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The economic and environmental performance of dual sourcing: A newsvendor approach

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Abstract

We extend the dual sourcing model based on the newsvendor framework by considering the environmental impact of transport. In our context, dual sourcing means that a company, e.g. a retailer, uses an offshore and an onshore supplier. We include environmental regulations for transport in the model. Firstly, emission taxes for the transport from the offshore source are considered. It can be shown that with increasing emissions taxes the company sources less from offshore. This improves the environmental performance but the economic performance (expected profit) is severely harmed. Secondly, we propose that an emission trading scheme is valid for transport activities. In this case, the optimal policy turns out to be a two-sided control-limit policy. If the emission limit (expressed in product units) is set to the minimal offshore order quantity the environmental impact of transport can be reduced while the economic performance is nearly not affected. Thus, from managerial perspective emission trading is preferred to an emission tax on transport. Also from the perspective of policy-making emission trading is reasonable as it helps to limit the negative environmental impact of transport but does not strongly reduce the competitiveness of individual companies.

1 Introduction

Supply chains consist of all processes which are needed in order to supply customers with the required products. These are, for instance, production, sourcing, transport or warehousing processes. Traditionally, supply chain management decisions are based on the economic performance of the involved parties which can be expressed by (non-)financial measures, like profit or total landed costs and customer service (see, e.g., Chopra and Meindl, 2010; van Mieghem, 2008). Based on the economic performance measures different supply chain strategies, like outsourcing, offshoring or centralization of production and warehousing facilities turned out to be advantageous in certain industries. But in recent years, other criteria, such as quality, flexibility or environmental issues, have become important as well (Ferreira and Prokopets, 2009). Especially carbon emissions related to the activities of companies are high on the political agenda because they are considered to be a major cause of the greenhouse gas effect (IPCC, 2007). Based on this, regulations concerning carbon emissions of companies' activities have been introduced. One example is the EU Emissions Trading Scheme (ETS) which restricts the carbon emissions of energy-intensive industries within the European Union (European Community, 2005). Beside these industries, which account for approximately half of the carbon emissions, transport is the second largest polluter (Eurostat, 2009). The reduction of carbon emissions from transport are a major issue in the European Union as they are the only ones which have significantly grown between 1990 and 2006 (+26%). Carbon emissions from international aviation and navigation have witnessed an even stronger increase of 102% and 60%, respectively, between 1990 and 2007 (EEA, 2008, 2009). Therefore, also stricter regulations with respect to carbon emissions of transport are expected to be implemented. For instance, based on an EU directive agreed in 2008 (European Community, 2008) aviation will be included in the EU ETS by 2012. Alternatively, within the EU authorities it is discussed that a transport carbon emission tax or charge could be introduced to make companies pay a part of the external costs of transport.

Mainly stricter regulations and increasing customer awareness with respect to the environment encourage companies to reconsider their supply chain strategies by incorporating the environmental dimension in decision-making (Walker et al., 2008). Companies will have to search for strategies that are at the same time cost-efficient, provide the required customer service and have a low negative impact on the environment. In this respect, we evaluate one possible strategy, namely dual sourcing relying on an offshore and an onshore supplier. The offshore supplier is cheap but far away from the market. It has a long lead time and is therefore slow and inflexible. The onshore supplier is close to the market and flexible. It can deliver on short notice but is expensive. Past work has already shown that dual sourcing – instead of single offshore sourcing – can help companies to improve the performance with respect to profit and customer service (see, for instance, Warburton and Stratton, 2005; Cachon and Terwiesch, 2009). We consider, in addition to the economic performance measures, also the environmental impact of dual sourcing. We analyse a dual sourcing model based on the newsvendor framework and incorporate environmental aspects, i.e. carbon emissions of transport, into the decision of how much to order from the offshore supplier. A very interesting question in this respect is whether economic and environmental criteria contradict each other. In other words, is there a trade-off between economic and environmental performance of supply chains? Furthermore, we evaluate the effect of regulations on the decision-making of individual companies. In the first step, we analyse the effect of a linear carbon emission tax on transport and in the second step, we propose that an emission trading scheme for the transport sector is implemented. We analyse how the optimal ordering decision and the profitability of the company are influenced by including the additional parameters. Furthermore, we have a closer look at the development of the related transport carbon emissions. Based on the analytical models and the numerical results including

sensitivity analyses, we derive implications for management and policy-making.

The paper is structured as follows. In Section 2 the literature related to our work is presented. In Section 3 we introduce the transport-focused dual sourcing framework which describes the general setting. In addition, we outline the basic dual sourcing model and discuss its relation to transport carbon emissions. In Section 4 we extend the basic dual sourcing model by including regulations concerning transport carbon emissions. Using the analytical results we investigate in Section 5 numerically for which values of the policy parameters the economic performance is not negatively affected. In Section 6 we derive implications for management and policy-making. Section 7 summarizes the main findings of our work and points out further research opportunities.

2 Literature review and related work

In this paper we integrate two streams of research. We deal, on the one hand, with supply chain management with a focus on dual sourcing based on the newsvendor framework. On the other hand, our work is related to the environmental performance of supply chains and the impact of environmental regulations on the decision-making of individual companies.

The decision of how much inventory to hold and how much to order from a certain source is very important with respect to traditional performance measures, such as expected profit and customer service. Therefore, inventory management is an essential building block of operations management and supply chain management. An overview of inventory models can be found in various operations and supply chain management textbooks, like Cachon and Terwiesch (2009), Chopra and Meindl (2010), Nahmias (2009) or Silver et al. (1998). A basic classification can be made between deterministic and stochastic models, single- and multi-period models as well as with respect to the number of suppliers. The focus of our work is on the single-period, stochastic inventory model, also known as the newsvendor or newsboy model. The term single-period refers to the fact that the ordering decision has to be taken before the selling season when demand is still unknown; the products which remain unsold after the selling season are of no or only little value. A review of the single-period model and its extensions can be found in Khouja (1999). Specifically, we consider the newsvendor model with two ordering possibilities which is usually called dual sourcing model. In this respect, dual sourcing means that the company relies on two supply sources. These two supply sources need not be two distinct entities; it can be the same supplier with two delivery options. However, in general, the first supply source is the cost-efficient, inflexible supply source. The second supply source is flexible and can deliver on short notice. But for this flexibility a premium has to be paid. Furthermore, the two suppliers may have different lead times due to their remoteness or proximity to the market. Warburton and Stratton (2005) present a dual sourcing model with an offshore and an onshore source based on the newsvendor model. In line with Gallego and Moon (1993) and Khouja (1996), they show that dual sourcing can help to improve expected profit and customer service level compared to single (offshore) sourcing, i.e. the classical newsvendor model with a single ordering opportunity. A similar approach can be found in Cachon and Terwiesch (2009) whereby they call the strategy quick response with reactive capacity. They assume that the second order can be placed at the same supplier which charges a premium for the fast delivery.

Concerning the second stream of literature, the work of Bloemhof-Ruwaard et al. (1995) is one of the first reviews about how operations research and environmental management (might) interact. Another literature review is provided by Srivastava (2007) who defines green supply chain management as “[...] integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the customer as well as end-of-life management of the product after its useful life.” A topic which is very

often covered in this field is the recovery of used products, i.e. reverse logistics (see, e.g., Dyckhoff et al., 2004; Fleischmann et al., 1997), and the design and management of closed-loop supply chains which are supply chains taking care of items once they are no longer needed or used (Flapper et al., 2005). In this respect, it is usually assumed that by “closing the loop” a positive environmental performance is achieved. Less work has been done with respect to the environmental impact of forward supply chain and how to integrate environmental issues or regulations into decision-making. With our work we want to contribute to this field of research.

Generally, the environmental dimension can be integrated into decision-making in different ways, by monetarisation in the form of environmental costs, as constraint(s) or by an additional objective function and relying on multi-objective optimization. In the field of production planning, Letmathe and Balakrishnan (2005) formulate two models where the environment is explicitly considered in the decision of how much to produce in a certain period. They pay special attention to the emissions produced during the production process and they consider regulations concerning emissions (taxes, thresholds and emission trading) in the decision. Radulescu et al. (2009) formulate a multi-objective program for production processes in which they integrate (pollution) emissions. They consider two objectives, i.e. minimize pollution risk and maximize expected return. Subramanian et al. (2010) develop a non-linear mathematical programming model for engine manufacturing and remanufacturing. The objective function is profit maximization and the environmental dimension is included on the different stages, i.e. product design, production and recovery. They consider emission limits and the selling and buying of emission allowances for the (re)manufacturing processes. In the field of transport, Hoen et al. (2012) deal with the problem of transport mode choice and focus on how to derive emission factors per product unit for the different modes.

In the field of inventory management, Benjaafar et al. (2010) and Hua et al. (2011) extend deterministic, multi-period inventory models by also accounting for the emissions produced in transport and storage and by integrating environmental regulations. Both point out that in this new and emerging field of research it is important to start with simple models to analyse the new trade-offs which arise when environmental criteria are considered. Chen et al. (2011) enriches the work of Benjaafar et al. (2010) by providing analytical support for the numerical observations with the help of the EOQ model. In addition, they discuss an environmentally extended newsvendor model with two objective functions, i.e. the total expected cost and the total expected emissions. The general importance of extending classical models to also account for the environmental impacts is underlined by Bonney and Jaber (2011). A recent work investigating the classical single-period (newsvendor) problem under carbon emission policies is provided by Song and Leng (2012). They analyse the impact of a strict carbon cap, a carbon emission tax and a cap-and-trade system on the firm’s optimal decision showing that the parameters of the regulations should vary depending on the profit margin of the respective company. In contrast to their work, we analyse a stochastic, single-period dual sourcing model with respect to economic and environmental performance and we consider environmental regulations concerning transport carbon emissions.

3 The dual sourcing newsvendor: A transport-focused framework

Firstly, we outline the basic dual sourcing model based on the newsvendor framework. Secondly, we point out the relation of dual sourcing and transport and relate the company’s decision to environmental regulations concerning transport carbon emissions. Furthermore, we develop the transport-focused dual sourcing framework with an offshore and an onshore supplier which summarizes the general setting.

3.1 Basic dual sourcing newsvendor model

As starting point for our analysis we use the dual sourcing model proposed by Warburton and Stratton (2005). In the classical newsvendor model, it is assumed that the company, e.g. a retailer, has to order before the start of the selling season and no additional orders are possible. As an extension to the classical newsvendor model, it is assumed that in addition to the order before the selling season the company can receive supplementary units of the product during the selling season from a second supply source. We assume that the company relies on a cheap but slow and inflexible supply source as well as on an expensive but fast and flexible supply source. According to Warburton and Stratton (2005), the first supply source is located in a low-cost country, like China, which is far away from the market and has a long lead time. This supply source is called the offshore supplier. Because of the long procurement lead time for delivering the products from the offshore supplier to the market products from this source can be ordered only once before the selling season when demand is still random. The second supply source is located close to the market and is denoted as the onshore supplier. The onshore supplier can react immediately to changes in demand and is assumed to have unlimited capacity. The onshore supplier is used as backup in order to fulfil any demand which can not be satisfied by the order quantity from the offshore supplier. It can also be considered as a manufacturing facility owned by the company which carries out make-to-order production (see, e.g., Chung et al., 2008). Note that the decision of how much to order from the offshore supplier has to be taken under demand uncertainty while the products from the onshore supplier are procured after demand has been realized, i.e. this decision is taken under certainty. Such a strategy is especially suitable in the apparel, fashion and sporting goods industry, as pointed out by Warburton and Stratton (2005), Cachon and Terwiesch (2009) and Chopra and Meindl (2010) with industry examples.

An overview of the different stages in the supply chain is given in Figure 1. The products are sold to the market for the selling price per unit p . On the procurement side, the purchase price per unit differs between the two suppliers. The purchase price per unit from the offshore supplier is the product price per unit c ; the purchase price per unit from the onshore supplier is obtained by adding a domestic premium per unit d to the product price per unit c . This premium is mainly due to higher labour costs which have to be paid in the onshore production facility and also reflects the flexibility provided by the onshore supplier. Any leftover inventory which results from the offshore order quantity can be sold at the end of the season for a salvage value per unit z which also captures inventory holding costs. To avoid trivial situations, we assume $p > c > z$. The notation for the basic dual sourcing model is summarized in Table 1.

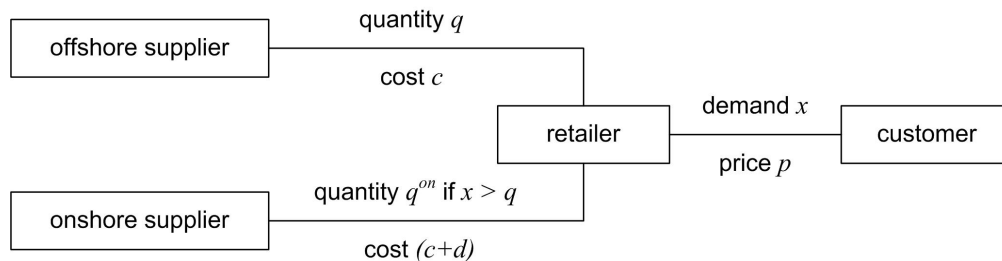


Figure 1: Framework for dual sourcing with off- and onshore supplier

Then, the company's profit P depends on the offshore order quantity q and on the realized demand x :

Table 1: Notation for the basic dual sourcing newsvendor model

p	selling price per unit
c	product price per unit/purchase price per unit from the offshore supplier
d	domestic premium per unit
z	salvage value per unit
q	offshore order quantity
q^*	optimal offshore order quantity with dual sourcing
q^{on}	expected onshore order quantity
x	realized demand
X	random demand
F	demand distribution function
F^{-1}	inverse of demand distribution function
$P(q, x)$	profit depending on offshore order quantity q and realized demand x
$P(q)$	expected profit depending on offshore order quantity q
$E()$	expected value
$(x)^+$	$\max(x, 0)$

$$P(q, x) = \begin{cases} p \cdot x - c \cdot q + z \cdot (q - x) & x \leq q \\ p \cdot x - c \cdot q - (c + d) \cdot (x - q) & x > q \end{cases} \quad (1)$$

For $x \leq q$, only the offshore supplier is used to fulfil demand and any leftover inventory can be salvaged for the value z . For $x > q$, additional units are procured from the onshore supplier in order to satisfy all demand. The expected profit depending on the offshore order quantity q is given by:

$$P(q) = E(p \cdot X + z(q - X)^+ - c \cdot q - (c + d)(X - q)^+) \quad (2)$$

whereby X is the random demand, $E()$ represents the expected value and $(x)^+$ is $\max(x, 0)$. The expected profit consists of the revenue generated by the selling of the products for p per unit during the season and for z per unit after the season less the cost for ordering from the offshore supplier for c per unit and the onshore supplier for $(c + d)$ per unit. As shown in Khouja (1996, 1999) $P(q)$ is a concave function. By maximizing the expected profit, the optimal offshore order quantity for the risk-neutral decision maker is given by (see, for instance, Warburton and Stratton, 2005; Cachon and Terwiesch, 2009):

$$q^* = F^{-1} \left(\frac{d}{d + c - z} \right) \quad (3)$$

F^{-1} represents the inverse of the demand distribution function. The expression in the brackets is known as the critical fractile or critical ratio which represents the probability that the realized demand is lower than or equal to the order quantity, i.e. cycle service level. No fixed ordering costs are considered in this model because it is assumed that the ordering has to take place anyway. The offshore order quantity decisively depends on the cost of overstocking and the cost of understocking. The cost of overstocking arises when a unit remains unsold in stock, i.e. $(c - z)$. The cost of understocking per unit, which arises when too few units have been ordered from the offshore supplier, equals to the domestic premium d . By ordering the profit-maximizing offshore order quantity q^* , the expected mismatch costs, i.e. the sum of the expected costs of overstocking and understocking,

which are due to a misalignment of demand and supply, are minimized (Cachon and Terwiesch, 2009). As long as the domestic premium d is smaller than the contribution margin per unit ($p - c$) the onshore supplier is used to some extent. If $d > (p - c)$ demand is exclusively satisfied from the offshore supplier. Generally, the offshore order quantity in the dual sourcing model is smaller than in the model with a single order opportunity (see, for instance, Gallego and Moon, 1993; Khouja, 1996; Warburton and Stratton, 2005; Cachon and Terwiesch, 2009), which is in our case single offshore sourcing. The onshore order quantity then is used to fulfil any demand that can not be satisfied by the offshore order quantity. However, when taking the offshore ordering decision before the selling season the decision maker considers the expected onshore order quantity q^{on} . It equals to the expected lost sales in the newsvendor model, i.e. the expected number of units which exceeds the offshore order quantity and is given by:

$$q^{on} = E((X - q)^+) \quad (4)$$

The dual sourcing strategy outperforms a single offshore sourcing strategy with respect to expected profit. In various works it is shown that using dual sourcing instead of single sourcing leads to an increase of the expected profit. Furthermore, a higher cycle service level can be achieved. The offshore order quantity in the dual sourcing model is generally smaller than in the classical newsvendor model as some part of demand is satisfied by the onshore supplier. It is intuitive that the offshore order quantity as well as the increase in profitability highly depend on the domestic premium and the demand uncertainty. On the one hand, a higher domestic premium leads to a higher offshore order quantity as the cost advantage outweighs the uncertainty under which the decision has to be taken. On the other hand, the higher the demand uncertainty the more the company is willing to rely on the onshore supplier thereby reducing the risk of overstocking (see, for instance, Warburton and Stratton, 2005; Cachon and Terwiesch, 2009).

3.2 Dual sourcing and transport carbon emissions

Due to the fact that the first supplier is located in an offshore country a long transport distance has to be overcome in order to bring the products to the market. We assume that the products are delivered to a distribution centre from which then the market is supplied. The long transport distance results in high transport activity and high carbon emissions from transport. The transport from offshore locations, in general, is carried out by sea or by air whereby the latter is considered as being much more environmentally unfriendly. In contrast to this, it is assumed that there is (nearly) no transport needed to deliver the products from the onshore supplier to the market. This assumption is reasonable when the onshore supplier is close to the distribution centre to which also the offshore order quantity is delivered or when the company uses its own production site with an associated distribution centre as second supply source.

In order to illustrate the different environmental impact of transport from the two suppliers we exemplarily compare the CO_2e (equivalent) emissions from transport with the help of a carbon emission calculation tool for transport called EcoTransIT (EcoTransIT, 2010). The transport from Beijing (China) to Vienna (Austria) via ocean shipping as main transport mode is compared to the transport from Bratislava (Slovakia) to Vienna (Austria) by truck. The calculation is done for one ton of an average product as defined in the calculation tool. The transport from the offshore supplier results in CO_2e emissions of 129 kg; the transport from the onshore supplier produces considerably lower emissions and results in only 5.8 kg CO_2e . This clearly shows the negative environmental impact of offshore sourcing if only carbon emissions from transport are considered. The difference

is even greater when air transport is used instead of ocean shipping. Then, the air transport from the offshore location would result in 5444 kg CO_2e for one ton of the transported goods.

In our framework, we do not explicitly consider the production processes of the two suppliers and thereby assume that the same amount of emissions stems from the two production processes. Even though this is a limiting assumption, it allows us to investigate the impact of the sourcing strategy on the transport carbon emissions within the supply chain.

In the following we consider regulations concerning emissions produced by the transport from the offshore supplier to the market. Table 2 gives an overview of the transport-focused dual sourcing framework. External conditions, which are in our case environmental regulations for transport, impose restrictions on companies and therefore influence the policies they choose. Two possible environmental regulations are examined in more detail in our work. First, a linear transport emission tax is imposed on each unit ordered from the offshore supplier. Second, the implementation of an emission trading scheme for transport which would be valid on a global scale is investigated. The company has to decide before the selling season how much to order from the offshore supplier and the offshore order quantity is directly related to the transport carbon emissions. Therefore, the offshore ordering decision is influenced by the environmental regulations; it determines which amount of emission tax has to be paid or how many emission allowances are needed.

Table 2: Transport-focused dual sourcing framework

External conditions	Environmental regulations for transport Linear emission tax <i>or</i> Emission trading
Policy	Dual sourcing (off- and onshore supplier)
Decisions	Offshore order quantity

As already stated, the (offshore) order quantity with a single order opportunity is larger than the offshore order quantity with a dual sourcing strategy. Due to the fact that the offshore order quantity is directly related to the transport carbon emissions it can be concluded that by using a dual sourcing strategy instead of single offshore sourcing the transport carbon emissions can be reduced while improving the economic performance.

In order to be able to model the different environmental regulations, the emission tax, the emission prices and the emission limit, i.e. the number of emission allowances allocated to a certain company, have to be related to product units. Hoen et al. (2012) show how to derive emission factors of different transport modes and how to allocate the emission factors of a vehicle to one product unit which is transported. By analogy with their idea we assume that the policy instruments are broken down to company level and related to one unit of the product.

In general, an emission tax is given as monetary unit per ton of CO_2e and it is fixed by policy-making. For our purpose, then, the emission tax per product unit depends on the carbon emission produced by the transport of a product unit from the offshore supplier. The transport carbon emissions mainly depend on the parameters transport mode and vehicle type used, distance travelled, load factor and type of product (volume and weight). The distance and the transport mode are determined by the location of the offshore supplier. Assuming that the transport is carried out by a logistics service provider average values can be taken for the other parameters and an average transport carbon emission factor (CO_2e tons per product unit) can be derived. By multiplying the transport emission tax per CO_2e ton with the average transport carbon emission factor the emission tax per product unit can be derived. This idea is related to an import tax based on the carbon content of products as proposed by Huebler (2009).

The average transport carbon emission factor is also necessary for operationalizing an emission trading scheme. Under an emission trading scheme the company receives a certain number of allowances free of charge which are then used to cover the carbon emissions produced by the company's activities. In general, an emission allowance certifies the right to emit one ton of CO_2e . Additional emission allowances have to be bought if more emissions are produced than covered by the allowances or remaining emission allowances can be sold (OECD, 2001). We assume that the authorities allocate the emission allowances to the company which takes the ordering decision. The company then has to provide the necessary emission allowances to the logistics service provider to cover the transport carbon emissions produced. In order to be able to directly relate the order quantity and the emission limit to each other the emission limit has to be translated into product units. This can again be done with the help of the average transport carbon emission factor per product unit. According to Raux (2010) emission trading could be particularly appropriate for the transport sector because the agents in the transport sector are more sensitive to quantitative regulations than price signals, such as an emission tax.

4 Environmental extensions of the dual sourcing newsvendor model

Based on the framework developed in Section 3, we now present the extensions of the dual sourcing newsvendor model with respect to environmental regulations. Table 3 summarizes the additional notation for the models.

Table 3: Additional notation for the extensions of the basic dual sourcing newsvendor model

t	emission tax per unit ordered from the offshore supplier
L	emission limit expressed in product units
b	buying price of emission allowance for one product unit
s	selling price of emission allowance for one product unit
$P_t(q)$	expected profit including emission tax t
$P_b(q)$	expected profit including costs of buying emission allowances
$P_s(q)$	expected profit including revenue of selling emission allowances
$P_L(q)$	expected profit with emission trading
q^t	optimal offshore order quantity with emission tax t
q^b	$\operatorname{argmax} P_b(q)$
q^s	$\operatorname{argmax} P_s(q)$
q^L	optimal offshore order quantity with emission trading

4.1 The dual sourcing newsvendor with a transport emission tax

In the first step, the basic model is extended by including a linear transport emission tax which has to be paid for each unit ordered from the offshore supplier. It is assumed that no transport emission taxes arise for the onshore supplier. A related framework and model including emission costs can be found in Rosič et al. (2009).

The transport emission tax per product unit is denoted by t . The additional cost has to be included in the objective function of the company, i.e. the expected profit. The offshore supplier is only used if it is overall cheaper than the onshore supplier which is the case as long as $t < d$. As soon as $t \geq d$ the product is exclusively procured from the onshore supplier on demand. The optimal offshore ordering decision can again be derived by maximizing the expected profit which now also includes the emission tax t . The optimal offshore order quantity is given by:

$$q^t = F^{-1} \left(\frac{d - t}{d + c - z} \right) \quad (5)$$

The offshore order quantity q^t depends on the relative cost advantage that can be achieved by offshore sourcing. With increasing emission tax t the company sources less from the offshore supplier as the cost advantage is reduced. The (expected) total order quantity also decreases as t increases. This is due to the following relation:

$$q^t + q^{on} = E(X) + E((q - X)^+) \quad (6)$$

The left hand side of (6) is the expected total order quantity, i.e. the sum of the offshore order quantity q^t and the expected onshore order quantity q^{on} . The total order quantity is either used to fulfil the demand or results in leftover inventory. Due to the fact that the decision of how much to order from the onshore supplier is taken under demand certainty no leftovers result from that decision. Leftover inventory only results from the offshore ordering decision. So with increasing t the offshore order quantity and the expected leftover inventory $E((q - X)^+)$ decrease and overall, the total order quantity converges to the expected demand $E(X)$.

Comparing (3) and (5) it is evident that the offshore order quantity with an emission tax $t > 0$ is smaller than the offshore order quantity without emission tax, i.e. $q^t < q^*$. Due to this fact, also the transport activity from the offshore supplier and the transport emissions are reduced. This helps to improve the environmental performance of the company. But as a negative side-effect the expected profit is reduced due to the additional costs and the economic performance of the company is harmed.

4.2 The dual sourcing newsvendor with emission trading for transport

In the second step, we include emission trading for transport in the basic model. The company receives a certain number of emission allowances free of charge. Therefore, in contrast to the previous model, transport emission costs do not arise for each unit ordered from the offshore supplier, but only if a certain threshold is exceeded. When the offshore order quantity q exceeds the emission limit L , which is expressed in units of the product, the company has to acquire extra emission allowances at the emission buying price per unit b . In the opposite case, when $q < L$ the company is able to sell the remaining unused emission allowances at the emission selling price per unit s . According to Letmathe and Balakrishnan (2005) and Song and Leng (2012) it is assumed that $b \geq s$. Also Gong and Zhou (2011) assume that the buying price is higher than the selling price of the allowance due to bid-ask price spreads and transaction costs. In addition to that, we make the following assumptions for the emission trading scheme for transport. Firstly, as already stated, the emission limit L is expressed in units of the product and an allowance is used to cover the emissions produced by the transport of one product unit from the offshore supplier to the market. Secondly, the prices for emission allowances are exogenously fixed. Actually, they are fixed on the market and depend on the scarcity of emission allowances which is mainly determined by the overall emission limit imposed by the authorities. Therefore, the prices of emission allowances could be modelled as a decreasing function of the emission limit, as mentioned by Hua et al. (2011), but this is beyond the scope of our work. Thirdly, we assume that the company's number of emission allowances to be sold/bought is rather small compared to the whole market volume for emission allowances. So the company can buy and sell any quantity of emission allowances.

Considering emission trading for transport, the expected profit of the company is derived as follows. The expected profit of the company is composed of the base profit $P(q)$ given by (2) which is the expected profit of the dual sourcing model without environmental regulations. Depending on the relation between q and L , revenue for the selling of emission allowances is added or the cost for buying additional emission allowances is deducted. The expected profit for the emission limit $L > 0$ and offshore order quantity q is then given by:

$$P_L(q) = \begin{cases} P_s(q) & \text{for } q \leq L \\ P_b(q) & \text{for } q > L \end{cases} \quad (7)$$

with

$$P_s(q) = P(q) + s(L - q) \quad (8)$$

$$P_b(q) = P(q) - b(q - L) \quad (9)$$

As long as the order quantity q is below or equal to the emission limit L the profit $P_s(q)$ is generated which consists of the base profit and the revenue from the selling of unused emission allowances. When more units are ordered from the offshore supplier than covered by the emission limit L , additional allowances have to be bought which reduces the base profit to $P_b(q)$.

As the expected profit $P(q)$ is a concave function this property obviously carries over to $P_s(q)$ and $P_b(q)$. Because of $b \geq s$ the following inequalities hold:

$$P_s(q) \leq P_b(q) \text{ for } q \leq L \quad (10)$$

$$P_s(q) > P_b(q) \text{ for } q > L \quad (11)$$

Therefore, according to (7), the expected profit $P_L(q)$ can be written in the following way:

$$P_L(q) = \min(P_s(q), P_b(q)) \quad (12)$$

Consequently, $P_L(q)$ is a concave function as the minimum of concave functions is again concave (see, e.g., Rockafellar, 1997, Theorem 5.5.).

To derive the optimal offshore order quantity q^L , we define $q^b = \operatorname{argmax} P_b(q)$ and $q^s = \operatorname{argmax} P_s(q)$ with

$$q^b = F^{-1} \left(\frac{d - b}{d + c - z} \right) \quad (13)$$

and

$$q^s = F^{-1} \left(\frac{d - s}{d + c - z} \right) \quad (14)$$

Note that q^b and q^s are derived like the optimal order quantity in the classical newsvendor model.

Due to the fact that the selling price s is smaller than or equal to the buying price b the quantity q^s is always larger than or equal to q^b , i.e. $q^s \geq q^b$. Note that q^b and q^s do not depend on the emission limit L . Therefore, q^L can be characterized in dependence of L .

If $L < q^b \leq q^s$, then according to (11) $q^L = q^b$. Complementary, if $L > q^s \geq q^b$, then $q^L = q^s$ because of (10). Finally, if $q^b \leq L \leq q^s$, P_L attains its maximum for $q^L = L$ because

$$P(L) = P_b(L) = P_s(L) \quad (15)$$

Summarizing, for an emission limit $L > 0$ the optimal offshore order quantity q^L is a two-sided control-limit policy given by:

$$q^L = \begin{cases} q^b & \text{for } L < q^b \\ L & \text{for } q^b \leq L \leq q^s \\ q^s & \text{for } L > q^s \end{cases} \quad (16)$$

Thus, the optimal offshore order quantity q^L given by (16) crucially depends on the relation between the lower control limit q^b , the upper control limit q^s and the emission limit L . For $L < q^b \leq q^s$, it is better for the enterprise to buy some extra allowances than to order more from the onshore supplier. For $L > q^s \geq q^b$, it is better to generate revenue through the selling of allowances and rely to a larger extent on the onshore supplier than sourcing more units from the offshore supplier and risking leftover inventory. For $q^b \leq L \leq q^s$, it is not reasonable for the company to either sell or buy emission allowances.

The difference between the upper and lower control limit depends on the values of the emission buying and selling price. If there is no difference between the buying and selling price of emission allowances, i.e. $b = s$, the impact of emission trading on the company's ordering decision is similar to an emission tax as concluded in, for instance, Letmathe and Balakrishnan (2005) and Benjaafar et al. (2010). If $b = s$, then by (15) the company orders $q^L = q^b = q^s$. But it has to be kept in mind that the level of the emission limit has a decisive impact on the economic performance of the company.

The previously presented models are special cases of the model including emission trading. The basic dual sourcing model without environmental regulations is represented by setting $s = 0$ and $b = 0$. The dual sourcing model with a linear transport emission tax corresponds to the extended model with $L = 0$ and $t = b$.

From the optimal ordering policy (16) we immediately see that irrespective of L , b and s the offshore order quantity with emission trading q^L is smaller than the offshore order quantity q^* given by (3). On the one hand, for any emission limit L the offshore order quantity is not larger than q^s , i.e. q^s is the maximal offshore order quantity. An emission limit $L > q^s$ allows the company to generate additional revenue without having to improve its environmental performance. On the other hand, for any emission limit L the offshore order quantity is not smaller than q^b , i.e. q^b is the minimal offshore order quantity. An emission limit $L < q^b$ would not help to reduce transport carbon emissions but would only lower the economic performance and competitiveness of the company. For environmental policy-making it is, thus, reasonable to set the emission limit L to the minimal offshore order quantity, i.e. $L = q^b$. Specifying $L > q^b$, the transport carbon emissions are higher whereas $L < q^b$ leads to lower expected profit for the company because $P_L(q)$ is increasing in the emission limit L . These effects are further explored in the following numerical analyses.

5 Numerical analyses

In order to gain more insights into the basic dual sourcing newsvendor model and its extensions we perform numerical analyses with the cost and price parameters shown in Table 4.

Table 4: Numerical analyses: Basic cost and price parameters

Selling price per unit p	20
Product price per unit c	10
Salvage value per unit z	5
Domestic premium per unit d	2
Emission tax per unit t	1.5
Emission buying price per unit b	1.5
Emission selling price per unit s	1.2

Demand is assumed to be normally distributed with the parameters listed in Table 5. Different values for the standard deviation are taken in order to show the effect of increased demand variability. The demand distribution with σ_1 which is a very low value should be considered as extreme scenario. This helps to underline that in the case of low demand variability the value of dual sourcing is limited; this holds true for the basic model as well as for its extensions.

Table 5: Numerical analyses: Demand scenarios

Mean demand μ	1000
Standard deviation σ_1	50
Standard deviation σ_2	150
Standard deviation σ_3	250

We compute the results for the basic dual sourcing model and its extensions based on the formulas in Sections 3 and 4 and perform sensitivity analyses in order to derive further implications for management and policy-making. The calculations are done with the help of MS Excel and the necessary functions for the spreadsheet calculations can be found in Chopra and Meindl (2010, pp. 349). It is intuitive that by switching from single offshore sourcing to dual sourcing the quantity ordered from the offshore supplier is reduced. The retailer to some extent relies on the onshore supplier for fulfilling demand. The total order quantity with dual sourcing, i.e. the sum of offshore and onshore order quantity, is lower than the order quantity with a single offshore sourcing strategy. The expected profit is higher with dual sourcing than with single offshore sourcing, whereby the value of dual sourcing increases with demand variability. By comparing the two strategies, it can be seen that simply by using dual sourcing instead of single offshore sourcing the offshore order quantity is reduced and thereby a positive result for the environment is achieved without imposing any environmental regulation.

5.1 Dual sourcing with a transport emission tax

In order to derive the numerical results for the dual sourcing model with a linear emission tax on transport from the offshore order quantity, we include an emission tax $t = 1.5$. It is intuitive that by introducing an emission tax the cost advantage of the offshore supplier is narrowed and therefore, the offshore order quantity and the related transport activity are reduced. Furthermore, the expected profit is lower than in the basic dual sourcing model. The numerical results for the model with a linear emission tax in comparison to the basic dual sourcing model are shown in Table 6.

For products with low demand variability, the expected profit is strongly reduced by the introduction of the transport emission tax while the offshore order quantity and the related transport

Table 6: Comparison of basic dual sourcing and dual sourcing with emission tax $t = 1.5$

	σ_1	σ_2	σ_3
Offshore order q - basic DS	972	915	859
Offshore order q - DS with emission tax	927	780	634
Difference in %	-4.6	-14.8	-26.2
Expected profit - basic DS	9881	9643	9405
Expected profit - DS with emission tax	8452	8357	8261
Difference in %	-14.5	-13.3	-12.2

DS... dual sourcing

carbon emissions are rather insensitive. The opposite holds true for products with a higher demand variability. With an emission tax $t = 1.5$, the transport carbon emissions are reduced by 4.6%, 14.8% and 26.2% while the expected profit is reduced by 14.5%, 13.3% and 12.2% for σ_1 , σ_2 and σ_3 , respectively.

In order to show the impact of an increasing transport emission tax on the optimal decision the emission tax t is varied in the range $0 \leq t < d$. Figures 2(a), 2(b) and 2(c) show the results depending on the emission tax t for the three demand scenarios. It is shown that with increasing emission tax t the offshore order quantity decreases and the onshore order quantity increases. As a result, the total order quantity converges to the mean demand, see also (6). First, the offshore order quantity decreases nearly linearly; as t is close to d it decreases more rapidly. The expected profit also decreases nearly linearly with increasing emission tax.

In addition, it can be of interest to compare the dual sourcing model with transport emission tax and the single offshore sourcing model. When assuming an emission tax $t = 1.5$ in the dual sourcing model the expected profit is even lower than in the case of single offshore sourcing. The expected profit is reduced by 13.1%, 9.0% and 4.4% for σ_1 , σ_2 and σ_3 , respectively, compared to single offshore sourcing. Even though the economic performance of the company is even reduced below the level of single offshoring it has to be pointed out that the impact on the environmental performance is very positive. The offshore order quantity and the related transport carbon emissions are reduced drastically by 9.3%, 26.8% and 42.8% for σ_1 , σ_2 and σ_3 , respectively.

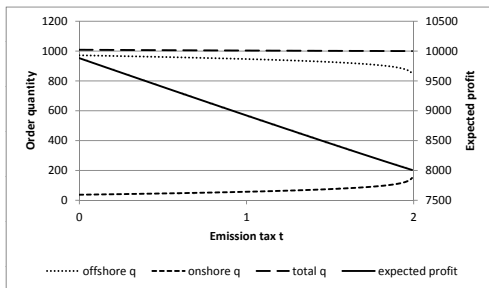
5.2 Dual sourcing with emission trading for transport

In the dual sourcing model including emission trading first the lower and upper control limits are computed depending on the demand distribution, the cost and price parameters as well as the emission buying price $b = 1.5$ and the emission selling price $s = 1.2$. The values of the emission prices are in accordance with the related literature where the buying price is assumed to be 25% higher than the selling price (Letmathe and Balakrishnan, 2005; Song and Leng, 2012). The results are summarized in Table 7.

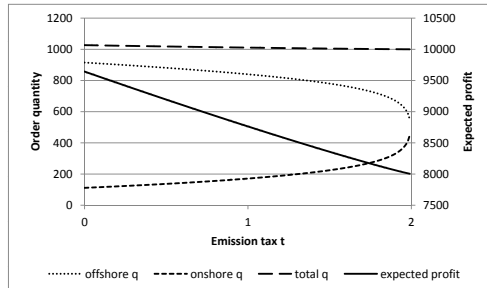
Table 7: Dual sourcing with emission trading: Lower and upper control limits

	σ_1	σ_2	σ_3
Lower control limit q^b	927	780	634
Upper control limit q^s	940	819	699

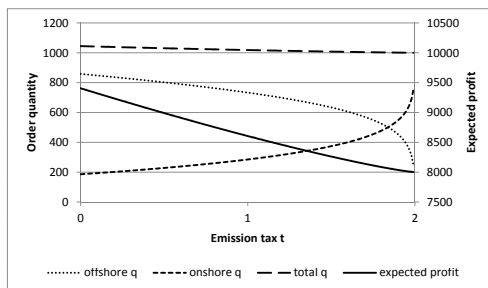
It has to be noted that the control limits can be computed independently of the emission limit L . But the value of the emission limit L has a decisive impact on the optimal decision and the corresponding expected profit. Three different cases can be identified depending on the emission limit L . We illustrate the impact of the two-sided control limit policy given with (16) by taking three



(a) $\mu = 1000$ and $\sigma_1 = 50$



(b) $\mu = 1000$ and $\sigma_2 = 150$



(c) $\mu = 1000$ and $\sigma_3 = 250$

Figure 2: Offshore, onshore and total order quantity and expected profit depending on the emission tax t

different emission limits (low, medium, high) for each demand scenario. The results for the dual sourcing model with emission trading in comparison to the basic dual sourcing model are summarized in Table 8 showing the optimal offshore order quantity and the resulting expected profit for each case. Varying the values of the prices for emission allowances, b and s , would change the lower and upper control limit whereby increasing values lead to decreasing limits, see (13) and (14).

By comparing these results to the basic dual sourcing model without environmental regulations it can be seen that the offshore order quantity with emission trading is always lower than the offshore order quantity in the basic model. This is simply due to the fact that $q^L \leq q^*$ because additional cost parameters, i.e. the emission buying price b and the emission selling price s , are considered. The introduction of emission trading helps to limit the offshore order quantity to at least q^s , i.e. the maximal offshore order quantity, irrespective of the emission limit L . This results in a reduction of transport carbon emissions of 3.3%, 10.5% or 18.6% for $s = 1.2$ and σ_1, σ_2 and σ_3 , respectively. The maximal reduction of transport carbon emissions which can be achieved when q^b is ordered is between 4.6% and 26.2% for $b = 1.5$ depending on the demand scenario. For low emission limits, the expected profit is reduced by 2.3% to 5.8% while for high emission limits, even a slight increase of the expected profit by 0.5% to 2.7% can be achieved.

Figures 3(a), 3(b) and 3(c) show how the profit curves develop in dependence on the offshore

Table 8: Optimal offshore order quantity and resulting expected profit for three values of emission limit L

(a) $\mu = 1000$ and $\sigma_1 = 50$			
	Emission limit L	Offshore q (% change compared to basic DS model)	Expected profit (% change compared to basic DS model)
Low	$L = 800$	927 (-4.6)	9652 (-2.3)
Medium	$L = 935$	935 (-3.8)	9854 (-0.3)
High	$L = 1000$	940 (-3.3)	9932 (+0.5)

(b) $\mu = 1000$ and $\sigma_2 = 150$			
	Emission limit L	Offshore q (% change compared to basic DS model)	Expected profit (% change compared to basic DS model)
Low	$L = 600$	780 (-14.8)	9257 (-4.0)
Medium	$L = 800$	800 (-12.6)	9555 (-0.9)
High	$L = 1000$	819 (-10.5)	9797 (+1.6)

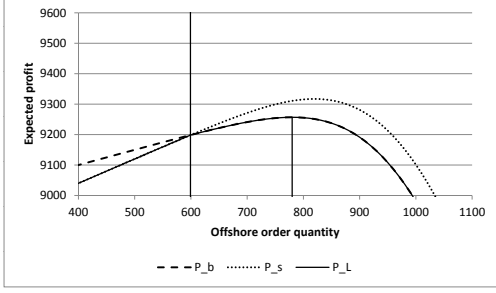
(c) $\mu = 1000$ and $\sigma_3 = 250$			
	Emission limit L	Offshore q (% change compared to basic DS model)	Expected profit (% change compared to basic DS model)
Low	$L = 400$	634 (-26.2)	8861 (-5.8)
Medium	$L = 6650$	665 (-22.5)	9257 (-1.6)
High	$L = 1000$	699 (-18.6)	9662 (+2.7)

order quantity for the demand distribution with $\mu = 1000$ and $\sigma = 150$ and the three cases of the emission limit L (low, medium, high), see also (12). The expected profit $P_L(q)$ is composed of the two curves $P_b(q)$ and $P_s(q)$ whereby depending on the emission limit different parts of the profit curves are realized. For low emission limits, i.e. $L < q^b$, the expected profit $P_b(q)$ is generated while for high emission limits, i.e. $L > q^s$, the expected profit $P_s(q)$ is realized. For medium emission limits, an offshore order quantity equal to L is ordered and the expected profit $P(L)$ is generated, see also (15).

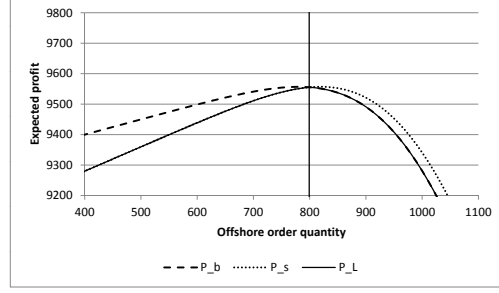
It is not straightforward whether the introduction of emission trading increases or decreases the expected profit of the company compared to the basic dual sourcing model. Depending on the value of the emission limit L the impact can be positive or negative. It is intuitive that a higher emission limit L leads to a higher expected profit because either less emission allowances have to be bought or more emission allowances can be sold. In Figures 4(a), 4(b) and 4(c) the off- and onshore order quantities as well as the expected profit depending on the emission limit L are presented. It can be seen that the expected profit increases with the emission limit L . For low and high emission limits the expected profit is a linear function with slope b and s , respectively, see also (8) and (9).

For policy-making it is of interest that q^b is the minimal offshore order quantity from the company's perspective. Under emission trading the company never orders less than q^b from the offshore supplier even when emission allowances have to be bought for that. Therefore, for policy-making it does not seem to be reasonable to set the emission limit L below q^b . An emission limit $L < q^b$ would not help to reduce transport carbon emissions but would only lower the economic performance and competitiveness of the company.

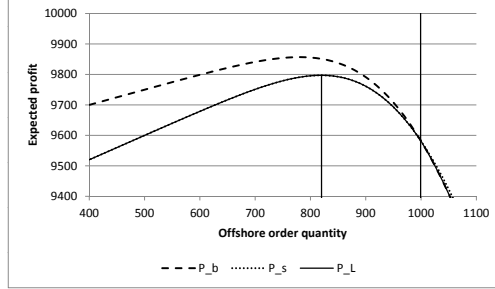
The results for the dual sourcing model with an emission limit $L = q^b$ are summarized in



(a) for $L = 600 : L < q^b$



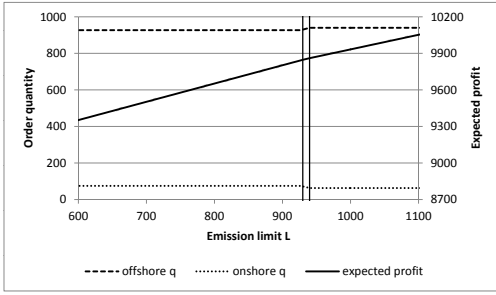
(b) for $L = 800 : q^b \leq L \leq q^s$



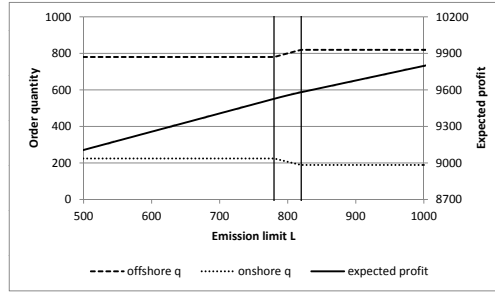
(c) for $L = 1000 : L > q^s$

Figure 3: Dual sourcing with emission trading: Expected profit depending on the offshore order quantity for normally distributed demand with $\mu = 1000$ and $\sigma_2 = 150$

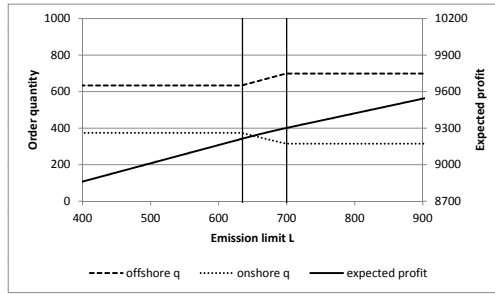
Table 9. The results are compared to the basic dual sourcing model and to the dual sourcing model including an emission tax. From the perspective of policy-making, by setting $L = q^b$ the maximal reduction of transport carbon emissions which is possible under an emission trading scheme is reached. Compared to the basic dual sourcing model the transport carbon emission are reduced by 4.6% to 26.2%. It seems that an emission limit $L = q^b$ is also compatible from the company perspective as it does not significantly reduce the economic performance; the expected profit is only reduced by 0.4%, 1.2% and 2.1% for σ_1 , σ_2 and σ_3 , respectively, compared to basic dual sourcing. Furthermore, if the company had to choose between a transport emission tax and emission trading the company would be much better off with an emission trading scheme for transport. Assuming an emission tax equal to the emission buying price, i.e. $t = b = 1.5$, the expected profit can be improved by 16.4%, 14.0% and 11.4% for σ_1 , σ_2 and σ_3 , respectively. By setting $L = q^b$ and varying the emission buying price b it turns out that the expected profit is less sensitive to increasing values of the emission buying price b . This means that the economic performance is less strongly harmed by an increasing emission buying price b . This is in contrast to the dual sourcing model with emission tax where the expected profit decreases nearly linearly with increasing emission tax t (see Figure 2).



(a) $\mu = 1000$ and $\sigma_1 = 50$



(b) $\mu = 1000$ and $\sigma_2 = 150$



(c) $\mu = 1000$ and $\sigma_3 = 250$

The vertical lines represent the lower and upper control limit, see also Table 7.

Figure 4: Off- and onshore order quantity and expected profit depending on emission limit L

6 Implications for management and policy-making

Based on the analytical and numerical results, it can be concluded that by using a dual sourcing strategy instead of a single offshore sourcing strategy the negative environmental impact of transport can be reduced while the economic performance is improved. Dual sourcing becomes even more environmentally friendly if regulations for transport carbon emissions are included. The considered environmental regulations help to control the company's decision to some extent and the transport carbon emissions can be further reduced. However, the impact on the expected profit can be positive or negative depending on the regulatory measure and the policy parameters.

6.1 Implications for management

The introduction of an emission tax for the transport from the offshore supplier narrows the cost advantage of the offshore supplier and therefore induces the company to reduce its offshore order quantity compared to the basic dual sourcing model. Thereby, the transport carbon emissions can be further lowered which improves the environmental performance of the company. But at the same time the economic performance of the company is severely harmed and the expected profit falls below the value of the basic dual sourcing model. The expected profit in the dual sourcing model with

Table 9: Dual sourcing with emission trading $L = q^b$: Optimal offshore order quantity and expected profit

	σ_1	σ_2	σ_3
Optimal offshore order quantity $L = q^b$	927	780	634
Difference to basic dual sourcing in %	-4.6	-14.8	-26.2
Difference to dual sourcing with $t = 1.5$ in %	0.0	0.0	0.0
Expected profit with $L = q^b$	9840	9527	9206
Difference to basic dual sourcing in %	-0.4	-1.2	-2.1
Difference to dual sourcing with $t = 1.5$ in %	+16.4	+14.0	+11.4

emission tax is even lower than in the single offshore sourcing model (for an emission tax $t = 1.5$).

By implementing an emission trading system for transport the ordering decision of the company can also be guided to some extent. When considering a buying and a selling price for emission allowances with $b \geq s$ and $L > 0$ the optimal decision is given by a two-sided control-limit policy. Irrespective of the emission limit L , a reduction of the offshore order quantity and the related transport carbon emissions can always be achieved with the introduction of emission trading for transport compared to the basic dual sourcing model because $q^L \leq q^*$. For medium to high emission limits, only a slight decrease of the expected profit has to be accepted compared to the basic dual sourcing model. Even an increase of the profit can be achieved when enough emission allowances can be sold due to a high emission limit. But the influence of emission trading on the ordering decision and thereby on the environmental improvement is limited. As the company never orders less than q^b an emission limit below that value does not improve the environmental performance of the company. Setting the emission limit to $L = q^b$ seems to be compatible for the company with respect to economic and environmental performance; compared to the basic dual sourcing model the expected profit is almost the same but transport emissions are considerably reduced. In Table 9, an emission reduction of 4.6% to 26.2% is shown. With an emission tax of $t = b = 1.5$ the same reduction of transport carbon emissions could be achieved. However, it has to be noted that the expected profit in the dual sourcing model with emission trading is considerably higher than in the dual sourcing model with emission tax. Compared to dual sourcing with an emission tax, the expected profit in the dual sourcing model with emission trading can be increased by 11.4% to 16.4%. This result indicates that emission trading is preferred to an emission tax from the company's perspective.

6.2 Implications for policy-making

From the perspective of policy-making, it can be concluded that the emission limit should be set to q^b . Thereby the negative environmental impact of transport can be reduced and the company can still achieve a considerably high profit. Policy-makers have to be aware of the fact that the minimal offshore order quantity q^b strongly depends on the demand distribution F and on the emission buying price b , see (13). Setting $L = q^b$ and using (13) results in the following relation between the emission limit L and the emission buying price b :

$$b = d \cdot (1 - F(L)) - (c - z) \cdot F(L) \quad (17)$$

From that the basic relationship between the parameters can be seen: b decreases as L increases. Also, Hua et al. (2011) point out that the emission price could be modelled as a decreasing function of the emission cap, i.e. emission limit. For the offshore order quantity equal to L , (17) describes the difference between the expected onshore ordering costs $d \cdot (1 - F(L))$ and the expected offshore ordering costs $(c - z) \cdot F(L)$. In newsvendor terminology it is the difference of the expected

cost of understocking and the expected cost of overstocking for the basic dual sourcing model. Thus, the emission buying price b and the emission limit L should be fixed by considering the economic situation of the industry which is expressed by the offshore product cost c , the onshore product cost $(c + d)$ and the market demand of the product reflected by the demand distribution F . If the policy parameters are fixed in the described manner, the economic and the environmental performance of the company can be balanced by achieving a high reduction of transport carbon emissions while a satisfying expected profit can be generated.

7 Conclusions

In our work we evaluate the economic and environmental sustainability of dual sourcing with an offshore and an onshore supplier. In addition to evaluating dual sourcing based on expected profit, we also consider transport carbon emissions which are directly related to the offshore order quantity. We model two different regulations which could be valid for the transport sector in the future. We assume firstly that a linear emission tax is imposed on transport from the offshore supplier and secondly that an emission trading scheme for transport activities is valid. Thus, emission allowances have to be bought if the transport activity is too high or can be sold if not all emission allowances are used. We show that dual sourcing helps to reduce transport emissions compared to a single offshore sourcing strategy. Furthermore, dual sourcing helps to improve economic performance measures, like expected profit and customer service. By including a linear emission tax on transport the onshore supplier is used to a larger extent and thereby the transport carbon emissions are further reduced. But as a negative side-effect the expected profit is lowered as well. But if emission trading is used instead of an emission tax, the offshore order quantity and the related transport emissions can be reduced while the economic performance measures are nearly not harmed.

Our work helps to gain insights into new trade-offs which arise if in addition to economic criteria also environmental ones are considered. It can provide decision support for individual companies on how much to order from a certain supply source. Furthermore, we model different regulation schemes and therefore, our model can also be used to derive implications for policy-making with respect of the design of environmental regulations. However, it has to be noted that our work can be seen as a step in a new and emerging field of research. Our work also provides a starting point for further research opportunities. It has been shown that the parameters of the regulations, i.e. the emission tax, the emission limit and the prices of the emission allowances, are critical values. So further research is needed about how these parameters can be reasonably set and how they influence each other. For instance, the prices for emission allowances are not set by policy makers but determined by the market as a function of the emission limit. So the emission prices could be modelled as a decreasing function of the emission limit or with the help of a probability distribution function reflecting the stochastic behaviour of the prices. Furthermore, new developments of emission trading, such as the auctioning of emission allowances, could be considered in further research.

References

- Benjaafar, S., Li, Y., Daskin, M., 2010. Carbon footprints and the management of supply chains: Insights from simple models. Working Paper, University of Minnesota.
- Bloemhof-Ruwaard, J. M., van Beek, P., Hordijk, L., van Wassenhove, L. N., 1995. Interactions between operational research and environmental management. *European Journal of Operational Research* 85 (2), 229–243.
- Bonney, M., Jaber, M. Y., 2011. Environmentally responsible inventory models: Non-classical models for a non-classical era. *International Journal of Production Economics* 133 (1), 43–53.
- Cachon, G., Terwiesch, C., 2009. *Matching Supply with Demand – An Introduction to Operations Management*, 2nd Edition. McGraw-Hill.
- Chen, X., Benjaafar, S., Elomri, A., 2011. The carbon-constrained EOQ. Working Paper, University of Minnesota.
- Chopra, S., Meindl, P., 2010. *Supply Chain Management – Strategy, Planning & Operations*, 4th Edition. Pearson.
- Chung, C.-S., Flynn, J., Kirca, Ö., 2008. A multi-item newsvendor problem with preseason production and capacitated reactive production. *European Journal of Operational Research* 188 (3), 775–792.
- Dyckhoff, H., Lackes, R., Reese, J., 2004. *Supply chain management and reverse logistics*. Springer.
- EcoTransIT, 2010. EcoTransIT – Make your own calculation. Online.
URL <http://www.ecotransit.org/ecotransit.en.phtml>
- EEA, 2008. Greenhouse gas emission trends and projections in Europe 2008. European Environment Agency.
- EEA, 2009. Greenhouse gas emission trends and projections in Europe 2009. European Environment Agency.
- European Community, 2005. Questions and answers on emissions trading and national allocation plans. Online.
URL <http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/05/84&format>
- European Community, 2008. Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008 amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community. Online.
URL <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:008:0003:0021:EN:PDF>
- Eurostat, 2009. Panorama of Transport. Online.
URL http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-DA-09-001/EN/KS-DA-09-001-EN.PDF
- Ferreira, J., Prokopets, L., 2009. Does offshoring still make sense? *Supply Chain Management Review* 13 (1), 20–27.

- Flapper, S. D. P., van Nunen, J. A., Van Wassenhove, L. N. (Eds.), 2005. *Managing Closed-Loop Supply Chains*. Springer.
- Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., van der Laan, E., van Nunen, J. A. E. E., van Wassenhove, L. N., 1997. Quantitative models for reverse logistics: A review. *European Journal of Operational Research* 103 (1), 1–17.
- Gallego, G., Moon, I., 1993. The distribution free newsboy problem: Review and extensions. *The Journal of the Operational Research Society* 44 (8), 825–834.
- Gong, X., Zhou, S. X., 2011. Optimal production planning with emissions trading. In: 2011 MSOM Annual Conference.
- Hoen, K., Tan, T., Fransoo, J., Houtum, G., 2012. Effect of carbon emission regulations on transport mode selection under stochastic demand. *Flexible Services and Manufacturing Journal* 24, 1–26. URL <http://dx.doi.org/10.1007/s10696-012-9151-6>
- Hua, G., Cheng, T., Wang, S., 2011. Managing carbon footprints in inventory management. *International Journal of Production Economics* 132 (2), 178–185.
- Huebler, M., 2009. Can carbon based import tariffs effectively reduce carbon emissions? Working Paper, Kiel Institute for the World Economy.
- IPCC, 2007. IPCC Fourth Assessment Report. Online. URL http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm
- Khouja, M., 1996. A note on the newsboy problem with an emergency supply option. *The Journal of the Operational Research Society* 47 (12), 1530–1534.
- Khouja, M., 1999. The single-period (news-vendor) problem: Literature review and suggestions for future research. *Omega* 27 (5), 537–553.
- Letmathe, P., Balakrishnan, N., 2005. Environmental considerations on the optimal product mix. *European Journal of Operational Research* 167 (2), 398–412.
- Nahmias, S., 2009. *Production and Operations Analysis*. McGraw-Hill.
- OECD, 2001. *Domestic transferable permits for environmental management: Design and implementation*. Organisation for Economic Co-Operation and Development.
- Radulescu, M., Radulescu, S., Radulescu, C. Z., 2009. Sustainable production technologies which take into account environmental constraints. *European Journal of Operational Research* 193 (3), 730–740.
- Raux, C., 2010. The potential for CO2 emission trading in transport: The case of personal vehicles and freight. *Energy efficiency* 3 (2), 133–148.
- Rockafellar, R. T., 1997. *Convex analysis*. Princeton University Press.
- Rosič, H., Bauer, G., Jammerneegg, W., 2009. A framework for economic and environmental sustainability and resilience of supply chains. In: Reiner, G. (Ed.), *Rapid Modelling for Increasing Competitiveness*. Springer London, pp. 91–104.

- Silver, E. A., Pyke, D. F., Peterson, R., 1998. *Inventory Management and Production Planning and Scheduling*. Wiley.
- Song, J., Leng, M., 2012. Analysis of the single-period problem under carbon emissions policies. In: Choi, T.-M. (Ed.), *Handbook of Newsvendor Problems*. Vol. 176 of *International Series in Operations Research & Management Science*. Springer New York, pp. 297–313.
- Srivastava, S. K., 2007. Green supply-chain management: A state-of-the-art literature review. *International Journal of Management Reviews* 9 (1), 53–80.
- Subramanian, R., Talbot, F. B., Gupta, S., 2010. An approach to integrating environmental considerations within managerial decision-making. *Journal of Industrial Ecology* 14 (3), 378–398.
- van Mieghem, J. A., 2008. *Operations Strategy – Principles and Practice*. Dynamic Ideas.
- Walker, H., Di Sisto, L., McBain, D., 2008. Drivers and barriers to environmental supply chain management practices: Lessons from the public and private sectors. *Journal of Purchasing & Supply Management* 14 (1), 69–85.
- Warburton, R. D., Stratton, R., 2005. The optimal quantity of quick response manufacturing for an onshore and offshore sourcing model. *International Journal of Logistics: Research and Applications* 8 (2), 125–141.