper voluntarily imposes a constraint on the emissions for the group of products, even if the transport emissions of the shipper are not regulated. Self-imposed targets have been observed in practice and have been investigated by Reid & Toffel (2009) and Short & Toffel (2010). Companies may expect additional benefits by disclosing their emission targets and moving beyond environmental regulation, such as increased valuation of the firm or customer value, as studied by among others Klassen & McLaughlin (1996), Reinhardt (1999), Dowell *et al.* (2000), and Jacobs *et al.* (2010).

Let $J = \{1, 2, \ldots, n\}$ $(j \in J)$ denote the set of products which need to be shipped. The term "product" is used in the broad sense to refer to a combination of a product type and a customer (location). Note that the model allows for multiple production locations but each product is supplied to a customer from one production location. For each unit of product j produced the company incurs a unit cost, which is denoted by k_j $(k_j \geq 0)$. Note that this unit cost includes the direct labor and material cost incurred to manufacture one item. The weight of one unit of product j is denoted by w_j $(w_j > 0)$.

Let $I = \{1, 2, \ldots, m\}$ $(i \in I)$ denote the set of available transport modes. Please note that unless a truck is used to execute the transport, or the origin and destination are located near terminals, a combination of transport modes is required: intermodal rail or water transport. If it is undesirable that a particular mode is used for a customer, e.g. due to restrictions of the transportation network or the lead time, then the transport cost is set to infinite.

For each product shipped with transport mode i a unit transportation cost is incurred which is denoted by c_i $(c_i \geq 0)$, which is expressed as a monetary unit per ton of cargo shipped over 1 kilometer (e.g. € /ton km). The distance traveled for product j depends also on the transport mode used, and is denoted by $d_{i,j}$ $(d_{i,j} \geq 0)$. The deterministic lead time of product j and transport mode i is denoted by $l_{i,j}$ $(l_{i,j} \geq 0)$. The lead time is determined by the 3PL and includes waiting times between the different legs of a trip. We assume that the products are paid for by the customer when they are delivered. Hence, one unit of product j in transit corresponds with an opportunity

cost of value k_j. Let h ($h \geq 0$) denote the opportunity cost (or holding cost) rate for the items in transit. The logistics cost associated with using transport mode i for one unit of product j are then: $c_i d_{i,j} w_j + h k_j l_{i,j}$. Note that the parameters values of intermodal transport represent a weighted average for the total distance.

The emissions associated with transporting one unit of product j with mode i are denoted by $e_{i,j}$. We approximate $e_{i,j}$ with the following structure, which is based on emission measurement methodologies, e.g. NTM (2011):

$$e_{i,j} = w_j(a_i + b_i d_{i,j}),$$

where a_i and b_i are mode-specific emission constants. The fixed emission factor a_i ($a_i \geq 0$) is associated with the emissions generated during the beginning and end of a trip (most notably for air transport) and the variable emission factor b_i ($b_i > 0$) denotes the emissions generated per kilometer traveled. Both values are expressed per weight unit, e.g. kg, of load transported.

In the remainder of this section we describe our problem formulation, in Section 3.1, and the Lagrangian relaxation of the problem formulation, in Section 3.2.

3.1 Problem formulation

We assume that the company sets the price and observes demand. Let $p_{i,j}$ denote the sales price of product j when mode i is used and the demand (per time unit) is denoted by $q_{i,j}(p_{i,j})$. Note that the sales price would differ when a different mode with its corresponding cost is used for product j. We use an additive demand function:

$$q_{i,j}(p_{i,j}) = Q_j - \epsilon_j p_{i,j},$$

where Q_j ($Q_j \geq 0$) corresponds with the maximum demand and ϵ_j ($\epsilon_j \geq 0$) denotes the sensitivity of demand for product j to the sales price. To ensure that a nonnegative quantity is sold we restrict $p_{i,j}$: $p_{i,j} \leq \frac{Q_j}{\epsilon_j}$.

The objective function is the profit per time unit which is denoted by $\Pi_{i,j}(p_{i,j})$, for product j and mode i, and is determined by the profit per unit ($p_{i,j} - k_j - c_i d_{i,j} w_j - h k_j l_{i,j}$) and the quantity sold ($q_{i,j}(p_{i,j})$):

$$\Pi_{i,j}(p_{i,j}) = \epsilon_j \left(-p_{i,j}^2 + p_{i,j} \left(c_i d_{i,j} w_j + h k_j l_{i,j} + k_j + \frac{Q_j}{\epsilon_j} \right) \right) - Q_j(c_i d_{i,j} w_j + h k_j l_{i,j} + k_j). \quad (1)$$

The total emissions per time unit (denoted by $\Gamma_{i,j}(p_{i,j})$), for product j and mode i, are determined by the unit emissions ($e_{i,j}$) and the quantity sold ($q_{i,j}(p_{i,j})$):

$$\Gamma_{i,j}(p_{i,j}) = e_{i,j}(Q_j - \epsilon_j p_{i,j}). \quad (2)$$

We conclude this section with the definition of Problem (P) in which one transport mode is selected for each product and the sales price is set to maximize profit under an overall emission constraint. The maximum allowed amount of overall carbon emissions is denoted by β ($\beta > 0$). Let $x_{i,j}$ ($x_{i,j} \in \{0,1\}$) denote whether mode i is used for product j or not. In addition, this implies

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that when a positive quantity is sold for product j, it is shipped with mode i. Further we define the vectors $\mathbf{p}_j = (p_{1,j}, p_{2,j}, \ldots, p_{m,j})$, $\mathbf{x}_j = (x_{1,j}, x_{2,j}, \ldots, x_{m,j})$, for $j \in J$ and $\mathbf{p} = (\mathbf{p}_1, \ldots, \mathbf{p}_n)$, $\mathbf{x} = (\mathbf{x}_1, \ldots, \mathbf{x}_n)$.

$$(P) \quad \max_{\mathbf{p} \in \mathbf{P}, \mathbf{x} \in \mathbf{X}} \quad \Pi(\mathbf{p}, \mathbf{x}) = \sum_{j \in J} \sum_{i \in I} x_{i,j} \Pi_{i,j}(p_{i,j})$$

$$\text{subject to} \quad \Gamma(\mathbf{p}, \mathbf{x}) = \sum_{j \in J} \sum_{i \in I} x_{i,j} \Gamma_{i,j}(p_{i,j}) \leq \beta,$$

where $\mathbf{P} = (\mathbf{P}_1, \ldots, \mathbf{P}_n)$, $\mathbf{X} = (\mathbf{X}_1, \ldots, \mathbf{X}_n)$, $\mathbf{P}_j = \{\mathbf{p}_j \in \mathbb{R}^m | p_{i,j} \leq \frac{Q_j}{\epsilon_j}\}$, and $\mathbf{X}_j = \{\mathbf{x}_j \in \mathbb{R}^m | x_{i,j} \in \{0,1\}, \ \forall i \in I, \sum_{i \in I} x_{i,j} = 1\}$ for $j \in J$. Note that $\Pi(\mathbf{p}, \mathbf{x})$ and $\Gamma(\mathbf{p}, \mathbf{x})$ are nonlinear, so it is a nonlinear problem.

Special case: Cost-minimization model If the sales price and quantity are fixed for all products (on the medium-long term), then the problem reduces to selecting the mode for each product that minimizes costs given the overall emission constraint. Let q_j denote the sales quantity for product j, which is independent of the mode used. The revenue for product j is then fixed and the only costs that are impacted by the transport mode decision are the logistics cost. Hence, the objective function is the total costs per time unit, denoted by $C_{i,j}$ for product j and mode i:

$$C_{i,j} = q_j(c_i d_{i,j} w_j + h k_j l_{i,j}) \tag{3}$$

and the corresponding emissions are $\Gamma_{i,j} = q_j e_{i,j}$. The problem formulation in the cost-minimization model follows directly from Equation (3) and Problem (P).

3.2 Lagrangian relaxation

Problem (P) is a special type of a knapsack problem, an assignment problem, i.e. for each product one transport mode is assigned (Fisher, 1981). We decompose this problem into multiple single-product problems by Lagrange relaxation. In Lagrange relaxation, a penalty cost is introduced for violation of the constraint. The Lagrangian function for Problem (P) is defined as

$$L(\mathbf{p}, \mathbf{x}, \lambda) = \sum_{j \in J} \left(\sum_{i \in I} x_{i,j} \Pi_{i,j}(p_{i,j}) \right) - \lambda \left(\sum_{j \in J} \left(\sum_{i \in I} x_{i,j} \Gamma_{i,j}(p_{i,j}) \right) - \beta \right), \tag{4}$$

where $\lambda \geq 0$ is the Lagrange multiplier. Since the profit and emission function are separable in j as are the implicit constraints $((\mathbf{p}, \mathbf{x}) \in (\mathbf{P}, \mathbf{X}))$, the Lagrangian is also. Hence, we rewrite the Lagrangian as:

$$L(\mathbf{p}, \mathbf{x}, \lambda) = \sum_{j \in J} L_j(\mathbf{p}_j, \mathbf{x}_j, \lambda) + \lambda \beta, \tag{5}$$

where

$$L_j(\mathbf{p}_j, \mathbf{x}_j, \lambda) = \sum_{i \in I} x_{i,j} \Pi_{i,j}(p_{i,j}) - \lambda \sum_{i \in I} x_{i,j} \Gamma_{i,j}(p_{i,j}) \tag{6}$$

is the *decentralized Lagrangian* for product j. Note that the Lagrangians are only connected by a single multiplier λ of the emission constraint.

For a given value of λ let $(\mathbf{p}_j^*(\lambda), \mathbf{x}_j^*(\lambda))$ denote the solution that maximizes the decentralized Lagrangian of product j over $(\mathbf{p}_j, \mathbf{x}_j) \in (\mathbf{P}_j, \mathbf{X}_j)$. Then the solution $(\mathbf{p}^*(\lambda), \mathbf{x}^*(\lambda))$, where $\mathbf{p}^*(\lambda) = (\mathbf{p}_1^*(\lambda), \ldots, \mathbf{p}_m^*(\lambda))$ and $\mathbf{x}^*(\lambda) = (\mathbf{x}_1^*(\lambda), \ldots, \mathbf{x}_m^*(\lambda))$ maximizes the Lagrangian over $(\mathbf{p}, \mathbf{x}) \in (\mathbf{P}, \mathbf{X})$ for that value of λ.

If $\beta = \Gamma(\mathbf{p}^*(\lambda), \mathbf{x}^*(\lambda))$, then, by the *Everett result* (Everett, 1963), $(\mathbf{p}^*(\lambda), \mathbf{x}^*(\lambda))$ is the optimal solution to Problem (P) and the constraint will be met with equality. By varying, the value of λ we obtain different optimal solutions to problem (P) for specific values of β. It follows from Theorem 1 in Fox (1966) that these solutions are efficient solutions for problem (Q):

$$(Q) \quad \max_{\mathbf{p} \in \mathbf{P}, \mathbf{x} \in \mathbf{X}} \quad \Pi(\mathbf{p}, \mathbf{x})$$
$$\min_{\mathbf{p} \in \mathbf{P}, \mathbf{x} \in \mathbf{X}} \quad \Gamma(\mathbf{p}, \mathbf{x}).$$

The decentralized Lagrangian can be separated further in mode i, because it is separable and only connected by the implicit constraint $((\mathbf{p}_j, \mathbf{x}_j) \in (\mathbf{P}_j, \mathbf{X}_j))$. We denote this function by $L_{i,j}(p_{i,j}, \lambda)$: $L_{i,j}(p_{i,j}, \lambda) = \Pi_{i,j}(p_{i,j}) - \lambda \Gamma_{i,j}(p_{i,j})$. The decentralized Lagrangian can then be rewritten as follows, which follows directly from Equation (6):

$$L_j(\mathbf{p}_j, \mathbf{x}_j, \lambda) = \sum_{i \in I} x_{i,j} \left(\Pi_{i,j}(p_{i,j}) - \lambda \Gamma_{i,j}(p_{i,j}) \right) = \sum_{i \in I} x_{i,j} L_{i,j}(p_{i,j}, \lambda). \tag{7}$$

Solving the Lagrangean relaxation of Problem (P) is then done in time proportional to nm by evaluating $\max_{i \in I, p_{i,j} \leq \frac{Q_j}{\epsilon_j}} L_{i,j}(p_{i,j}, \lambda)$ for each j and setting the associated $x_{i,j} = 1$ and the remaining $x_{i,j}$ to zero (Fisher, 1981).

4 Analysis

To determine the optimal solution of the Lagrange relaxation of Problem (P), we exploit the special structure of the decentralized Lagrangian. We first solve the pricing problem for a given product and transport mode in Section 4.1. The result of the pricing problem, allows us to solve the mode allocation problem for a given product, which is described in Section 4.2. The structure of the decentralized Lagrangian enables us to derive two conditions that a transport mode should meet to maximize the decentralized Lagrangian for a given product for at least one value of the Lagrange parameter, this is presented in Section 4.3. Then, in Section 4.4 we describe the impact of emission reduction on sales price and profit (i.e. the triple bottom line: people, planet and profit). Lastly, we combine the results on product level to determine the solution to the Lagrangian relaxation of problem (P) in Section 4.5.

4.1 The pricing problem

Function $L_{i,j}(p_{i,j}, \lambda)$ is derived from Equation (1), (2), and (7):

$$L_{i,j}(p_{i,j}, \lambda) = \epsilon_j \left(-p_{i,j}^2 + p_{i,j} \left(u_{i,j} + \lambda e_{i,j} + k_j + \frac{Q_j}{\epsilon_j} \right) \right) - Q_j(u_{i,j} + \lambda e_{i,j} + k_j), \tag{8}$$

where $u_{i,j} := hk_j l_{i,j} + c_i d_{i,j} w_j$ which represents the logistics cost. It is observed that $L_{i,j}(p_{i,j}, \lambda)$ is concave in $p_{i,j}$. Let $p_{i,j}^*(\lambda)$ maximize $L_{i,j}(p_{i,j}, \lambda)$, then:

$$
\begin{aligned}
p_{i,j}^*(\lambda) &= \min\{\tfrac{1}{2}\left(u_{i,j} + \lambda e_{i,j} + k_j + \tfrac{Q_j}{\epsilon_j}\right), \tfrac{Q_j}{\epsilon_j}\}, \\
q_{i,j}(p_{i,j}^*(\lambda)) &= \max\left\{\tfrac{1}{2}\left(Q_j - \epsilon_j(u_{i,j} + \lambda e_{i,j} + k_j)\right), 0\right\}.
\end{aligned}
\tag{9}
$$

The optimal sales price (sales quantity) is increasing (decreasing) in h, k_j, $l_{i,j}$, c_i, $d_{i,j}$, and w_j. The optimal sales price and quantity are decreasing as a function of ϵ_j and increasing as a function of Q_j. The smallest value of λ for which the constraint on the sales price is binding is $\hat{\lambda}_{i,j} := \frac{1}{e_{i,j}}\left(\frac{Q_j}{\epsilon_j} - k_j - u_{i,j}\right)$. We typically assume that $\hat{\lambda}_{i,j} > 0$ (or $u_{i,j} < \frac{Q_j}{\epsilon_j} - k_j$) to avoid trivial cases. The corresponding maximum value is denoted by $L_{i,j}^*(\lambda) := L_{i,j}(p_{i,j}^*(\lambda), \lambda)$.

$$
L_{i,j}^*(\lambda) = \begin{cases} \frac{1}{4}\left(\epsilon_j(z_{i,j}(\lambda) + k_j)^2 - 2Q_j(z_{i,j}(\lambda) + k_j) + \frac{Q_j^2}{\epsilon_j}\right) & \text{if } 0 \leq \lambda \leq \hat{\lambda}_{i,j}, \\ 0 & \text{otherwise,} \end{cases}
\tag{10}
$$

where $z_{i,j}(\lambda) := u_{i,j} + \lambda e_{i,j}$.

Remark 1 The function $L_{i,j}^*(\lambda)$ is convex in $z_{i,j}(\lambda)$ and attains its minimum for $z_{i,j}(\lambda) = \frac{Q_j}{\epsilon_j} - k_j$, or $\lambda_{i,j} = \hat{\lambda}_{i,j}$. As a result, $L_{i,j}^*(\lambda)$ is nonincreasing on the domain of λ, i.e. it is decreasing for $\lambda \in [0, \frac{Q_j}{\epsilon_j} - k_j)$ and constant for $\lambda \in [\frac{Q_j}{\epsilon_j} - k_j, \infty)$.

Since the optimum sales quantity is 0 for $\lambda \geq \hat{\lambda}_{i,j}$, the optimum profit and emissions are also 0. From the expressions, it can be seen that a tighter emission constraint, i.e. an increase of λ, results in an increase in the optimal price and a decrease in optimal demand, profit and emissions. This is caused by the fact that an emission reduction for product j and mode i is realized by selling less products at a higher price.

4.2 The assignment problem

In this section we describe the solution that maximizes the decentralized Lagrangian of product j: determine the mode that maximizes $L_j(\mathbf{p}_j, \mathbf{x}_j, \lambda)$ given the value of λ and the optimal sales prices $\mathbf{p}_j^*(\lambda)$. For a given λ, only the value of $z_{i,j}(\lambda)$ determines the differences in the values of $L_{i,j}^*(\lambda)$ for different modes of product j. This implies that we are indifferent between selecting a product with lower logistics cost and higher emissions, and higher logistics cost and lower emissions, if the values of $z_{i,j}(\lambda)$ for the two modes are equal. Consider two modes: $y_1, y_2 \in I$. Using the result in Remark 1 we find that $z_{y_1,j}(\lambda) \leq z_{y_2,j}(\lambda) \iff L_{y_1,j}^*(\lambda) \geq L_{y_2,j}^*(\lambda)$ for $0 \leq z_{y_1,j}(\lambda), z_{y_2,j}(\lambda) \leq \frac{Q_j}{\epsilon_j} - k_j$.

For a given λ, let $I^j(\lambda)$ be defined as the set of modes for product j for which the optimal sales quantity is nonzero, i.e. $I^j(\lambda) = \{i \in I | \hat{\lambda}_{i,j} \geq \lambda\}$. Consider $\mathbf{p}_j^*(\lambda)$ and $\mathbf{x}_j \in \mathbf{X}_j$, then $L_j(\mathbf{p}_j^*(\lambda), \mathbf{x}_j, \lambda)$ can be rewritten as follows, using Equation (7) and (10):

$$
L_j(\mathbf{p}_j^*(\lambda), \mathbf{x}_j, \lambda) = \begin{cases} \frac{1}{4}\left(\epsilon_j(z_j(\lambda, \mathbf{x}_j) + k_j)^2 - 2Q_j(z_j(\lambda, \mathbf{x}_j) + k_j) + \frac{Q_j^2}{\epsilon_j}\right) & \text{if } |I^j(\lambda)| \neq \emptyset, \\ 0 & \text{otherwise,} \end{cases}
\tag{11}
$$

where $z_j(\lambda, \mathbf{x}_j) = \sum\limits_{i \in I^j(\lambda)} x_{i,j} z_{i,j}(\lambda)$ for $\mathbf{x}_j \in \mathbf{X}_j$. Let $L_j^*(\lambda) := L_j(\mathbf{p}_j^*(\lambda), \mathbf{x}_j^*(\lambda), \lambda)$. In the following proposition we define the allocation vector $\mathbf{x}_j$ that maximizes the decentralized Lagrangian for a given value of λ, using Equation (11) and the fact that it is decreasing in $z_j(\lambda, \mathbf{x}_j)$.

Proposition 1 Consider product $j \in J$ and $\lambda \geq 0$. Mode y maximizes the decentralized Lagrangian, $L_j^*(\lambda) = L_{y,j}^*(\lambda)$ and $x_{y,j} = 1$ for $y = \text{argmin}(z_{i,j}(\lambda) : i \in I^j(\lambda))$.

So, the transport mode that has the lowest value for $u_{i,j} + \lambda e_{i,j}$, maximizes $L_j(\mathbf{p}_j^*(\lambda), \mathbf{x}_j, \lambda)$. When mode y maximizes $L_j(\mathbf{p}_j^*(\lambda), \mathbf{x}_j, \lambda)$, we state that mode y is the preferred mode. We note that, allowing multiple modes to be used per product would not affect the optimal solution compared to the current model, because one mode is preferred for a given value of λ, as long as the demand is deterministic.

Special case: cost-minimization In the cost-minimization model the decentralized Lagrangian follows from Equation (3) and (7):

$$L_j'(\mathbf{x}_j, \lambda) = \sum_{i \in I} x_{i,j} q_j (u_{i,j} + \lambda e_{i,j}).$$

Minimizing the decentralized Lagrangian over $\mathbf{x}_j \in \mathbf{X}_j$ is equivalent to selecting the mode that minimizes $z_{i,j}(\lambda)$ and the results for the profit-maximization model apply. Note that $\hat{\lambda}_{i,j}$ is not defined since q_j is fixed.

4.3 Conditions

Proposition 1 states that for product j the mode that minimizes $z_{i,j}(\lambda)$ maximizes the decentralized Lagrangian, i.e. mode i is preferred for λ. We now derive two conditions on the logistics cost $(u_{i,j})$ and the emissions $(e_{i,j})$ that determine whether mode i is preferred for product j for any value of λ. Let the subset of transport modes that maximize $L_j(\mathbf{p}_j, \mathbf{x}_j, \lambda)$ for at least one value of λ for product j be denoted by $\mathcal{I}^j = \{1, \ldots, |I^j|\}$. Note that mode 1 for product j_1 may be a different mode than mode 1 for product j_2 (we choose this notation for brevity).

Remark 2 It is easily observed that the mode that minimizes the total logistics cost for product j is preferred for small values of λ, i.e. at least for $\lambda = 0$.

For larger values of λ switches occur to more expensive and less polluting modes. We introduce a running example to illustrate the procedure of determining the preferred modes.

Example *Consider $J = \{a, b\}$ and $I = \{1, 2, 3, 4, 5, 6\}$, and the following parameter values: $Q_a = 100, Q_b = 80, \epsilon_a = 1.25, \epsilon_b = 1.10, k_a = 15, k_b = 6$. The logistics cost and unit emissions for each mode and product are given in Table 1.*

Table 1: *Parameter values for logistics cost and unit emissions*

Mode i	1	2	3	4	5	6
$e_{i,a}$	1.00	0.80	0.60	0.55	0.25	0.10
$u_{i,a}$	5	10	13	20	30	50
$e_{i,b}$	2.00	1.90	1.91	1.25	1.20	0.90
$u_{i,b}$	10	12	15	20	21	25

Consider two modes y_1 and y_2 ($y_1, y_2 \in I$) and assume w.l.o.g. $u_{y_1,j} \le u_{y_2,j}$. We define λ_{y_1,y_2}^j such that $L_{y_1,j}^*(\lambda_{y_1,y_2}^j) = L_{y_2,j}^*(\lambda_{y_1,y_2}^j)$ (and $z_{y_1,j}(\lambda_{y_1,y_2}^j) = z_{y_2,j}(\lambda_{y_1,y_2}^j)$), then:

$$\lambda_{y_1,y_2}^j := \frac{u_{y_1,j} - u_{y_2,j}}{e_{y_2,j} - e_{y_1,j}} = \frac{hk_j(l_{y_1,j} - l_{y_2,j}) + w_j(c_{y_1}d_{y_1,j} - c_{y_2}d_{y_2,j})}{w_j(a_{y_2} - a_{y_1} + b_{y_2}d_{y_2,j} - b_{y_1}d_{y_1,j})}. \tag{12}$$

Equation (12) represents a threshold value of λ such that mode y_1 is preferred over mode y_2 for λ values less than the threshold value or vice versa. The order of the values of λ_{y_1,y_2}^j, $\hat{\lambda}_{y_1,j}$, and $\hat{\lambda}_{y_2,j}$ determines whether mode y_2 is preferred or not, which is determined by the threshold value for $e_{y_2,j}$ in the following theorem.

Theorem 1 Consider $y_1, y_2 \in I$ and $u_{y_1,j} < u_{y_2,j}$.
a If $\tilde{e}_{y_1,y_2}^j < e_{y_1,j} < e_{y_2,j}$, then $\lambda_{y_1,y_2}^j < 0 < \hat{\lambda}_{y_2,j} < \hat{\lambda}_{y_1,j}$ and
$z_{y_1,j}(\lambda) \le z_{y_2,j}(\lambda)$ for $\lambda \in [0, \infty)$.
b If $\tilde{e}_{y_1,y_2}^j < e_{y_2,j} < e_{y_1,j}$, then $\hat{\lambda}_{y_2,j} < \hat{\lambda}_{y_1,j} < \lambda_{y_1,y_2}^j$ and
$z_{y_1,j}(\lambda) \le z_{y_2,j}(\lambda)$ for $\lambda \in [0, \lambda_{y_1,y_2}^j]$ and $z_{y_1,j}(\lambda) \ge z_{y_2,j}(\lambda)$ for $\lambda \in [\lambda_{y_1,y_2}^j, \infty)$.
c If $e_{y_2,j} \le \tilde{e}_{y_1,y_2}^j \le e_{y_1,j}$, then $\lambda_{y_1,y_2}^j \le \hat{\lambda}_{y_1,j} \le \hat{\lambda}_{y_2,j}$ and
$z_{y_1,j}(\lambda) \le z_{y_2,j}(\lambda)$ for $\lambda \in [0, \lambda_{y_1,y_2}^j]$ and $z_{y_1,j}(\lambda) \ge z_{y_2,j}(\lambda)$ for $\lambda \in [\lambda_{y_1,y_2}^j, \infty)$.
Where

$$\tilde{e}_{y_1,y_2}^j = e_{y_1,j}\frac{\frac{Q_j}{\epsilon_j} - k_j - u_{y_2,j}}{\frac{Q_j}{\epsilon_j} - k_j - u_{y_1,j}} \tag{13}$$

Proof:
PROOF: *In Section A.1.* □

The threshold value of Equation (13) represents the case that $\hat{\lambda}_{y_1,j} = \hat{\lambda}_{y_2,j}$. For simplicity assume for now that only mode y_1 and y_2 are available for product j, then Theorem 1 gives us the following insight: One out of three possible scenarios applies. First, if the emissions of mode y_2 are also larger than those of mode y_1, then mode y_2 is not a preferred mode. Second, if the emissions of mode y_2 are smaller than those of mode y_1 but not small enough ($e_{y_2,j} > \tilde{e}_{y_1,y_2}^j$), then it is more profitable to reduce emissions by selling less units, shipped with mode y_1, than to ship products with mode y_2. Lastly, if the emissions of mode y_2 are small enough, then there is a range of λ values ($\lambda \in [\lambda_{y_1,y_2}^j, \infty)$) such that mode y_2 is preferred over mode y_1. If mode y_2 is preferred, then it meets the emission constraints of Equation (13) for all other modes.

Condition 1 Non-dominance Consider mode $y_2 \in I$. Then if $\exists y_1 \in I$ such that $u_{y_1,j} < u_{y_2,j}$ and $e_{y_2,j} > \tilde{e}_{y_1,y_2}^j$, then $y_2 \notin \mathcal{I}^j$.

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Example *In Table 3 in Appendix A.2 the threshold values for all pairs of modes are given. For product 'a' this implies that mode 4 is excluded since $e_{4,a} > \tilde{e}^a_{3,4}$, case b of Theorem 1. For product 'b' mode 3 is excluded since $e_{4,b} > e_{3,b}$ (and $u_{4,b} > u_{3,b}$), case c of Theorem 1.*

In addition, if mode i performs better (in terms of $z_{i,j}(\lambda)$ value) than any combination of two preferred modes, then mode i is preferred, which is specified in the following theorem.

Theorem 2 Consider $y_1, y_2, y_3 \in I$ for product j such that $u_{y_1,j} < u_{y_2,j} < u_{y_3,j}$ and
$e_{y_1,j} > e_{y_2,j} > e_{y_3,j}$.
a If $e_{y_2,j} \geq \bar{e}^j_{y_2}(y_1, y_3)$, transport mode y_2 is not preferred for any $\lambda \geq 0$
    $(z_{y_2,j}(\lambda) \geq \min\{z_{y_1,j}(\lambda), z_{y_3,j}(\lambda)\}$ for $\lambda \geq 0)$,
b If $e_{y_2,j} \leq \bar{e}^j_{y_2}(y_1, y_3)$, transport mode y_2 is preferred over mode y_1 and y_3 for $\lambda \in [\lambda^j_{y_1,y_2}, \lambda^j_{y_2,y_3}]$,
where

$$\bar{e}^j_{y_2}(y_1, y_3) = e_{y_1,j} + (e_{y_3,j} - e_{y_1,j})\frac{u_{y_1,j} - u_{y_2,j}}{u_{y_1,j} - u_{y_3,j}}. \tag{14}$$

Proof:
PROOF: *In Section A.1.* □

Remark 3 Note that Theorem 2 does not apply to the mode that maximizes $u_{i,j}$ of all modes that meet Condition 1: this mode is denoted by $|I^j|$. It follows from Theorem 1 that $\hat{\lambda}_{|I^j|,j}$ is largest for this particular mode, which implies that this mode is preferred for at least one value of λ and hence in $|I^j| \in \mathcal{I}^j$.

In the next lemma we derive the ordering of the threshold values of Equation (13) and (14).

Proposition 2 If $y_1, y_2, y_3 \in I$ for product j such that $u_{y_1,j} < u_{y_2,j} < u_{y_3,j}$ and $e_{y_3,j} < \tilde{e}^j_{y_1,y_3}$, then $\bar{e}^j_{y_2}(y_1, y_3) < \tilde{e}^j_{y_1,y_2}$.

Proof:
PROOF: *In Section A.1.* □
Proposition 2 implies that if y_3 meets the condition in Theorem 1, then the threshold value in Equation (14) is tighter than the threshold value in Equation (13). If the emissions of mode y_2 are small enough, $e_{y_2,j} \leq \bar{e}^j_{y_2}(y_1, y_3)$, then there is a range of λ values for which $z_{y_2,j}(\lambda) \geq \min\{z_{y_1,j}(\lambda), z_{y_3,j}(\lambda)\}$. If for all pairs y_1, y_3 there exists such a range of λ, then mode y_2 is preferred.

Condition 2 Superefficiency Consider mode $y_2 \in I$ and any $y_1, y_3 \in \mathcal{I}^j$ and $u_{y_1,j} < u_{y_2,j} < u_{y_3,j}$ and $e_{y_2,j} < \tilde{e}^j_{y_1,y_2}$ and $e_{y_3,j} < \tilde{e}^j_{y_2,y_3}$. If $e_{y_2,j} \leq \bar{e}^j_{y_2}(y_1, y_3)$, $y_2 \in \mathcal{I}^j$.

Example *Mode 1 and 6 are preferred for both products. It remains to determine whether mode 2, 3 and 5 are preferred for product a and mode 2, 4 and 5 are preferred for product b. We calculate $\bar{e}^j_{y_2}(y_1, y_3)$ for any combination of y_1 and y_3, which are given in Table 4 in Appendix A.2. E.g. for*

mode 2 of product a we calculate $\bar{e}_2^a(1,3), \bar{e}_2^a(1,5), \bar{e}_2^a(1,6)$. *Mode 2 is excluded since* $e_{2,a} > \bar{e}_2^a(1,3)$. *For product b mode 3 and 5 are excluded* $(e_{3,b} > \bar{e}_3^b(1,4)$ *and* $e_{5,b} > \bar{e}_5^b(4,6))$.

Recall that $\mathcal{I}^j := \{1, \ldots, |I^j|\}$ denotes the set of all modes that meet the requirements specified in Condition 1, and 2. Assume w.l.o.g. that the modes are ordered in increasing values of $u_{i,j}$ (and by decreasing (increasing) values of $e_{i,j}$ ($\hat{\lambda}_{i,j}$), which follows from Theorem 1). Let $\lambda_{\max}^j$ be defined as the smallest value of λ such that the optimal emissions of product j are 0 (because nothing is shipped), hence, $\lambda_{\max}^j = \hat{\lambda}_{|I^j|,j}$.

Let $\Lambda^j = \{\lambda_{1,2}^j, \cdots, \lambda_{|I^j|-1,|I^j|}^j, \lambda_{\max}^j\}$ denote the solution to the assignment problem for product j: $x_{ij} = 1$ for $\lambda \in [\lambda_{i-1,i}^j, \lambda_{i,i+1}^j]$ for $i \in \{1, \ldots, |I^j|\}$, where $\lambda_{0,1}^j = 0$ and $\lambda_{|I^j|,|I^j|+1}^j = \infty$.

Example *We find the following two sets of preferred modes and vectors:* $\mathcal{I}^a = \{1,3,5,6\}$ *and* $\mathcal{I}^b = \{1,4,6\}$, *and* $\Lambda^a = (25.0, 48.6, 133.3, 150.0)$ *and* $\Lambda^b = (13.3, 14.3, 46.4)$.

Special case: cost-minimization The results presented in this section also hold for the cost-minimization case with two exceptions. First, Condition 1 is less strict for the cost-minimization model. For mode $y_1, y_2 \in I$ $L'_{y_1,j}(\lambda)$ dominates $L'_{y_2,j}(\lambda)$ for the domain of λ if and only if $u_{y_1,j} < u_{y_2,j}$ and $e_{y_1,j} < e_{y_2,j}$, which corresponds with case a of Theorem 1. This results follows since $L'_{i,j}(\lambda)$ is linear in $z_{i,j}(\lambda)$. Second, $\lambda_{\max}^j$ is not defined since a positive quantity is sold for any $\lambda \geq 0$.

The expression for λ_{y_1,y_2}^j (Equation (12)) provides us with a number of insights, which we formulate in the following proposition.

Proposition 3 Consider two identical products j_1 and j_2 and two transport modes $i, i+1 \in \mathcal{I}^j$ and $e_{i,j} > e_{i+1,j}$.
a) Assume that j_1 and j_2 only differ in terms of weight, i.e. $w_{j_1} > w_{j_2}$. From Equation (12) it follows that for the heavy product (product j_1) a switch to mode $i+1$ occurs for a smaller emission reduction target (for smaller values of λ) than for product j_2. So for heavier products cleaner and more expensive modes are used for smaller emission reductions.
b) The opposite result holds when the products only differ in terms of unit cost $(k_{j_1} > k_{j_2})$, the more polluting mode (mode i) is used for a lower value of the emission target, because inventory is more expensive for product j_1.
c) Assume that the modes only differ in terms of $u_{i,j}$ values: $u_{i+1,j_1} < u_{i+1,j_2}$ $(u_{i,j_1} < u_{i+1,j_1})$, either due to smaller lead time and/or distance. Then it holds that $\lambda_{i,i+1}^{j_1} < \lambda_{i,i+1}^{j_2}$, which implies that for product j_1 the switch to a less polluting mode is done for a more strict emission reduction target.
d) The opposite result holds when $e_{i+1,j_1} > e_{i+1,j_2}$ $(e_{i,j_1} > e_{i+1,j_1})$: mode $i+1$ is preferred for product j_1 for a less strict emission reduction target.

Moreover, modes with lower emissions and higher logistics cost may not be preferred for higher values of the unit cost and weight of the product due to Condition 1. In that case part of the

emission reductions are realized by selling fewer products instead of using less polluting transport modes.

We have developed a solution procedure that generates for specific values of the emission constraint the assignment of modes to products that maximizes the decentralized Lagrangian. Note that this procedure can also be used in the situation that a carbon or fuel tax is added for transport and the transport cost of the shippers increase by a factor proportional to the emissions allocated to one unit of the product.

4.4 People, Planet, and Profit

In this section we examine the interactions between planet, people, and profit (the triple bottom line), i.e. the total emissions, the sales price, and the profit. Consider modes $i, i+1 \in \mathcal{I}^J$ and $u_{i,j} < u_{i+1,j}$ $(e_{i,j} > e_{i+1,j})$.

Planet The total emissions associated with $q_{i,j}(p_{i,j}^*(\lambda))$, mode i, and product j are denoted by $\Gamma_{i,j}^*(\lambda)$:

$$\Gamma_{i,j}^*(\lambda) = \frac{1}{2} e_{i,j} \left(Q_j - \epsilon_j(u_{i,j} + \lambda e_{i,j} + k_j) \right).$$

Now consider $\Gamma_j^*(\lambda) = \Gamma_{i,j}^*(\lambda)$ for $i = argmin\{z_{i,j}(\lambda)|i \in \mathcal{I}^j\}$. When a switch occurs from mode i to $i+1$, i.e. $\lambda = \lambda_{i,i+1}^j$, then $z_{i,j}(\lambda) = z_{i+1,j}(\lambda)$, but $\Gamma_{i,j}^*(\lambda) > \Gamma_{i+1,j}^*(\lambda)$ since $e_{i,j} > e_{i+1,j}$. Hence, a switch from mode i to mode $i+1$ results in a decrease in total emissions. This implies that not for every value of the emissions Γ_j, say α, there exists a value of λ such that $\alpha = \Gamma_j^*(\lambda)$.

People Recall the expression for the sales price as a function of λ for a given product j and mode i: $p_{i,j}^*(\lambda) = \frac{1}{2} \epsilon_j \left(u_{i,j} + \lambda e_{i,j} + k_j + \frac{Q_j}{\epsilon_j} \right)$. Let the total emissions $(\Gamma_{i,j}^*)$ be α, then

$$p_{i,j}^*(\alpha) = Q_j - \frac{\alpha}{e_{i,j}}.$$

The equation follows from using λ, as a function of α, as input. It follows that for a given product and mode, $p_{i,j}^*$ is linearly decreasing in α (increasing in emission reductions), i.e. the price is highest when the emissions are 0. This implies that the rate of increase is increasing when switching from mode i to $i+1$, since $e_{i,j} > e_{i+1,j}$.

Profit The realized profit associated with $p_{i,j}^*(\lambda)$, mode i and product j is denoted by $\Pi_{i,j}^*(\lambda)$:

$$\Pi_{i,j}^*(\lambda) = \frac{1}{4} \left(\frac{1}{\epsilon_j} (Q_j - \epsilon_j(u_{i,j} + k_j))^2 - \epsilon_j(e_{i,j})^2 \lambda^2 \right).$$

Let $\bar{\lambda}_{i,i+1}^j$ be defined such that $\Pi_{i,j}^*(\bar{\lambda}_{i,i+1}^j) = \Pi_{i+1,j}^*(\bar{\lambda}_{i,i+1}^j)$:

$$\bar{\lambda}_{i,i+1}^j = \sqrt{\frac{u_{i+1,j} - u_{i,j}}{e_{i,j} - e_{i+1,j}} \frac{2(\frac{Q_j}{\epsilon_j} - k_j) - (u_{i,j} + u_{i+1,j})}{e_{i,j} + e_{i+1,j}}}$$

Proposition 4 Consider $i, i+1 \in \mathcal{I}^j$, then $\bar{\lambda}_{i,i+1}^j \geq \lambda_{i,i+1}^j$.

Proof:

PROOF: *In Section A.1.* □

This proposition implies that for $\lambda = \lambda_{i,i+1}^{j}$ $\Pi_{i,j}^{*}(\lambda) \geq \Pi_{i+1,j}^{*}(\lambda)$. Hence, a switch from mode i to mode $i+1$ results in a decrease in profit. Let the total emissions $(\Gamma_{i,j}^{*})$ be α then

$$\Pi_{i,j}^{*}(\alpha) = \frac{1}{e_{i,j}}\left(\alpha\left(\frac{Q_j}{\epsilon_j} - (u_{i,j} + k_j)\right) - \frac{1}{\epsilon_j e_{i,j}}\alpha^2\right).$$

From this equation, it follows that $\Pi_{i,j}^{*}$ is quadratic and increasing in α (decreasing in emission reductions) for a given product and mode. So there is a diminishing rate of return, i.e. emission reductions become increasingly costly. This also implies that for low values of emission reduction, the solution (in terms of profit and sales price) is relatively insensitive but as the constraint tightens (the reduction increases) the solution becomes more sensitive.

Example *For product a and b the sales price and profit as a function of the emission reduction (relative to the emissions in the case of no reduction) is given in Figure 1. Note that a 'gap' in the graph is caused by a switch from one mode to another. As described before, it can be seen that the sales price (profit) is piecewise linearly increasing (quadratically deceasing) in the emission reduction for each mode, where it is defined.. The sales price and profit for product a (or b) is also linear and quadratic in the sales price and profit, respectively.*
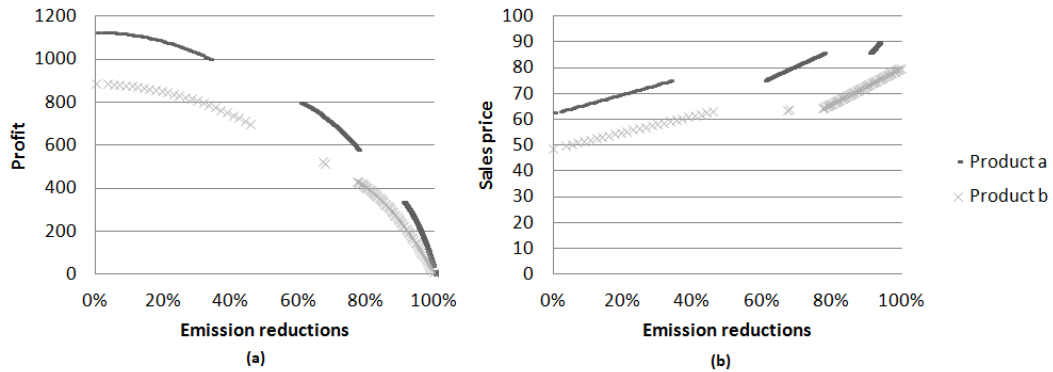
Figure 1: Profit (a) and sales price (b) as a function of emission reductions

4.5 Overall mode selection

Combining the solutions to the decentralized Lagrangians results in efficient solutions to Problem (Q), which are denoted by Λ ($\Lambda = \{\Lambda^1, \Lambda^2, \cdots, \Lambda^n\}$). The efficient solutions to Problem (Q) can then be determined as follows: Let Λ' denote set Λ in which all elements are ordered in increasing values. The solution for $\lambda = 0$ is to select mode 1 for all products. The minimum of $\lambda_{1,2}^{j}$ (or the first element of Λ') denotes the lowest value of λ such that mode 1 is selected for all products but one for which mode 2 is selected. Continuing in the same fashion, the result is a set of transport mode allocations for the range of λ. These solutions can then be used to determine the total profit

and emissions. The solution to Problem (P) can be found from the efficient solutions to Problem (Q).

Example *The efficient solutions to Problem (Q) for the example are displayed in Figure 2. The solutions are distinguished for the seven different combinations (in terms of modes selected for each product). The notation 6* refers to the fact that no units of product b are sold. Note that also the combined profit for both products is quadratic in the total emissions reduction where it is defined. As a result, the solution is increasingly sensitive to the emission reduction. It is expected that the gaps decrease when the number of products increases, since each single products contributes a smaller part of the total emissions.*
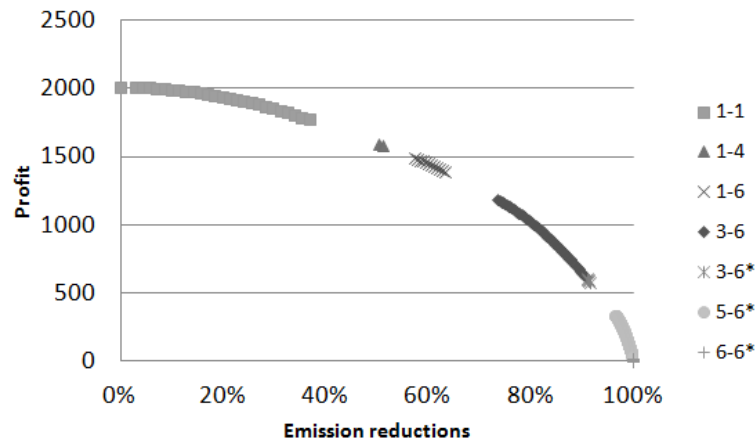
Figure 2:   Solutions to Problem (Q)

5   Case study

In this section we apply our method to a real life case study. The case applies to a few products of Cargill in Europe, which are food ingredients that are supplied to the food industry in dedicated containers. Cargill decided to cap the emissions from transport by shifting away from road (or ferry) transport to intermodal transport. In a Request for Quotation (RFQ), Third Party Logistics Providers (3PLs) were asked to provide Cargill with intermodal bids, which are used in the analysis. The emissions were calculated using the NTM methodology, which is described in Section 5.1. In Section 5.2 the results of the analysis of the case study are presented. An extension of the case study to a profit-maximization model is presented in Section 5.3.

5.1   Emission calculation

An approximate calculation methodology has to be used to calculate transport emissions, unless the fuel consumption of vehicles is known exactly. We have used the NTM methodology because it

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focuses on Europe (which is where our data applies), allows for a high level of detail and provides parameter estimates (NTM, 2011).

First, a transport modality and vehicle, plane or vessel type has to be specified. Then the emission calculation is done in two steps: first calculate the emissions for the entire vehicle and subsequently allocate the appropriate part to one unit of product, where the allocation is done based on the weight of the product. 3PLs use the volumetric weight of a product for their transport cost to account for the fact that for low-density products, the volume of the product is restricting, in contrast to the weight for heavier products. For the products we consider the weight is restricting, so we allocate emissions based on the weight. The general structure for the unit emissions is:

$$e_{i,j} = (A_i + B_i d_{i,j}) \frac{w_j}{\tilde{w}_i},$$

where A_i is the constant emission factor for the vehicle (in $tonne\ CO_2$), B_i is the variable emission factor for the vehicle (in $tonne\ CO_2/km$), and $\tilde{w}_i$ the average load of the vehicle (in $tonne$).

Data obtained from the 3PLs are the *payload* (the maximum load of a shipment), the modality type, the vehicle/vessel type, and the loading and unloading location (location of the intermodal terminal). In Appendix A.3 the required parameters and the assumptions for the emission calculation are specified.

5.2 Results

To apply the analysis we require the transport cost, lead time, (both are obtained from the 3PL), the annual demand and the unit cost of the product (obtained from Cargill), and emissions per ton of cargo per product-mode combination. The company always ships full containers, therefore the number of shipments is determined by the payload. In total the data set contains 56 products, of which the origins and destinations are all located within Europe. The 3PLs made 279 intermodal bids and the amount of bids per product varies from 0 to 14 (5 products received no intermodal bids). Multiple bids of the same modality type, e.g. rail, for one product are allowed as long as they differ in terms of lead time, transport cost, or emissions. In total 335 product-mode combinations are available, including the current modality: road or ferry for each product.

The annual demand (q_j) varied between 300 and 6,000 tonne (on average 1,500), which corresponds with 11 to 240 shipments per product per year (payload between 21 and 29 tonne). The lead time ($l_{i,j}$) is between 1 and 12 days. The transport cost per shipment ($c_{i,j}$), which takes into account the distance of the route and the weight of the shipment, expressed in normalized monetary units varies between 1 and 6.2 (on average 1.9). The distance of the product ($d_{i,j}$) varies from 300 km to 3,300 km (on average 1,150 km). A holding cost rate of 25% per year was assumed.

Five transport modality types are used: road transport, intermodal rail transport, intermodal water transport (coastal shipping or short sea), ferry transport (road transport plus a ferry crossing) and inland water transport (using rivers and/or canals). Note that ocean shipping is not taken into account since our data set is limited to locations in Europe. For the remainder of the article, we denote these modes by road, rail, short sea, ferry and inland water.

No information is available on the demand functions for each product, so we first apply the cost-minimization model to our case study and later, in Section 5.3, extend it by considering various demand functions. Applying the Lagrange relaxation has resulted in a set of efficient solutions, which are displayed in Figure 3. The solutions are expressed in terms of cost increase and emission reduction compared to minimum cost solution ($\lambda = 0$).
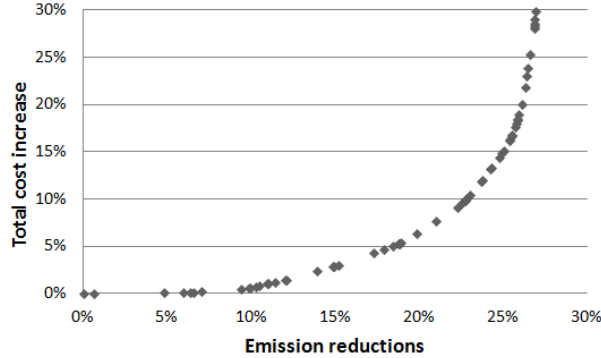

Figure 3: Emission reductions and total cost increase compared to lowest cost setting

It can be seen that the costs increase exponentially, i.e. a diminishing rate of return which is in line with our finding in Section 4.5. As a result, the curve is relatively flat for the first 10% emission reduction. A maximum emission reduction of 27% can be achieved, at a cost increase of 30%. Given the size of the total cost over all products (several million euros), this is substantial. The total emissions are in the order of several thousand tonnes per year. In this case the company can reduce emissions by 10% virtually without a cost increase (0.7%). Currently, the company is operating at a setting which has 32% higher emissions and 4% more costs than the minimum cost solution we calculated. This implies that in practice it may be expected that an emission reduction can be achieved while decreasing logistics cost.

In addition we determined the share of emissions attributable to each of the modality types for the solutions, represented by Figure 4. Note that inland water is not displayed in the graph because it is not preferred, as Condition 1 is not met. Moreover, in Table 2 the emissions per modality type are compared for the current transport allocation, the minimum-cost transport allocation and the minimum-emission transport allocation. All emissions are expressed as a share of the emissions of the minimum-cost solution. In the minimum cost solution the majority of emissions are due to road transport and rail transport is the second largest contributor. This is reduced to less than 10% in the emission-optimal solution, mainly due to a shift towards rail transport. Also note that a switch is made from ferry transport to short sea transport for 7 products. From the graphs and table can be seen that for this case study switching from road transport to rail transport provides the largest emission reduction potential.

From this case study we obtain the following insights: Firstly, in contrast with the general belief, intermodal transport is not necessarily the most cost-efficient option in meeting emission targets. In particular, we observe that for a number of products (31) road transport results in

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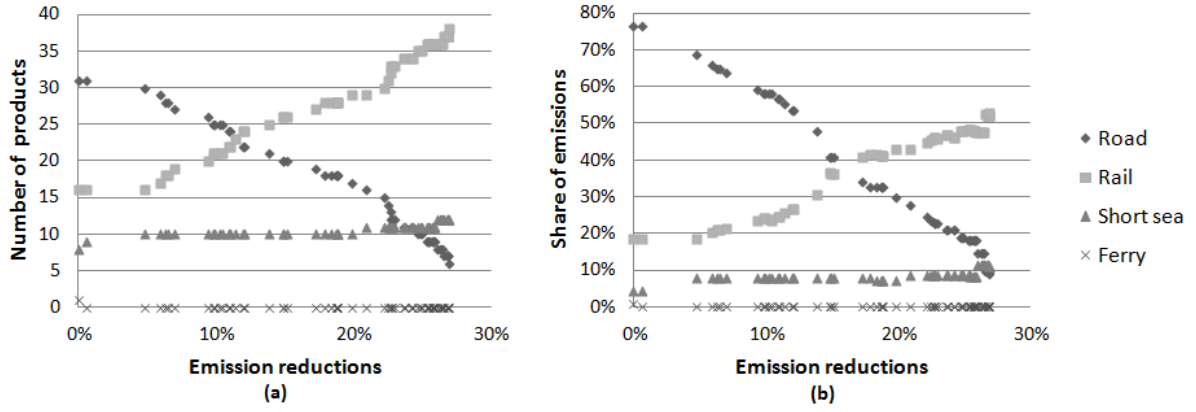
Figure 4: The share of the emission per modality types as a function of the emission reduction, both in number of products (a) and fraction of emissions (b).

Table 2: *Transport mode shares*

	Actual transport assignment		Cost-optimal transport assignment		Emission-optimal transport assignment	
	No. of products	Emission share	No. of products	Emission share	No. of products	Emission share
Road	49	123%	31	76%	6	9%
Rail	0	0%	16	19%	38	53%
Short sea	0	0%	8	4%	12	11%
Ferry	7	9%	1	1%	0	0%
Inland water	0	0%	0	0%	0	0%

lowest total logistics cost, which implies that for those particular products, although intermodal might result in lower emissions than road transport it is also more expensive. The cost difference is due to longer lead times and additional handling costs. We believe that this observation is not restricted to our case study. Secondly, we observe that for this case study the biggest emission reduction comes from shifting from road to rail transport. This finding is not generalizable because location to rail terminals and available capacity of the rail network may limit the applicability of intermodal rail transport in other cases. Nevertheless, it holds in general that emission reductions will be obtained by switching from air to road, road to rail, road to water or short sea, and rail to water or short sea.

5.3 Extension

An extension of the case study to the profit-maximization model requires the estimation of demand parameters for all products (ϵ_j and Q_j). For each product the actual demand is already given in the case study. However, the sensitivity of demand to the sales price is not available, we therefore use a number of alternatives to obtain managerial insights. We set the demand parameters such that the demand corresponds with the actual demand when $\lambda = 0$, the case without an emission

constraint. Given a value of ϵ_j, Q_j can be calculated with the following formula:

$$Q_j = 2\tilde{q}_j + \epsilon_j(k_j + u_{1,j}),$$

where $\tilde{q}_j$ is the actual demand and $u_{1,j}$ is used since mode 1 is always chosen when $\lambda = 0$. Unless stated otherwise, the value of ϵ_j is the same for all products and we remove the subscript j. For the demand function we use, the demand elasticity varies as a function of $p_{i,j}$, hence the same value of ϵ may refer to different elasticity values across products. Therefore we determine the solutions for several ϵ values ($\epsilon \in \{0.01, 1, 3\}$). We believe that this range of ϵ covers a broad range of realistic values for our data set.

We also consider two instances in which ϵ_j is non-homogenous across products. We divide the 56 products in three groups: low-demand (18), medium-demand (19), and high-demand (19) and assign the following values $\epsilon_j = 0.01$, 1, or 3, to each group respectively, which is denoted by "ϵ_j dem dep" in the graph. In the second instance, $\epsilon_j = 3$ is assigned to lanes with low demand and $\epsilon_j = 0.01$ to lanes with high demand, which is denoted by "ϵ_j dem dep v2" in the graph. Note that "ϵ_j dem dep" ("ϵ_j dem dep v2") represents a case where the majority of the business value is defined by price-elastic (inelastic) demand.

Lastly, we determine the solutions for the *item approach* for $\epsilon = 1$. In an item approach an emission constraint is set per product instead of per group of products. The solutions are denoted by "Item" in Figure 5. The profit, in relative value, as a function of the emission reduction is given for the different settings in Figure 5. The solution curves are defined up to 100% emission reduction (at a 0% profit), represented in the graph (a) in Figure 5. For most practical purposes smaller profit reductions are desirable, we therefore focus on the solutions for at most 50% emission reduction, represented in the graph (b) in Figure 5.

The absolute value of the profit for a product and mode, and as a consequence the total profit,
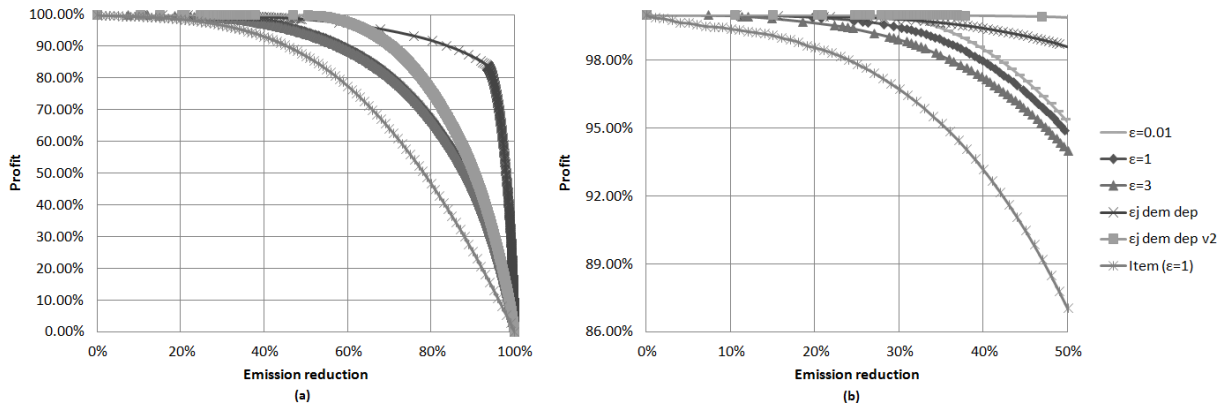
Figure 5: The profits as a function of emission reductions.

is decreasing in ϵ. When demand is less sensitive to price, higher prices can be charged. If the price elasticity is non-homogenous, then the absolute value of the total profit is smaller than when $\epsilon = 0.01$ and larger than when $\epsilon = 3$.

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From Figure 5, it can be seen that a diminishing rate of return applies similarly as in the cost-minimization case. For a 1% profit reduction, 30 to 38% emission reductions can be realized, depending on the value of ϵ, compared to 16% emission reduction when the item approach is used. For a given emission reduction target the profit reduction of the item approach vs. the aggregate approach for $\epsilon = 1$ differs up to 21% (relative to the maximum profit without emission reduction) which is substantial. We also observe that the larger ϵ, the larger the profit reduction for a given value of the total emissions because a price increase leads to relatively larger demand decrease (the differences are small though). When the price elasticity is non-homogenous, the profit reduction is smaller than for the case $\epsilon_j = 0.01$, for a given value of Γ. This is explained by the fact that the profit of the high-demand products is smaller compared to e.g. the situation in which $\epsilon = 0.01$. Emission reductions are first realized by reducing emissions for high-demand products, which leads to large emission reductions for relatively smaller profit reductions. For the "ϵ_j dem dep v2" case, the high-demand products dominate the solutions and as a consequence it resembles the $\epsilon = 0.01$ graph more.

For different levels of ϵ the set of preferred modes per product changes. As ϵ increases, $\hat{\lambda}_{i,j}$ decreases, i.e. demand is more affected by a change in price. It may be the case that mode i no longer meets condition 1, since $\tilde{e}_{i-1,i}^j$ is decreasing as a function of ϵ (the threshold value in condition 2 is not affected). In the numerical study it holds that this only occurs for mode $|I^j|$. When the high-volume demand is price-inelastic, the company can achieve emission reductions with less profit loss by switching modes and adjusting prices of high-volume product accordingly.

The value of using an aggregate approach instead of an item approach can in this case be as high as 21% of the maximum profit without emission reduction. The difference is already substantial but might be even higher when the unit cost of the products (k_j) is more diverse across products and when the total logistics cost are higher compared to the unit cost.

We also observe that the majority of the emission reductions are attributed to modal switches, rather than price adjustment. In other words, if we compare the emission reduction within a mode (i.e. for the range of λ for which that mode is preferred) to the emission reduction between modes (i.e. from a switch), the reductions between modes can be much higher, up to 80%.

From this extended case study we generate the following insights: First, large emissions reductions can be achieved at relatively small profit losses. Second, while the required profit reduction to obtain a certain emission reduction target is determined by the price-sensitivity of customers, the solutions are relatively robust the price elasticity. Finally, we find that the portfolio effect can achieve emissions reduction at at most 21% higher profits (compared to the maximum profit in the situation without emission reduction) than an item approach.

6 Conclusion

In this study, we have considered a shipper, who has outsourced all transport activities to a 3PL, wanting to determine the profit-maximizing transport mode allocation and sales price for each

product, such that an overall emission target is met. An overall emission target allows for taking advantage of the portfolio effect, i.e. the emissions are reduced where it is cheapest, which is also the idea behind an emission trading scheme.

Lagrangian relaxation is employed to solve the problem, which is separable in the products. The pricing decision can be solved separately and used as input to the transport mode selection decision. For a given product we have derived two conditions (in terms of the logistics cost and emissions) to determine which mode maximizes the profit for a certain range of the emission target. We have showed that the optimal price is linear in the total emissions and the profit is quadratic in the total emissions, for a given mode and product. This implies that a diminishing rate of return applies, i.e. emission reductions become increasingly expensive. We have observed that this also holds for the combined profit of all products.

We have applied our method to a real-life case study by considering the prices given to us by the problem owner as fixed, and we found that the transport emissions can be reduced by as much as 27%. In the profit-maximization extension of the case study we found that the emissions can be reduced by 30% for at most a 1.2% profit reduction, which does not appear to be sensitive to different price elasticity scenarios. The value of allocating the emission target to individual products in such a way that the portfolio effect is exploited rather than using the same target for individual products is very significant: For example, an emission reduction of 50% results in a profit loss of 5% using the portfolio effect, whereas the profit loss for the same reduction without using portfolio effect is 13% under the same price sensitivity.

For this data set the emission reductions are mainly achieved by switching from road transport to rail transport, due to the characteristics of the European network and the problem environment. The general belief about transportation emissions is that the cheaper a mode is, the less carbon it emits. While this intuition holds for unimodal transport in general, it is not necessarily the case for intermodal transport. In particular, our case study shows that intermodal transport is often more expensive than road transport due to longer lead times and additional handling costs associated with intermodal transport, but it results in low emissions. Hence, this demonstrates that maximizing profit does not necessarily result in minimizing emissions.

The emission reductions in the case study are achieved for relatively small profit reductions (or cost increase). In particular, a 10% emission reduction at only a 0.7% cost increase in the case study is a significant reduction given the fact that we only consider lanes within Europe (maximum distance 3,300 km) and that road transport is currently used. If the method is applied to a larger-scale case study with intercontinental transport, one can expect larger emission reductions, because switching from air to ocean freight results in an extremely substantial emission reduction. Note that for intercontinental transport the less carbon emitting transport options (ocean or rail) have a higher share in the total transport as the first and last leg will be only a small part of the total distance. Nevertheless, this comes at the cost of increased lead times and furthermore ocean freight is not necessarily less costly for expensive items, considering the pipeline inventory costs.

Finally, we conclude that switching transport modes is an effective measure to reduce carbon

emissions from transport, especially for small emission reduction targets, e.g. up to 20%. To reduce emissions even further (given the same infrastructure), an integrated approach that considers interactions with the 3PL and other shippers is more efficient than switching transport modes alone. Possible such means are e.g. collaboration with other shippers to decrease empty returns and increase load factors, and sharing stock points.

Acknowledgements

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A Appendix

A.1 Proofs

Theorem 1   Consider $y_1, y_2 \in I$ and $u_{y_1,j} < u_{y_2,j}$.

a If $e_{y_2,j} \leq \tilde{e}^j_{y_1,y_2} \leq e_{y_1,j}$, then $\lambda^j_{y_1,y_2} \leq \hat{\lambda}_{y_1,j} \leq \hat{\lambda}_{y_2,j}$ and

$z_{y_1,j}(\lambda) \leq z_{y_2,j}(\lambda)$ for $\lambda \in [0, \lambda^j_{y_1,y_2}]$ and $z_{y_1,j}(\lambda) \geq z_{y_2,j}(\lambda)$ for $\lambda \in [\lambda^j_{y_1,y_2}, \infty)$.

b If $\tilde{e}^j_{y_1,y_2} < e_{y_2,j} < e_{y_1,j}$, then $\hat{\lambda}_{y_2,j} < \hat{\lambda}_{y_1,j} < \lambda^j_{y_1,y_2}$ and

$z_{y_1,j}(\lambda) \leq z_{y_2,j}(\lambda)$ for $\lambda \in [0, \lambda^j_{y_1,y_2}]$ and $z_{y_1,j}(\lambda) \geq z_{y_2,j}(\lambda)$ for $\lambda \in [\lambda^j_{y_1,y_2}, \infty)$.

c If $\tilde{e}^j_{y_1,y_2} < e_{y_1,j} < e_{y_2,j}$, then $\lambda^j_{y_1,y_2} < 0 < \hat{\lambda}_{y_2,j} < \hat{\lambda}_{y_1,j}$ and

$z_{y_1,j}(\lambda) \leq z_{y_2,j}(\lambda)$ for $\lambda \in [0, \infty)$.

Where

$$\tilde{e}^j_{y_1,y_2} = e_{y_1,j} \frac{\frac{Q_j}{\epsilon_j} - k_j - u_{y_2,j}}{\frac{Q_j}{\epsilon_j} - k_j - u_{y_1,j}}$$

Proof:

Proof of part a Let $e_{y_2,j} = \tilde{e}^j_{y_1,y_2} - \zeta$, where $\zeta \geq 0$.

Let us first show that $\lambda^j_{y_1,y_2} \leq \hat{\lambda}_{y_1,j}$.

$$\lambda^j_{y_1,y_2} = \frac{u_{y_1,j} - u_{y_2,j}}{e_{y_2,j} - e_{y_1,j}} = \frac{u_{y_1,j} - u_{y_2,j}}{e_{y_1,j} \frac{\frac{Q_j}{\epsilon_j} - k_j - u_{y_2,j}}{\frac{Q_j}{\epsilon_j} - k_j - u_{y_1,j}} - \zeta - e_{y_1,j}} = \frac{u_{y_1,j} - u_{y_2,j}}{e_{y_1,j} \frac{u_{y_1,j} - u_{y_2,j}}{\frac{Q_j}{\epsilon_j} - k_j - u_{y_1,j}} - \zeta} \leq \frac{u_{y_1,j} - u_{y_2,j}}{e_{y_1,j} \frac{u_{y_1,j} - u_{y_2,j}}{\frac{Q_j}{\epsilon_j} - k_j - u_{y_1,j}}} = \hat{\lambda}_{y_1,j}$$

where the inequality follows since the nominator and the denominator are negative.

Next we show that $\hat{\lambda}_{y_1,j} \leq \hat{\lambda}_{y_2,j}$.

$$\hat{\lambda}_{y_2,j} = \frac{1}{\tilde{e}^j_{y_1,y_2} - \zeta} \left(\frac{Q_j}{\epsilon_j} - k_j - u_{y_2,j} \right) \geq \frac{1}{\tilde{e}^j_{y_1,y_2}} \left(\frac{Q_j}{\epsilon_j} - k_j - u_{y_2,j} \right) = \hat{\lambda}_{y_1,j}.$$

where the inequality follows since $\frac{Q_j}{\epsilon_j} - k_j - u_{i,j} > 0$ and the last equality follows from the definition of $\tilde{e}^j_{y_1,y_2}$.

Hence, $\lambda^j_{y_1,y_2} \leq \hat{\lambda}_{y_1,j} \leq \hat{\lambda}_{y_2,j}$.

Proof of part b   The proof follows that of part a with the exception that $e_{y_2,j} = \tilde{e}^j_{y_1,y_2} + \zeta$, where $\zeta > 0$.

$\lambda^j_{y_1,y_2} > \hat{\lambda}_{y_1,j}$ and $\hat{\lambda}_{y_1,j} > \hat{\lambda}_{y_2,j}$.

Hence, $\hat{\lambda}_{y_2,j} < \hat{\lambda}_{y_1,j} < \lambda^j_{y_1,y_2}$.

Proof of part c   Recall that $e_{y_1,j} < e_{y_2,j}$.

Hence, $\hat{\lambda}_{y_1,j} = \frac{1}{e_{y_1,j}} \left(\frac{Q_j}{\epsilon_j} - k_j - u_{y_1,j} \right) > \frac{1}{e_{y_2,j}} \left(\frac{Q_j}{\epsilon_j} - k_j - u_{y_2,j} \right) = \hat{\lambda}_{y_2,j} > 0$,

where the inequality follows since $\frac{Q_j}{\epsilon_j} - k_j - u_{i,j} > 0$.

$\lambda^j_{y_1,y_2} = \frac{u_{y_1,j} - u_{y_2,j}}{e_{y_2,j} - e_{y_1,j}} < 0$

Hence, if $e_{y_1,j} < e_{y_2,j}$, then $\lambda^j_{y_1,y_2} < 0 < \hat{\lambda}_{y_2,j} < \hat{\lambda}_{y_1,j}$.   □

Theorem 2   Consider $y_1, y_2, y_3 \in I$ for product j such that $u_{y_1,j} < u_{y_2,j} < u_{y_3,j}$ and

$e_{y_1,j} > e_{y_2,j} > e_{y_3,j}$.

a If $e_{y_2,j} \geq \bar{e}^j_{y_2}(y_1, y_3)$, transport mode y_2 is not preferred for any $\lambda \geq 0$

$(z_{y_2,j}(\lambda) \geq \min\{z_{y_1,j}(\lambda), z_{y_3,j}(\lambda)\}$ for $\lambda \geq 0)$,

b If $e_{y_2,j} \leq \bar{e}_{y_2}^{j}(y_1, y_3)$, transport mode y_2 is the preferred transport mode for $\lambda \in [\lambda_{y_1,y_2}^{j}, \lambda_{y_2,y_3}^{j}]$, where

$$\bar{e}_{y_2}^{j}(y_1, y_3) = e_{y_1,j} + (e_{y_3,j} - e_{y_1,j})\frac{u_{y_1,j} - u_{y_2,j}}{u_{y_1,j} - u_{y_3,j}}.$$

Proof:

Proof of part a Assume that $e_{y_2,j} \geq \bar{e}_{y_2}^{j}(y_1, y_3)$.

We need to prove that $u_{y_2,j} + \lambda e_{y_2,j} \geq \min\{u_{y_1,j} + \lambda e_{y_1,j}, u_{y_3,j} + \lambda e_{y_3,j}\} \ \forall \lambda \geq 0$.

We first show that $\lambda_{y_1,y_2}^{j} \geq \lambda_{y_1,y_3}^{j}$.

$$
\begin{aligned}
-\lambda_{y_1,y_2}^{j} &= \frac{u_{y_2,j} - u_{y_1,j}}{e_{y_2,j} - e_{y_1,j}} \leq \frac{u_{y_2,j} - u_{y_1,j}}{\bar{e}_{y_2}^{j}(y_1,y_3) - e_{y_1,j}} \\
&= \frac{u_{y_2,j} - u_{y_1,j}}{e_{y_1,j} + (e_{y_3,j} - e_{y_1,j})\frac{u_{y_1,j} - u_{y_2,j}}{u_{y_1,j} - u_{y_3,j}} - e_{y_1,j}} = \frac{u_{y_3,j} - u_{y_1,j}}{e_{y_3,j} - e_{y_1,j}} \\
&= -\frac{u_{y_1,j} - u_{y_3,j}}{e_{y_3,j} - e_{y_1,j}} = -\lambda_{y_1,y_3}^{j}
\end{aligned}
$$

(where the inequality follows since $e_{y_2,j} - e_{y_1,j} \leq 0$.)

Next, we show that $\lambda_{y_2,y_3}^{j} \leq \lambda_{y_1,y_3}^{j}$.

$$\lambda_{y_2,y_3}^{j} = \frac{u_{y_2,j} - u_{y_3,j}}{e_{y_3,j} - e_{y_2,j}} \leq \frac{u_{y_2,j} - u_{y_3,j}}{e_{y_3,j} - \bar{e}_{y_2}^{j}(y_1,y_3)}$$
$$= \frac{u_{y_2,j} - u_{y_3,j}}{e_{y_3,j} - e_{y_1,j} - (e_{y_3,j} - e_{y_1,j})\frac{u_{y_1,j} - u_{y_2,j}}{u_{y_1,j} - u_{y_3,j}}} = \frac{u_{y_1,j} - u_{y_3,j}}{e_{y_3,j} - e_{y_1,j}} = \lambda_{y_1,y_3}^{j}.$$

So we find the following ordering $\lambda_{y_2,y_3}^{j} \leq \lambda_{y_1,y_3}^{j} \leq \lambda_{y_1,y_2}^{j}$, which determines the ordering of the profits for any value of λ:

$$
\begin{aligned}
u_{y_1,j} + \lambda e_{y_1,j} \leq u_{y_2,j} + \lambda e_{y_2,j} \leq u_{y_3,j} + \lambda e_{y_3,j} \quad &\text{for } 0 \leq \lambda \leq \lambda_{y_2,y_3}^{j} \\
u_{y_1,j} + \lambda e_{y_1,j} \leq u_{y_3,j} + \lambda e_{y_3,j} \leq u_{y_2,j} + \lambda e_{y_2,j} \quad &\text{for } \lambda_{y_2,y_3}^{j} \leq \lambda \leq \lambda_{y_1,y_3}^{j} \\
u_{y_3,j} + \lambda e_{y_3,j} \leq u_{y_1,j} + \lambda e_{y_1,j} \leq u_{y_2,j} + \lambda e_{y_2,j} \quad &\text{for } \lambda_{y_1,y_3}^{j} \leq \lambda \leq \lambda_{y_1,y_2}^{j} \\
u_{y_3,j} + \lambda e_{y_3,j} \leq u_{y_2,j} + \lambda e_{y_2,j} \leq u_{y_1,j} + \lambda e_{y_1,j} \quad &\text{for } \lambda_{y_1,y_2}^{j} \leq \lambda \leq \lambda_{\max}^{j}
\end{aligned}
$$

Recall $u_{y_1,j} + \lambda e_{y_1,j} \leq u_{y_3,j} + \lambda e_{y_3,j}$ for $\lambda \leq \lambda_{y_1,y_3}^{j}$ and $u_{y_1,j} + \lambda e_{y_1,j} \geq u_{y_3,j} + \lambda e_{y_3,j}$ for $\lambda \geq \lambda_{y_1,y_3}^{j}$. For $\lambda > \lambda_{\max}^{j}$, all profits are by definition equal to 0.

From this we can conclude that $u_{y_2,j} + \lambda e_{y_2,j} \geq \min\{u_{y_1,j} + \lambda e_{y_1,j}, u_{y_3,j} + \lambda e_{y_3,j}\} \ \forall \lambda \geq 0$.

Proof of part b The proof follows the same lines as the proof of part 1.

If $e_{y_2,j} \leq \bar{e}_{y_2}^{j}(y_1, y_3)$, $\lambda_{y_1,y_2}^{j} \leq \lambda_{y_1,y_3}^{j}$ and $\lambda_{y_2,y_3}^{j} \geq \lambda_{y_1,y_3}^{j}$, hence $\lambda_{y_1,y_2}^{j} \leq \lambda_{y_1,y_3}^{j} \leq \lambda_{y_2,y_3}^{j}$.

The ordering of the profits for any value of λ is:

$$
\begin{aligned}
u_{y_1,j} + \lambda e_{y_1,j} \leq u_{y_2,j} + \lambda e_{y_2,j} \leq u_{y_3,j} + \lambda e_{y_3,j} \quad &\text{for } 0 \leq \lambda \leq \lambda_{y_1,y_2}^{j} \\
u_{y_2,j} + \lambda e_{y_2,j} \leq u_{y_1,j} + \lambda e_{y_1,j} \leq u_{y_3,j} + \lambda e_{y_3,j} \quad &\text{for } \lambda_{y_1,y_2}^{j} \leq \lambda \leq \lambda_{y_1,y_3}^{j} \\
u_{y_2,j} + \lambda e_{y_2,j} \leq u_{y_3,j} + \lambda e_{y_3,j} \leq u_{y_1,j} + \lambda e_{y_1,j} \quad &\text{for } \lambda_{y_1,y_3}^{j} \leq \lambda \leq \lambda_{y_2,y_3}^{j} \\
u_{y_3,j} + \lambda e_{y_3,j} \leq u_{y_2,j} + \lambda e_{y_2,j} \leq u_{y_1,j} + \lambda e_{y_1,j} \quad &\text{for } \lambda \geq \lambda_{y_2,y_3}^{j}
\end{aligned}
$$

From this we can conclude that $u_{y_2,j} + \lambda e_{y_2,j} = \min\{u_{y_1,j} + \lambda e_{y_1,j}, u_{y_2,j} + \lambda e_{y_2,j}, u_{y_3,j} + \lambda e_{y_3,j}\}$ for $\lambda \in [\lambda_{y_1,y_2}^{j}, \lambda_{y_2,y_3}^{j}]$. $\qquad \square$

Proposition 2 If $y_1, y_2, y_3 \in I$ for product j such that $u_{y_1,j} < u_{y_2,j} < u_{y_3,j}$ and $e_{y_3,j} < \tilde{e}^j_{y_1,y_3}$, then $\bar{e}^j_{y_2}(y_1, y_3) < \tilde{e}^j_{y_1,y_2}$.

Proof:

Consider that $e_{y_3,j} < \tilde{e}^j_{y_1,y_3}$, which implies that (using Theorem 1)

$$\hat{\lambda}_{y_1,j} > \lambda^j_{y_1,y_3}. \tag{15}$$

It needs to be shown that $\bar{e}^j_{y_2}(y_1, y_3) - \tilde{e}^j_{y_1,y_2} < 0$.

Let $\xi := e_{y_1,j} - \tilde{e}^j_{y_1,y_2}$. It holds that $\xi \geq 0$ since $e_{y_1,j} \geq \tilde{e}^j_{y_1,y_2}$ for $u_{y_1,j} \leq u_{y_2,j}$.

$$
\begin{aligned}
\bar{e}^j_{y_2}(y_1, y_3) - \tilde{e}^j_{y_1,y_2} &= e_{y_1,j} + (e_{y_3,j} - e_{y_1,j})\frac{u_{y_1,j} - u_{y_2,j}}{u_{y_1,j} - u_{y_3,j}} - \tilde{e}^j_{y_1,y_2} \\
&= \tilde{e}^j_{y_1,y_2} + \xi + (e_{y_3,j} - e_{y_1,j})\frac{u_{y_1,j} - u_{y_2,j}}{u_{y_1,j} - u_{y_3,j}} - \tilde{e}^j_{y_1,y_2} \\
&= \xi + (e_{y_3,j} - e_{y_1,j})\frac{u_{y_1,j} - u_{y_2,j}}{u_{y_1,j} - u_{y_3,j}}.
\end{aligned}
\tag{16}
$$

Let us simplify both terms in (16).

$\xi = e_{y_1,j} - e_{y_1,j}\frac{\frac{Q_j}{\epsilon_j} - k_j - u_{y_2,j}}{\frac{Q_j}{\epsilon_j} - k_j - u_{y_1,j}} = e_{y_1,j}\frac{u_{y_2,j} - u_{y_1,j}}{\frac{Q_j}{\epsilon_j} - k_j - u_{y_1,j}} = (u_{y_2,j} - u_{y_1,j})\frac{1}{\hat{\lambda}_{y_1,j}}$.

$(e_{y_3,j} - e_{y_1,j})\frac{u_{y_1,j} - u_{y_2,j}}{u_{y_1,j} - u_{y_3,j}} = (e_{y_3,j} - e_{y_1,j})\frac{u_{y_2,j} - u_{y_1,j}}{u_{y_3,j} - u_{y_1,j}} = (u_{y_2,j} - u_{y_1,j})\frac{1}{\lambda^j_{y_1,y_3}}$.

Implementing this in Equation (16) yields the following results:

$$
\begin{aligned}
\bar{e}^j_{y_2}(y_1, y_3) - \tilde{e}^j_{y_1,y_2} &= (u_{y_2,j} - u_{y_1,j})\frac{1}{\hat{\lambda}_{y_1,j}} - (u_{y_2,j} - u_{y_1,j})\frac{1}{\lambda^j_{y_1,y_3}} \\
&= (u_{y_2,j} - u_{y_1,j})\left(\frac{1}{\hat{\lambda}_{y_1,j}} - \frac{1}{\lambda^j_{y_1,y_3}}\right) < 0
\end{aligned}
$$

where the inequality follows from Expression (15) and the fact that $u_{y_2,j} > u_{y_1,j}$. $\square$

Proposition 4 Consider $i, i+1 \in \mathcal{I}^j$, then $\bar{\lambda}^j_{i,i+1} \geq \lambda^j_{i,i+1}$.

Proof:

We need to show that $\bar{\lambda}^j_{i,i+1} \geq \lambda^j_{i,i+1}$, where

$$\bar{\lambda}^j_{i,i+1} = \sqrt{\frac{u_{i+1,j} - u_{i,j}}{e_{i,j} - e_{i+1,j}}\frac{2(\frac{Q_j}{\epsilon_j} - k_j) - (u_{i,j} + u_{i+1,j})}{e_{i,j} + e_{i+1,j}}} = \sqrt{\lambda^j_{i,i+1}\frac{2(\frac{Q_j}{\epsilon_j} - k_j) - (u_{i,j} + u_{i+1,j})}{e_{i,j} + e_{i+1,j}}}.$$

From the definition of $\bar{\lambda}^j_{i,i+1}$ it is clear that this is equivalent to showing that:

$\frac{2(\frac{Q_j}{\epsilon_j} - k_j) - (u_{i,j} + u_{i+1,j})}{e_{i,j} + e_{i+1,j}} \geq \lambda^j_{i,i+1}$ (since both terms are positive for $i, i+1 \in \mathcal{I}^j$).

Let $e_{i+1,j} = \tilde{e}^j_{i,i+1} - \phi$, where $\phi \geq 0$. Since $i+1 \in \mathcal{I}^j$, $e_{i+1,j} \leq \tilde{e}^j_{i,i+1}$.

$\frac{2\left(\frac{Q_j}{\epsilon_j} - k_j\right) - (u_{i,j} + u_{i+1,j})}{e_{i,j} + e_{i+1,j}} = \frac{\frac{Q_j}{\epsilon_j} - k_j - u_{i,j} + \frac{Q_j}{\epsilon_j} - k_j - u_{i+1,j}}{e_{i,j} + \tilde{e}^j_{i,i+1} - \phi} \geq \frac{\frac{Q_j}{\epsilon_j} - k_j - u_{i,j} + \frac{Q_j}{\epsilon_j} - k_j - u_{i+1,j}}{e_{i,j} + \tilde{e}^j_{i,i+1}}$

$= \frac{1}{e_{i,j}}\left(\frac{Q_j}{\epsilon_j} - k_j - u_{i,j}\right) = \hat{\lambda}_{i,j} \geq \lambda^j_{i,i+1}$. The first inequality follows from the fact that all terms are positive, including ϕ and the last inequality follows from Theorem 1. We use the result that

$e_{i,j} + \tilde{e}^j_{i,i+1} = e_{i,j}\frac{\frac{Q_j}{\epsilon_j} - k_j - u_{i+1,j} + \frac{Q_j}{\epsilon_j} - k_j - u_{i,j}}{\frac{Q_j}{\epsilon_j} - k_j - u_{i,j}}$.

Hence, we have shown that $\bar{\lambda}^j_{i,i+1} \geq \lambda^j_{i,i+1}$. $\square$

A.2 Details of the running example calculations

Table 3 determines the values of $\tilde{e}^j_{y_1,y_2}$ for all pairs of modes of product a and b

Table 3: *Threshold values for all mode pairs for product a and b*

	Product a							Product b						
Mode i	1	2	3	4	5	MIN	$e_{i,a}$	Mode i	1	2	3	4	5	MIN	$e_{i,b}$
$\tilde{e}^a_{i,2}$	0.92					0.92	0.80	$\tilde{e}^b_{i,2}$	1.93					1.93	1.90
$\tilde{e}^a_{i,3}$	0.87	0.76				0.76	0.60	$\tilde{e}^b_{i,3}$	1.82	1.80				1.80	1.91
$\tilde{e}^a_{i,4}$	0.75	0.65	0.52			0.52	0.55	$\tilde{e}^b_{i,4}$	1.65	1.62	1.73			1.62	1.25
$\tilde{e}^a_{i,5}$	0.58	0.51	0.40	0.43		0.40	0.25	$\tilde{e}^b_{i,5}$	1.61	1.59	1.69	1.22		1.22	1.20
$\tilde{e}^a_{i,6}$	0.25	0.22	0.17	0.18	0.11	0.11	0.10	$\tilde{e}^b_{i,6}$	1.47	1.45	1.54	1.12	1.10	1.10	0.90

Table 4 determines the values of $\bar{e}^j_{y_2}(y_1, y_3)$ for all pairs of modes of product a and b that meet Condition 1. Note that for product a mode 3 the minimum is attained for $y_1 = 2$, which is not superefficient.

Table 4: *Threshold values for all mode pairs for product a and b*

	Product a				Product b			
	y_2	2	3	5	y_2	2	4	5
$y_1 = 1, y_3 = 3$		0.750			$y_1 = 1, y_3 = 4$	1.850		
$y_1 = 1, y_3 = 5$		0.850	0.760		$y_1 = 1, y_3 = 5$	1.855	1.273	
$y_1 = 1, y_3 = 6$		0.900	0.840	0.500	$y_1 = 1, y_3 = 6$	1.853	1.267	1.193
$y_1 = 2, y_3 = 5$			0.718		$y_1 = 2, y_3 = 5$		1.278	
$y_1 = 2, y_3 = 6$			0.748	0.450	$y_1 = 2, y_3 = 6$		1.285	1.208
$y_1 = 3, y_3 = 6$				0.370	$y_1 = 4, y_3 = 6$			1.180
MIN		0.750	0.718	0.370	MIN	1.850	1.267	1.180
e_{ia}		0.80	0.60	0.25	e_{ib}	1.90	1.25	1.20

A.3 Details of emission calculation

The required parameters and the source (assumption or actual data) to calculate the emissions from transport with the TERRA tool in the Cargill case are:

Transport mode: Given by LSP and Cargill, road or ferry by default, intermodal rail, water or short sea for the intermodal bids.

Distance per mode: calculated based on origin, destination, and transshipment locations.

Weight and volume of product: given by Cargill, weight is restricting factor.

Payload: given by the LSP.

TEU (twenty-foot equivalent unit): determined by product density and capacity of equipment (1 or 1.5 TEU).

Vehicle/vessel type: assume for road a truck semi-trailer, for short sea a bulk water type Feeder,

for inland water default NTM values for a container vessel.

Load factor: assume for rail 72% and or short-sea load factor of 80%. For inland water use default NTM value. For road the load factor is determined by the payload.

Cleaning: steam cleaning is assumed for all shipments.

Positioning distance: assume 20% is added to the travel distance.

Empty returns: no empty returns are assumed.

Share of electrical rail: assume 76.6% electrical and 23.4% diesel.

Gross weight of the train: assume 1,000 tonne.

Road allocation: assume 85% highway, 10 % rural and 5 % urban.

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