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Where to exert abatement effort for sustainable operations considering supply chain interactions?

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Abstract

We consider the problem of how firms can take into account the dynamics of supply chain interactions when "greenifying" their operations. We introduce a framework which firms can use in defining the right optimization problem and system boundaries when they want to exert abatement effort by considering the supply chain wide effect of abatement options. Our framework, which is applied at a chemical company, can help firms in determining which impact certain decisions have on other firms' emissions in the supply chain and the resulting total footprint of the product.

Keywords: Carbon emission; Carbon footprint; Sustainable operations; Value chain; Operations management

1 Introduction

The widespread concern over global warming puts pressure on companies to reduce carbon emissions and become green. It is imminent that the global pressure will increase in an increasing manner and that sustainability will -and should- increasingly drive Supply Chain Management Decisions. The external pressure on the companies is basically three-fold:

1. Customers: Individual consumers in B2C environments (especially in developed countries), as well as customers in B2B environments apply increasing pressure to improve sustainability.

2. Regulations: There are legal requirements of the European Union and some national governments in the area of carbon dioxide and also other greenhouse gas (GHG) emissions, which enforce the companies to become greener. Governments have also changed the laws to reflect a cradle-to-grave perspective, which makes it essential to consider the problem whole supply chain-wide. A very important regulation is the EU Emission Trading Scheme (ETS), which is the largest multinational, multi-sector greenhouse gas emissions trading scheme worldwide. The ETS is currently restricted in scope, but it already covers approximately half of the EU's carbon emissions and is expected to be expanded (sector wise, scope wise, and country wise).

3. Environmental groups: Initiatives such as the Carbon Disclosure Project (CDP) gain more attention and support globally. In particular, CDP reports indicate that 82% of Global 500 companies disclosed their emissions in 2012 (Carbon Disclosure Project, 2012). Europe has been leading in both disclosing its emission and introducing ETS, but there are also other initiatives and developments making a global emission trading scheme visible in the horizon. Currently, the carbon market in the United States is largely a voluntary market dominated by financial players and companies that want to hedge their exposure to potential future emission-reduction rules. Nevertheless, the northeastern states have started the 'Regional Greenhouse Gas Initiative' in 2009[1], which is the first mandatory, market-based cap-and-trade program to cut carbon emissions in the United States. Similarly, the California Air Resources Board (CARB) adopted a Cap and Trade Regulation on October 20, 2011[2]. Furthermore, there are initiatives such as Western Climate Initiative (WCI)[3] and Chicago Climate Exchange (CCX)[4], where the former is an initiative started by states and provinces along the western rim of North America to combat climate change caused by global warming, independent of their national governments, and the latter is a voluntary, legally binding greenhouse gas reduction and trading system for emission sources and offset projects in North America and Brazil.

Companies increasingly realize that often a large part of their carbon footprint is outside of their control, i.e. Scope 3 emissions, following the terminology of the GHG protocol. Nevertheless, many companies that are not even bound to regulatory enforcements measure, report, and offset their emissions, including their Scope 3 emissions, as a part of their corporate responsibility policy. For example, Natura Cosmeticos has the policy of offsetting more than its declared emissions -to cover for uncertainties in the measurement process-, resulting in "carbon negative" products, even though only 3% of their emissions are of Scope 1 and 1% of their emissions are of Scope 2, resulting in 96% of their declared emissions being accounted for in Scope 3[5].

Other than the external pressure on companies to become green, there also exist economic reasons for companies to "green" their supply chains, which coincide with the reasons for them to green their operations: Partly because of the correlation between cost and energy use, i.e. carbon hot spots are good places to look for potential cost savings; and partly for marketing reasons, where a green image might help them gain competitive advantage. Whether it is a regulation or own initiative,

[1] http://www.rggi.org, last accessed June 4, 2013
[2] http://www.c2es.org, last accessed May 28, 2013
[3] http://www.wci-inc.org, last accessed May 28, 2013
[4] http://www.chicagoclimatex.com, last accessed June 4, 2013
[5] Natura Cosméticos. 2009. Carbon Neutral 2009. http://www2.natura.net/Web/Br/Inst/CarbonoNeutro2009/src/EN/_PDF/NaturaCarbonNeutral2009.pdf, last accessed June 11, 2013

companies that compensate for their emissions have direct economic consequences of their emission declarations which are mostly verified by independent bodies. Nevertheless, one critical question prevails: which company in the supply chain can be accounted for emissions of a final product or service? Each company in a supply chain contributes to the total carbon footprint of a product or service and also each company can exert effort in minimizing its contribution to this carbon footprint. However, such an approach overlooks the dynamics of supply chain interactions and neglects the operations in the upstream or downstream supply chain that are affected by these decisions. It can be therefore also useful for a company to exert effort in lowering the emissions of operations more upstream or downstream in the supply chain. This can for example be accomplished by changing the dimensions of a product, the required storage conditions, the durability, etc., resulting in less energy-intensive process requirements. For example, manufacturers of products that have a high water content and of which the water needs to be mixed with the product under special circumstances (e.g. under pressure, at a specific temperature etc.) can try to produce and sell concentrates (i.e. semi-finished product). The customer can finalize the product by adding the water itself under these special circumstances. Selling semi-finished products in this way and collaborating with the customer in order to finalize the product can reduce packaging waste because the volume of the product will be less and it would also decrease transport related carbon-emissions. Another example is a product of Eastman Chemical Company that can be sold to customers in a solid state or in a molten state. These different states have not only an impact on Eastman's carbon emissions but also on its customer emissions. The storage conditions of the solid state is different than that of the molten state: the solid state can be stored as pastilles in bags and the molten state needs to be stored in tanks that keep the product on a specific temperature 24/7 to assure that it will remain molten. Keeping a product on a specific temperature requires more energy than just storing it in a warehouse. The impact on carbon emission of the two different states will be discussed in more detail in Section 4 of this paper. Lowering the carbon emissions can also be accomplished by collaboration, coordination, economic power or information sharing. For example a manufacturer of fried potatoes can reward farmers who produce potatoes with low water content. In this way, the fried potato manufacturer decreases his emissions because potatoes which have low water content require less frying time and thus require less energy (The Carbon Trust, 2006).

Note that the improvements at a certain actor and his suppliers would not only result in a decrease in Scope 1, 2, and 3 emissions of that actor, but it could also abate the emissions of other parties in the supply chain for the reasons stated above -among others-, which goes beyond the scope classification and defined responsibilities in the GHG protocol (say, “Scope 3+” emissions). Those emissions also need to be taken into account if a complete supply chain perspective is to be considered instead of a myopic approach. In this article we introduce a simple but effective framework for addressing the problem of GHG emissions in a general supply chain with any number of firms, decomposing the total footprint into separate footprint components, each of which can be influenced by any combination of any number of firms in the supply chain. With that structure, we are able to represent the total footprint as a function of the decisions made in the supply chain. This framework enables firms to define the right optimization problem and also the right system boundaries.

For the parties collaborating and coordinating their abatement efforts, the parties involved in the supply chain exert effort to abate their emissions, which might be internally bound to offsetting all emissions that are attributed to a company, even if this concerns Scope 3 emissions and beyond - which we have referred to as Scope 3+ above-. A company that participates in the offsetting approach would be likely to do so with the motivation of social responsibility, competitive advantage, or customer requirements, as Scope 3 emissions are not regulated (yet). In any case, such a company has a natural additional motivation to abate its emissions: offsetting costs. Note that the carbon price at a cap-and-trade scheme serves a similar purpose, where the emissions above the cap are "offset" in the sense that the sellers of these emission rights have emitted less than what they are allowed to. Furthermore, it is most likely that a powerful leading company is involved in such a collaboration and coordination process, encouraging or even "forcing" her supply chain partners to abate their emissions. For example, WalMart conducts detailed carbon footprint analyses and sets improvement targets for her suppliers[6]. In that case, while WalMart's motivation is in terms of social responsibility and competitive advantage, it becomes an absolute necessity for the suppliers of WalMart to abate their emissions in order to be able to continue business with WalMart, as long as it is profitable to do so. A participating company's objective is then to maximize his value added less all carbon related costs. One could argue that coordination is not necessarily a result of companies not being willing to pay for offsetting, but an effort to actually cut down the emissions rather than "paying off" for them. Those who oppose offsetting also refer to non-verified offsetting options that actually do not have a significant or even positive impact on carbon emissions.

The major complicating factor in conducting such an analysis is that many emissions result from activities that multiple parties in the supply chain (can) influence. We depart from existing supply chain literature on carbon footprints, which assumes that emissions are uniquely and unambiguously linked to specific actors in the supply chain, and introduce a more general framework where carbon

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[6] Cremmins, B. 2013. CDP and Walmart: A partnership to reduce suppliers' greenhouse gas emissions. Walmart February 13, 2013. http://www.walmartgreenroom.com/2013/02/cdp-and-walmart-a-partnership-to-reduce-suppliers-greenhouse-gas-emissions/, last accessed June 11, 2013

footprints consist of multiple components, each of which can be influenced by one or more supply chain parties.

Our contribution in this paper is twofold: First, we propose a modelling framework to determine which impact certain decisions made by firms in a supply chain have on the total footprint of a product in the supply chain. Second, we introduce a case study where we apply our proposed framework and provide insights based on this case. The case study that was performed at Eastman Chemical Company, which has the ability to change the property of one of their products, in which case the buyer firm needs different production processes or keeping conditions. By using the proposed framework, the right boundaries were defined and the supply chain impact of the decision to change the property of the product was analysed, leading to a different conclusion then the one when the boundaries are myopically defined and the supply chain impact is ignored.

Section 5 describes the case study performed at Eastman Chemical Company. Eastman is a global specialty chemicals company that manufactures chemicals, fibers and plastic materials that are found in products people use every day. The case study treated in this report was initiated by Eastman. Particularly due to the fact that natural resources are becoming scarcer Eastman is committed to embed sustainability in their product development and innovation process, which does not only make sense for their business, but also makes sense for the world.

2 Literature

In this paper we focus on and aim to further develop two areas: sustainable supply chains and supply chain collaboration (or environmental collaboration). Accordingly, we first review the literature in which abatement options to reduce GHG emissions in supply chains are treated, and then the literature on supply chain collaboration. Seuring and Muller (2008) define sustainable supply chain as "the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e. economic, environmental and social, into account which are derived from customers and stakeholders' requirements". Literature reviews of Kleindorfer et al. (2005), Corbett and Klassen (2006), Srivastava (2007) show that research tends to be highly focused on abatement options like recycling or reuse. In addition, more and more articles are focused on reducing GHG emissions by optimizing operational decisions across the supply chain. For example, Benjaafar et al. (2013) introduce various variants of traditional lot sizing models which minimize costs and incorporate carbon dioxide emissions considerations. Hua et al. (2011) developed a modified EOQ model with which they examine how carbon emission trading mechanisms influence inventory management decisions. Hoen et al. (2014) analyze the problem of transport mode choice and focus on the impact of regulations and carbon costs. A situation is considered in which a company has the option to choose between different modes of transport to receive goods from its supplier. Companies can use this analysis to decide which transport mode to select when considering the environment. In our paper we also consider what kind of effects this kind of decision making has on other operations more up and/or downstream in the supply chain.

The carbon footprint of an entire supply chain is typically determined by using life cycle analysis (LCA). LCA can be used to assess and evaluate the environmental burden of products or services through all phases of its life. All types of impact upon the environment are covered in the term environmental burden, including emissions of greenhouse gases (GHG), different types of land use and extraction of different types of resources. An LCA limited to GHG emissions is often called carbon footprinting. Sundarakani et al. (2010) developed an analytical model that can be used to determine the carbon footprint of an entire supply chain. With the model of Sundarakani et al. (2010) companies can analyse which stage of a supply chain accumulates waste and can use this information to implement abatement options to reduce carbon emissions. Our study complements LCA by focusing on supply chain impact of abatement activities on processes that directly or indirectly influences carbon emissions of other parties in the supply chain.

Activities regarding green supply chain management also require collaboration with both suppliers and customers. Despite all efforts in the area of green supply chain management, literature is scarce with respect to environmental supply chain collaboration. Supply chain collaboration is defined as two or more companies within a supply chain sharing the responsibilities of exchanging common planning, management, execution, and performance information (Anthony, 2000; Vachon & Klassen, 2008). Vachon and Klassen (2006) split the inter-organizational activities in green supply chain management into environmental supply chain collaboration and environmental monitoring. Supply chain collaboration can be defined as 'activities comprising a direct involvement of the buying organization with its suppliers to jointly develop environmental solutions' (Vachon & Klassen, 2006). While this definition only focuses on the organization-supplier relationship we would like to stress that collaboration is not only a relationship between the organization and parties more upstream in the supply chain but also between the organization and parties more downstream in the supply chain. Vachon & Klassen (2008) examined the impact of environmental supply chain collaboration on manufacturing performance. Their study showed that environmental collaboration with suppliers was linked to improving processed based-performance and collaboration with customers was linked to improving product based-performance. In our paper we stress the fact that it is also important to know what kind of impact environmental collaboration with a supplier has on activities more downstream in the supply chain. For example, in the ink industry there is a measurement called volatile organic compound (VOC) which is a measurement of how many organic material in an ink will evaporate. Manufacturers in the ink industry reacted to customers' needs to reduce VOC by developing hybrid inks. During a print run, hybrid inks produce less VOC than petroleum-based printing inks (Vachon & Klassen, Environmental management and manufacturing performance: The role of collaboration in the supply chain, 2008). This however does not mean that the production of hybrid inks is cleaner than that of petroleum-based printing inks.

Caro et al. (2013) introduced a joint production model where carbon emissions of a whole supply chain are incorporated. Their paper answers the question: 'how should responsibility for the total supply chain emissions be allocated to the various firms in order to encourage jointly optimal emissions abatement effort?'. In the model that is used to tackle this question, the total footprint is decomposed into multiple processes and the emissions of each process can be affected by any company in the whole supply chain. It turns out that over-allocating emissions is required to achieve a "carbon-optimal" supply chain. While Caro et al. (2013) focus on the emission allocation problem for joint processes, our framework considers the supply chain wide effect of abatement options with the purpose of defining the right optimization problem and system boundaries.

3 Modeling Framework

In this section we introduce a realistic framework where a firm does not only cause emissions due to its own operations, but its emissions might also depend on the operations upstream and/or downstream in the supply chain due to joint processes. Similarly, the firm's operations might also affect the emissions upstream and/or downstream in the supply chain. We define joint processes in the general sense, such that a number of firms can affect total emissions of a process even through simple collaborative activities like information sharing or the lack of it. Such a framework enables representing the total footprint as a function of the decisions made in the supply chain. With this framework firms can define the right optimization problem and system boundaries. We focus on carbon dioxide emissions in this article, but it is also possible to use the same framework for other GHG emissions. We also consider a single product setting for simplicity of exposition.

The carbon accounting standard of the GHG protocol is used as a baseline in this framework. In this standard, three types of emissions are defined: Scope 1 (direct emissions, e.g. due to production processes), scope 2 (indirect emissions from energy usage) and scope 3 (other indirect emissions, e.g. due to transport). The total carbon footprint (F) of a product is the sum of its scope 1, 2, and 3 emissions, which might emanate from multiple components that are possibly carried out at different firms. Hence, multiple firms within a supply chain can influence the carbon footprint *F*. If firms collaborate as in the examples provided in Section 1, this would change their processes and impact their emissions in different scopes.

From this example we can see that a firm's decisions might affect its own emissions, as well as the other firms' emissions. We model this in our framework by separately defining the internal and external efforts (resulting in emission abatement) associated with each possible action *n* out of the set of all possible actions ***N*** of the focal firm. The reduction efforts that the firm would exert associated with each possible action *n* is given by $\mathbf{e}^i = e^i_n \; \forall \; n \in N$ for all internal efforts and $\mathbf{e}^e = e^e_n \; \forall \; n \in N$ for all external efforts. Internal efforts are the actions of the firm that influence its internal footprint F^i regarding the product (e.g. changing a production process), and external efforts are those that influence the external footprint F^e originating from the other firms in the same supply chain (e.g. changing the properties of the product, which will require operational changes at the buyer firm; or simply sharing advance demand information). We note that an internal (external) effort could require corresponding external (internal) effort, together which they constitute action *n*. Therefore, e^i_n and e^e_n may assume any value, including zero, for action *n*. Accordingly, we define the total carbon footprint of the focal firm as $F(\mathbf{e}^i, \mathbf{e}^e)$.

The decision as to how much effort a firm is going to exert in the abatement options must be aligned with the firm's sustainability strategy. We present four possibilities in Table A. Option 1 aims to minimize the total footprint subject to a total abatement budget. Option 2 is similar to option 1, except there is no overall budget to freely allocate, but separate budgets are assigned for some of the (pre-approved) actions in N. However, many firms operate under cost minimization (or profit maximization) objective and set a total footprint reduction target, as stated in options 3 and 4, where option 3 constrains the footprint with a target total footprint, and option 4 aims for a percent reduction of the current footprint with no additional efforts, denoted by F(0,0). Such reduction targets are commonly observed as in practice. To name a few examples, Tesco has committed to reduce the carbon footprint of the products they sell by 30% by 2020[7] and Unilever committed to halve the greenhouse gas impact of their products across the lifecycles by 2020[8]. This option might be seen as the most environmental friendly one as long as the reduction target is ambitious enough, because it would then mean that also costly effort needs to be exerted if the ``low hanging fruit" will

[7] Tesco. 2012. Corporate Responsibility Review 2012. http://www.tescoplc.com/files/pdf/reports/tesco_cr_review_2012.pdf, last accessed June 4, 2013

[8] Unilever Sustainability Living Plan, Available at http://www.unilever.com/sustainable-living/uslp/, last accessed June 4, 2013

not be sufficient. On the other extreme, if there is abundant number of cost-efficient actions for abatement, options 1 and 2 might be better for the environment, as abatement will not stop when easy targets are reached. It is of course possible to define other optimization strategies than the ones in table 1.

Table 1 optimization strategies

Option	Minimization problem
1	$Minimize\ F(\mathbf{e}^i, \mathbf{e}^e)$ $s.t.\ TC(\mathbf{e}^i, \mathbf{e}^e) \leq Total\ budget$
2	$Minimize\ F(\mathbf{e}^i, \mathbf{e}^e)$ $s.t.\ C(\mathbf{e}_n^i, \mathbf{e}_n^e) \leq Budget(\mathbf{e}_n^i, \mathbf{e}_n^e)\ \ \forall\, \mathrm{n} \in \mathrm{N}$
3	$Minimize\ TC(\mathbf{e}^i, \mathbf{e}^e)$ $s.t.\ F(\mathbf{e}^i, \mathbf{e}^e) \leq Target\ total\ footprint$
4	$Minimize\ TC(\mathbf{e}^i, \mathbf{e}^e)$ $s.t.\ F(\mathbf{e}^i, \mathbf{e}^e) \leq F(0,0) * \%\ reduction\ target$

Since the execution of a reduction action might also influence the emissions elsewhere, a crucial point for a firm in making carbon abatement effort decisions is how to define the boundaries of the problem. The left-hand side of figure 1 depicts a top-down emission framework that specifies different levels of boundary choice from a supply chain perspective, and the right-hand side depicts the corresponding costs. Level 1, which is the highest level in figure 1 represents the ideal boundary; the total carbon footprint within the whole supply chain, $F = F^i + F^e$. If supply chain collaboration is not possible for political, economic, or any other reason, or abatement efforts are considered to be an "internal issue" of the focal firm, then the second best alternative is to consider the total internal footprint F^i, which consists of three elements that can directly be influenced by the decision maker: $F^i{}_p$, the footprint originating from internal production processes that contribute to the production of the final usable product; $F^i{}_f$, the footprint due to process steps that come after production of the usable product and before transportation (e.g. packaging); and F_t, the transport footprint originating from outbound logistics, which might be internal, external, or joint, depending on the agreement made on terms of delivery. The corresponding external footprint components, $F^e{}_f$ (external emissions from process steps after transportation and before production) and $F^e{}_p$ (emissions due to the production processes of the customer) are then labelled as "out of scope" by the focal company.

When decision making cannot be bound even to level 2, then a myopic level 3 decision making is the next choice. Although we stop our framework at level 3, many practices address particular production process (say, level 4), ignoring even the interaction with other production processes. A boundary definition that is too narrow is clearly prone to result in poor decision making: The decisions made with level 2 scope could be suboptimal for the supply chain wide footprint of the product, and the decisions made with level 3 scope could be suboptimal for company wide footprint of the product. For example, if the decision is based solely on transport emissions, then the product needs to be made as small and light as possible and in such a way that it can be transported without particular air conditioning requirements, where the additional emissions in transforming the product this way might surpass the savings. On the other hand, that will not change as a function of the internal and external efforts associated with the available reduction options.

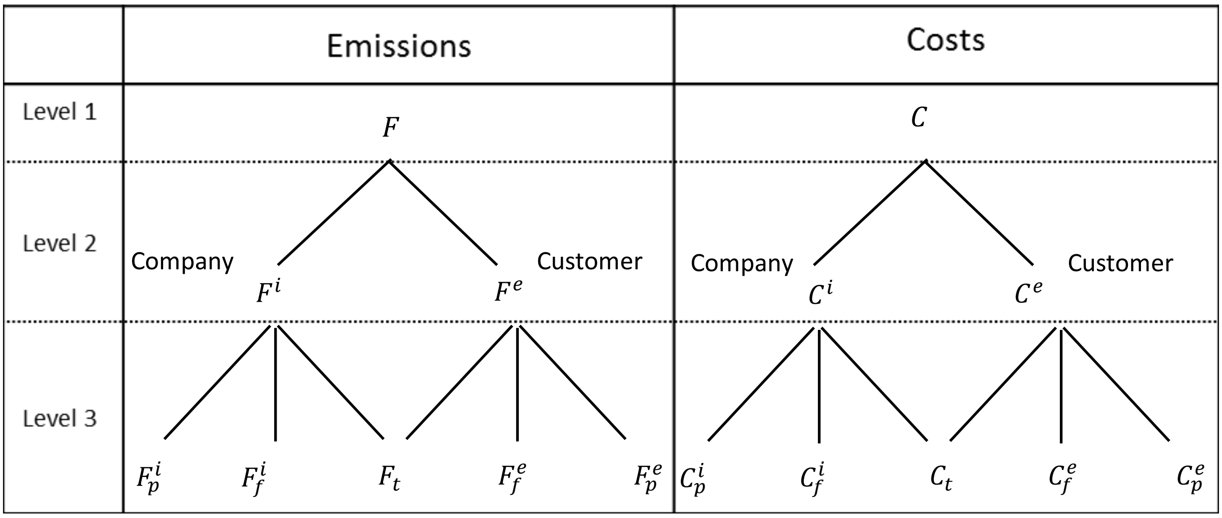

Figure 1 Top down framework

4 Case study

The framework described in the previous section was applied to the process of one of the products of the chemical company Eastman. Eastman is a global specialty chemicals company that manufactures chemicals, fibers and plastic materials that are found in products people use every day. Sustainability has become an essential component of Eastman's business, they define sustainability as 'the ability in creating value to all three aspect of the triple bottom line: environmental responsibility and stewardship, social responsibility, company's economic growth'[9]. This section describes a case study performed within Eastman.

For Eastman it is possible two sell one of its products in different states: in a solid state and in a molten state. Figure 4 in Appendix I gives an overview of the two different flows that are needed

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[9] Eastman Chemical Company 2013. Science and Sustainability: Positive progress. http://www.eastman.com/Literature_Center/Misc/2013ProgressReport.pdf, p. 22, last accessed June 20, 2013

when selling this product in these two states. The process steps before the intermediate tank are similar for both states. After the intermediate tank the process is split into two different processes, where the upper flow refers to the solid state and the lower one refers to the molten state.

If sold at solid state to a customer, the product goes from the intermediate tank to the packout. At the packout the product is first pastillated then filled into bags, stored on pallets and finally the pallets are wrapped into shrink cover. After this the packaged product is loaded onto a regular truck and shipped to the customer. At the customers' site the product must be heated again in order to use it in the remaining processes.

If a customer orders molten, the product goes from the intermediate tank to a bulk tank where it is stored. When the tank truck arrives the product is loaded into a heated bulk container and shipped to the customer. During the trip from the firm to the customer the container of the truck is kept on a high temperature. At the customers' site the product is loaded into a bulk tank again and can immediately be used in the remaining processes. Note that packout, packaging, and re-heating processes are eliminated in this case, at the expense of keeping the product hot at all times, including transport.

For this product it is not possible for Eastman to make a decision only based on its own processes; the different states require not only different process steps at Eastman but also at the customer. Due to involvement of the customer Eastman not only has to exert effort internally but also externally. The internal efforts are actions that are taken related to the packaging process. A decision must be made whether to make pastilles (solid) of the product and fill bags with these pastilles or store it in a bulk tank. In addition, effort needs to be put in transport: the solid product can be shipped with a normal truck and the molten requires a dedicated truck that is heated. This can be internal effort or external effort, depending on the agreement made on terms of delivery. For Eastman, it is internal. The external effort is the effort that is related to actions that need to be taken in order to store the product at the customer. The product can be stored in a warehouse when the product is in solid state and must be stored in a heated bulk tank when the product is in molten state. Only emissions and costs from the point in time where the processes are different until the point in time where they are similar again must be taken into account. This means that $F^i{}_f$, F_t and $F^e{}_f$ are within the boundary of this case study.

In this case, Eastman determined a specific budget for each action performed, i.e. the firm is willing to abate emissions as long as the corresponding costs do not exceed the budget. This means that the following minimization problem can be used:

$$minimize\ F_f^i + F_t + F_f^e \tag{1}$$

$$s.t.$$

$$C_f^i + C_t + C_f^e \leq Budget(\mathbf{e}_n^i, \mathbf{e}_n^e) \quad \forall\, \mathrm{n} \in \mathrm{N} \tag{2}$$

A more detailed overview of the model can be found in Appendix II. Figure 2 and 3 depict the carbon dioxide emissions and costs for the different processes described earlier. The percentage molten bulk (of the total sales of that product to the customer base) represents the “effort” level in the supply chain for greenification. In this case, both parties -Eastman and the customer(s)- need to exert effort. For example, both Eastman and its customer need to buy a bulk tank in order to store the molten product. Another effort of Eastman is to transport the molten product not in a regular tank but in a truck which has a dedicated tank that can be heated.

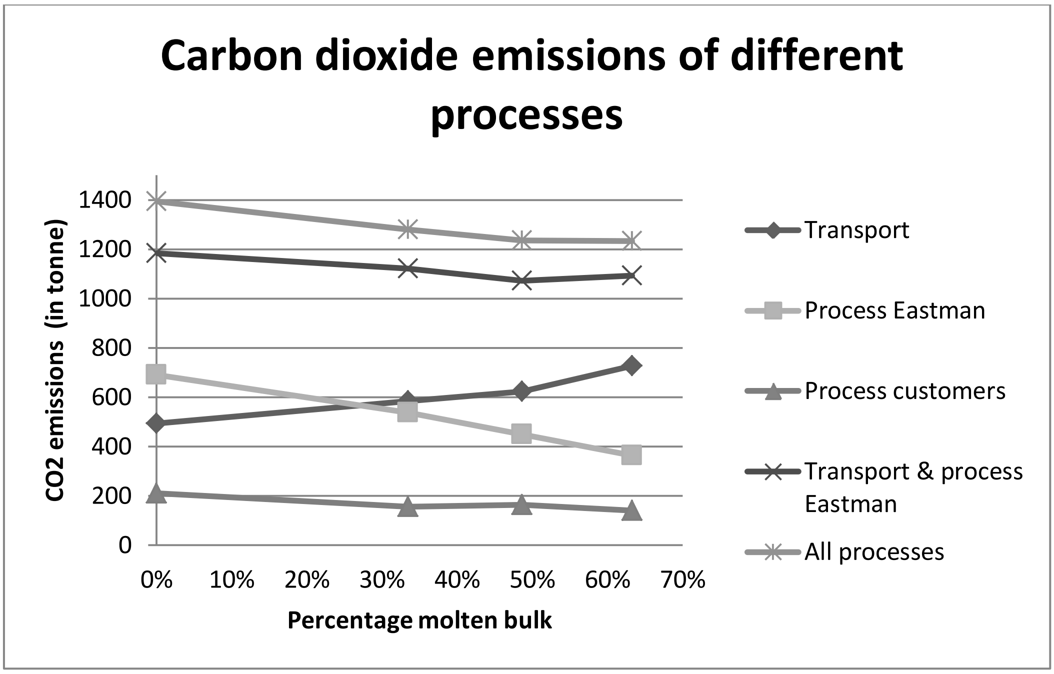

Figure 2 CO_2 emissions of different processes

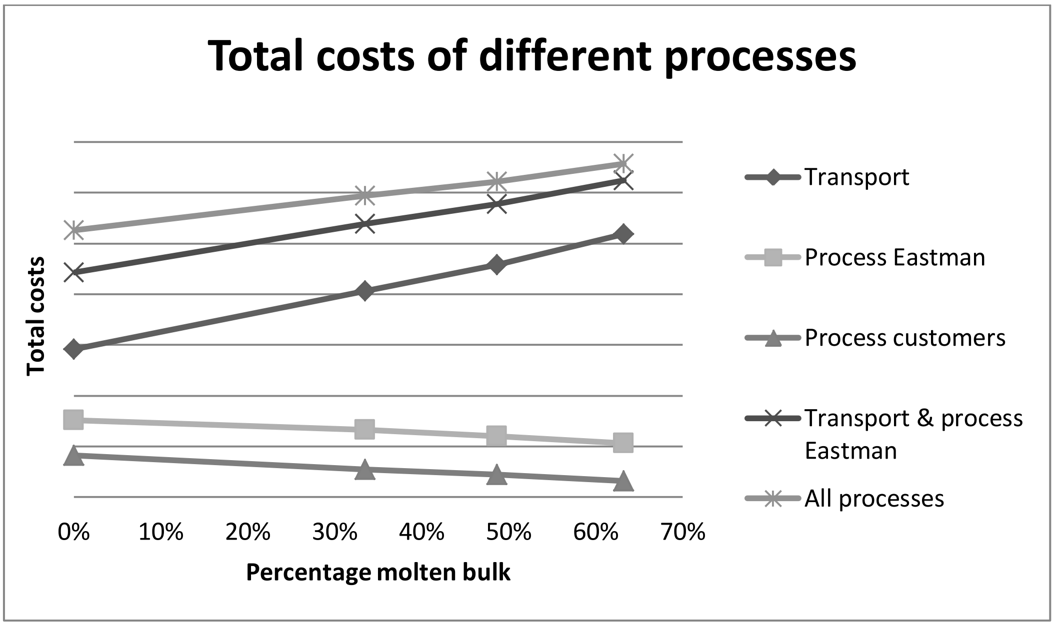

Figure 3 Total costs of different processes

Figures 2 and 3 show that the emissions and costs might be non-linear in effort level. This non-linearity has several causes. Increasing the molten volume means that a customer is added who originally bought the solid state and will buy the molten state instead. A first cause of the non-linearity is that the customers of Eastman are located in different European countries which means that for transport there are various distances that must be taken into account while calculating the transport emissions. In addition, the function to calculate the carbon dioxide emissions of the customer process is also non-linear. The explanation for this is twofold. First of all, the electricity generation in each country is different. For example, in France the primary source of electric power is nuclear power. Nuclear power is "cleaner" in terms of carbon emissions than electricity generation from fossil fuels - which is the primary source in the Netherlands. A second cause for the non-linearity is the size of the customers. Customers who have a large demand need larger tanks than customer with a small demand. This means that steam usage (and thus carbon dioxide emissions) per customer differs because the throughput time of the molten product in a tank (during which the product has to be kept hot) depends on the demand of the customer and is thus not the same for all customers.

This case study shows that it is important to define the right boundaries. When a firm defines myopic boundaries in an effort to abate carbon emissions, the decisions made might change when compared to a situation in which the impact of the supply chain is taken into account. For example, if Eastman is only considering the transport emissions F_t and costs C_t it will clearly prefer to sell solid material to its customer instead of selling molten, because carbon emissions are increasing when the percentage molten bulk increases. Shipping molten to a customer requires a special truck which can keep the molten product on high temperature and because the heated truck consumes more fuel than a regular truck the emissions increase. Total costs also increase when more molten is sold because the heated truck is more expensive. Eastman could also have defined the system boundary to be the emissions emanating from the production process. When only process steps after production and before transportation are considered (F^i_f) it is better to sell more molten to customers in terms of carbon dioxide emissions and costs (Figures 2 and 3). This is due to the fact that the packaging steps and the packout result in more emissions and higher costs than keeping the product stored in the heated tank. Nevertheless, if Eastman considers the emissions emanating from all of its own processes ($F^i_f + F_t$), it can be seen in Figure 2 that there is a cut-off point. After 49% it is not beneficial in terms of CO_2 emissions to sell molten to customers, as the increase of transport emissions is more than the saving on process emissions. Finally, if all processes within the supply chain that are influenced by the molten versus solid product decision are taken into account, the product should be sold and transported at molten form. From a cost perspective it is never beneficial to sell molten to customers.

5 Conclusion

In this paper we have focused on answering the following question: How can firms take into account the dynamics of supply chain interactions when “greenifying” their operations? To answer this question a framework is introduced which firms can use in defining the right optimization problem and boundaries when they want to exert effort in decreasing their carbon footprint. We stress that a firm’s decision to greenify its operations might not only affect its own emissions but also other firms’ emissions. Our framework can help firms in determining which impact certain decisions have on the footprint of a product. The case study that we have considered illustrates that the decision making process highly depends on which boundaries a firm takes into account and therefore we conclude that defining the right boundaries is essential for making sustainability decisions in supply chains.

Our framework can be extended to a multi-product case, where the highest level scope definition would include all emissions from all products, and Level 2 scope definition would include only the footprint due to a particular product. We also note that our methodology can be applied to other GHG emissions, water footprint, and the like.

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Appendix I

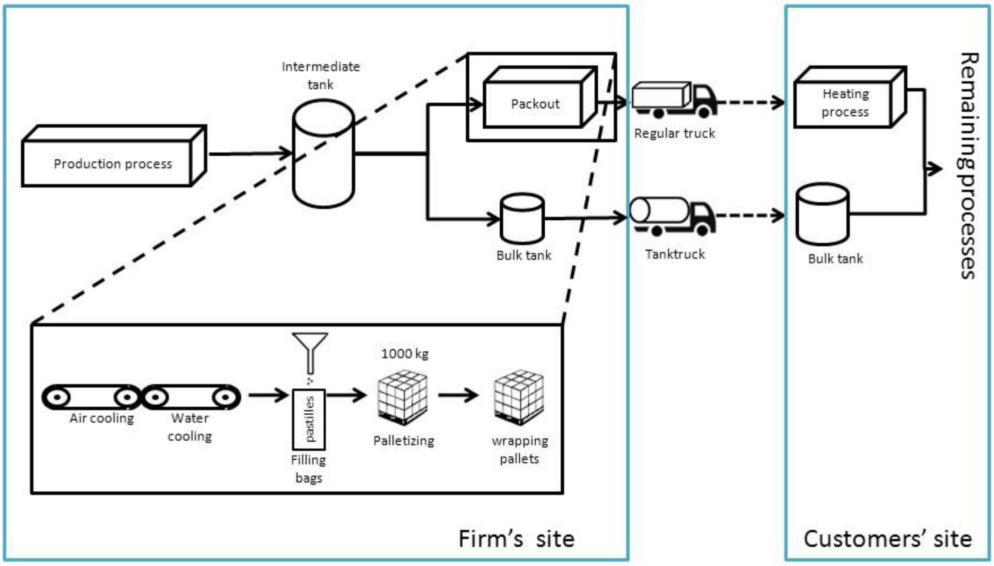

Figure 4 Process flow

Appendix II

The minimization problem of Section 3 can be rewritten as:

$$minimize\ F_f^i + F_t + F_f^e = F_{po}^i + F_{pm}^i + F_h^e + F_{mt}^i + F_{mt}^e + F_e^i + F_e^e + F_t \qquad (3)$$

$s.t.$

$$C_{po}^i + C_{pm}^i + C_{mt}^i + C_{mt}^e + C_i^i + C_i^e + C_h^e + C_l^e + C_t \leq Budget(\mathbf{e}_n^i, \mathbf{e}_n^e) \quad \forall\, \mathrm{n} \in \mathrm{N} \qquad (4)$$

<u>Equation 3</u>

In the equation above F^i_{po} represents the emissions from the packout. At the packout the product is first pastillated, then filled into bags, stored on pallets and finally the pallets are wrapped into shrink cover. The electricity usage of the packout was calculated in order to calculate the carbon dioxide emissions of the packout. For each engine in the packout the actual used capacity (in kW) was determined by the capacity (in kW), the efficiency of the engine and the allocation factor. This allocation factor was needed because some engines are also used in other processes. Finally, the amount of carbon dioxide emitted by the packout was calculated by multiplying the total energy usage with the electricity emission factor of country where the packout is located.

When selling the solid state, Eastman must also use packing material. F^i_{pm} represents the carbon dioxide emissions that are emitted due to the packaging material that Eastman uses. A Life Cycle Assessment (LCA) is conducted for the packaging material. In this case study, the emission factors until the gate of the packaging material suppliers were sourced from the database of the LCA software tool GaBi. The total CO_2 emissions until the gate of the suppliers are obtained when these emission factors are multiplied with the total packaging material used. The transport CO_2 emissions were calculated from the gate of the suppliers till Eastman's gate by using the NTM methodology (see next section for further explanation). Also the end-of-life was taken into account within the LCA. It is assumed that the materials will not be recycled and from the database of Eurostat[10] it is obtained that in Europe on average 34.69% of industrial waste is incinerated and 65.31% will end up in a landfill. The carbon dioxide emitted due to the end of life of a product was calculated by multiplying the total demand in kg with the emissions factor of the disposal treatment used.

The emissions from the heating process at the customer are F^e_h. The amount of energy required to raise one kilogram of product by 1 degree must be calculated in order to calculate the total energy usage and total carbon dioxide emissions of this process. The required energy for the heating process (in kJ/kg) can be calculated with $Q_h = m * c * \Delta t$, where m = total mass of products (in kg), c = specific

[10] Eurostat database. http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home, last accessed June 26, 2013

heat capacity (in kJ/kg/°C)=2.1 kJ/kg/°C and Δt = change in temperature (in °C). The carbon dioxide emissions were obtained when multiplying the total required energy with the right electricity emissions factor.

In order to sell the molten state to customers, both Eastman and its customers must have a molten bulk tank in which they can store the product and keep it on a high temperature. These bulk tanks are kept on temperature by steam. In equation (3), F^i_{mt} and F^e_{mt} represent the CO_2 emissions from steam use of a bulk tank at Eastman and its customer.

In addition, the molten bulk tanks also use electricity to mix the molten product with a stirring device and to load and unload the bulk tanks. The emissions from electricity use of the bulk tank are represented by F^i_e and F^e_e. These emissions were obtained by calculating the energy usage of the stirring device and the pump that is used for (un)loading and multiplying these with the right electricity emission factors.

F_t represents the emissions resulting from transport. There are several methodologies available to calculate transport emissions. Examples of methodologies are: Greenhouse Gas (GHG) protocol Artemis, EcoTransIT, NTM and STREAM. An overview of the characteristics per methodology is given in table 2. In this case study the carbon dioxide emissions resulting from transport are calculated with the NTM methodology. This method was chosen because it is focused on Europe, it has a high level of detail, it can calculate the emissions at various levels of detail, it offers the possibility of modifying or adding parameters and NTM is cooperating with the European Committee for Standardization to set a standard for calculating emissions resulting from transport, NTM (2011).

Table 2 Overview transport emissions calculation methodologies (obtained from van den Akker et al. (2009))

Method	**Background**	**Scope**	**Level of Detail**
Artemis[11]	Well defined	Europe	Very high
EcoTransIT[12]	Well defined	Europe (excluding some countries	Medium
GHG Protocol[13]	Well defined	World, focus on US	Low
NTM[14]	Well defined	Europe	High
STREAM (den Boer et al. (2008))	Well defined	The Netherlands	Medium

[11] ARTEMIS. http://www.trl.co.uk/artemis, last accessed June 26, 2013
[12] ECOTransIT. 2011. http://www.ecotransit.org, last accessed June 26, 2013
[13] Greenhouse Gas Protocol. 2011. http://www.ghgprotocol.org, last accessed June 26, 2013
[14] NTM. 2011. NTM Calc. http://www.ntmcalc.se/index.html, last accessed June 26, 2013

In this case study the carbon dioxide emissions from two types of road transport was calculated; road transport with a regular container and road transport with a heated container. All details to calculate the carbon dioxide emissions from road transport are taken from NTM Road (2008) and van den Akker (2009). For road transport the carbon dioxide emissions depend on the fuel consumption (FC_{LF}). The fuel consumption for a truck that has a regular container can be calculated as follows:

$$FC_{LF} = FC_{empty} + \left(FC_{full} - FC_{empty}\right) * LF$$

Where FC_{LF} = Fuel consumption at the specified load factor (liters per kilometre), FC_{empty}= Fuel consumption of the empty vehicle (liters per kilometre), FC_{full}= Fuel consumption of the fully loaded vehicle (liters per kilometre), LF= Specified load factor.

For the molten product a truck with a heated container is used. This heated container uses more fuel which changes the previous formula into:

$$FC_{LF} = FC_{empty} + \left(\left(FC_{full} * (1 + x\right) - FC_{empty}\right) * LF ,$$

where x represents the increase in fuel consumption when the container is heating the full container. Finally, the total carbon dioxide emitted can be calculated by

$$TE = FC_{LF} * D * FC_{co_2}$$

where TE =Total carbon dioxide emission, D = distance in km, FC_{co_2} = Emission factor for fuel

<u>Equation 4</u>

In equation (4) the costs regarding the electricity cost for the packout are C^i_{po}, and C^i_{pm} represents the packaging material costs. The costs to keep a molten bulk tank up and running are C^i_{mt} and C^e_{mt}. The inventory holding costs of internal and external location are C^i_i and C^e_i, respectively. C^e_h represents the electricity costs of the heating process and C^e_l are the labour costs when bags need to be cut at the customer. The costs regarding transport are depicted by C_t.

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