Assessment of a Methodology to Measure Carbon Footprint and Support Decision-Making Process in a Company's Supply Chain

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This study evaluates the potential supply chain–associated carbon footprint reduction with the implementation of CO_2e calculation in a company's strategic, tactical and operational supply chain network decisions. The proposed calculation approach, based on the Network for Transport Measures method, was applied in a case study for a major player in the metallurgical industry with an average outbound transportation carbon footprint of 308 kt of CO_2e for 2018–2019. The results show that application of network optimization trade-offs for the company's supply chain operations that include CO_2e could lead to carbon footprint reductions reaching greater than 50,000 tons of CO_2-equivalent per year, or 16% of current emissions.

With average temperatures on Earth increasing, the global community has acquired a sense of urgency to minimize the greenhouse effect by implementing measures to reduce carbon dioxide emissions (also referred to as CO_2 emissions, carbon emissions or carbon footprint). Carbon dioxide is the main contributor to the greenhouse effect and the increase in the amount of this gas in the atmosphere has led to the creation of carbon taxation policies that are gradually being applied to companies in several regions of the world and directly influencing organizations' balance sheets.[1]

In general, one of the largest portions of a company's carbon emissions is derived from the transportation of raw materials and finished goods. In 2019, it was estimated that transportation was responsible for 23% of the total CO_2 emissions worldwide.[2] In a globalized world context, transportation distances have increased significantly, together with an increase in the flow of materials also influenced by the growing world population. More specifically in the mining and metals industry, the depletion of ore bodies and reduction in metal grades have shifted the extraction activities away from the main production centers, thus increasing the movement of materials globally. This leads to an intensification of carbon emissions and impact on the climate, bringing challenges to supply chain management.

To deal with these challenges, existing supply chain decision-making systems, traditionally aided by optimization models based on cost minimization functions, are gradually being modified to include carbon emissions in the calculation procedure. However, the effectiveness of these systems depends on carbon emissions measurement, which is dependent on many factors such as distances, modes of transportation and quantity transported. In this context, mathematical models have recently been introduced to account for the carbon footprints of a company's supply chain, operations, assets and products — these are also called "carbon calculators."[2] Nevertheless, most organizations still struggle to effectively integrate these calculation tools in all their supply chain decision-making levels.

Under this global scenario, a major player in the metallurgical industry with high-intensity transportation activities was selected for a case study. The studied company acknowledges its contribution to the amount of carbon emitted and is

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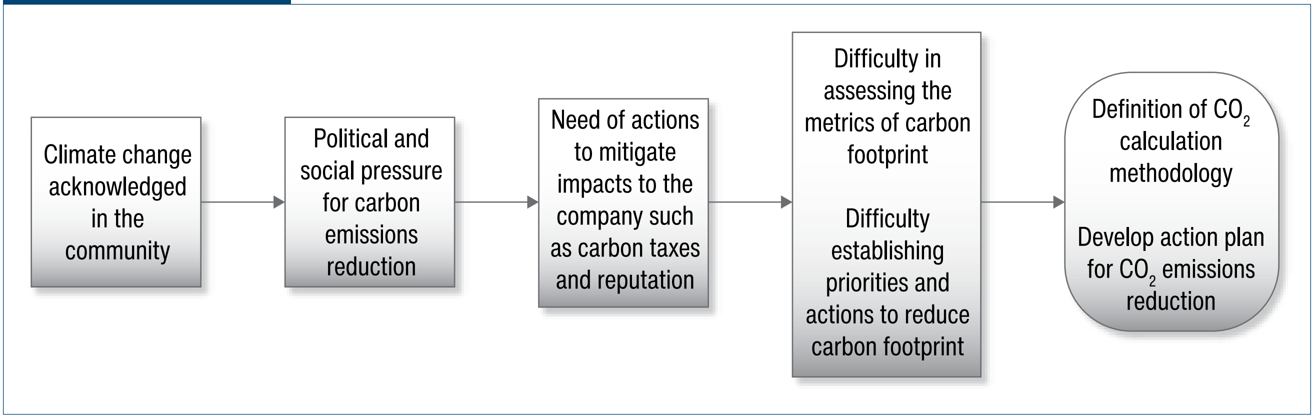
Figure 1



Problem-forming mechanism.

willing to implement the necessary changes to reduce its impact in the environment in the near future. However, there is a lack of knowledge on the actual CO_2 emissions from transportation activities. The lack of measurement implies a lack of understanding on the key factors that contribute to the carbon footprint within the company's logistics. This also creates a lack of awareness on the strategies that should be applied to be most effective in reducing its carbon footprint. Being so, the demand for the definition of a CO_2 calculation methodology becomes important within the company, as depicted in Fig. 1.

In order to provide a way of overcoming these challenges, the case study was conducted with the following objectives:

- Apply existing carbon footprint calculation models to estimate the company's supply chain–related carbon emissions.
- Incorporate these tools into each of the organization's supply chain decision-making levels to achieve a lower carbon footprint and reduce the company's impact on the environment.
- Demonstrate the potential to avoid or minimize financial downturns related to carbon taxation policies.

Theoretical Background

Structure and Decision-Making Models — Supply chain managerial decisions are commonly divided into three categories: strategic, tactical and operational. Table 1 summarizes the main activities attributed to each level.

The multi-level characteristics of supply chain management combined with the complex interactions and the number of variables involved have created an urge for the development of tools to aid in the decision-making process. These tools consist of mathematical and simulation models that aim to derive an optimal configuration for each phase of supply chain planning, while accounting for all the constraints posed by the variables and interactions mentioned here.[1]

Traditionally, the mathematical models were developed to provide an optimal configuration based on a single objective function: lowest supply chain cost. However, it has become paramount that the evaluation of a sustainable supply chain considers several criteria to ensure efficient decision support systems.[1] Therefore, a limited number of optimization models have been presented in an effort to combine lowest cost with lowest environmental impact when determining the configuration of a supply chain. Broadly speaking, these models aim at minimizing two objective functions: one associated to the overall operation

Table 1

Supply Chain Decision-Making Levels[1,3,4]

Decision level	Time frame	Decisions
Strategic	Long term	Type of products Production capacity Number and size of production plants Geographical location of plants and warehouses Make-or-buy decisions (vertical integration)
Tactic	Medium term	Distribution policies Selection of suppliers Levels of production Modes of transportation Quantities to be purchased and delivered
Operational	Short term	Routine decisions Scheduling Sequencing Vehicle load Route planning

costs, and the other related to carbon footprint. Another option adopted by some of the models is to include carbon emission costs (associated to a determined carbon emission price) in the existing single-objective function, weighted by a factor.

Strategic Network Optimization: The literature in strategic network optimization that also considers minimization of environmental impacts is somewhat limited. Chaabane[1] has developed a methodology for the design of a supply chain including sensitivity to carbon price in a carbon trading system. The proposed method consists of a multi-objective optimization model, integrating life cycle analysis (LCA) to account for the calculation of CO_2 emissions. Paksoy[5] has developed a mixed-integer programming model that considers environmental and social costs in the objective functions. The work presented by Wang et al.[6] also proposes a multi-objective optimization model with the intent to achieve a green supply chain network design, by capturing the trade-off between total costs and carbon footprint. In their model, two objective functions are explicitly considered. The first measures the total cost of the supply chain, including fixed, environmental protection, transportation and handling costs. The second objective function measures the carbon emissions in the distribution network.

Tactical Network Optimization: Significant effort has been found in the literature to represent environmental impacts in tactical planning models. Liotta et al.[7] have developed an optimization and simulation model that takes into consideration supply, production, transportation and carbon emission costs in a multi-modal transportation network, providing a framework for including carbon emission costs in tactical planning trade-offs. A similar approach with optimization and simulation to include carbon emissions in the tactical level decision-making process of supply chain planning is given by Hrusovsky, Demir, Jammernegg and Woensel,[8] but in this case, the carbon emissions are separate from the total costs. Hoen et al.[9] detail an additional optimization model. Perboli et al.[10] present a collaboration program, SYNCHRO-NET, that aims to improve the reliability and sustainability of supply chain planning. The work is also based on optimization models and collaboration in a multi-modal transport network.

None of the models found for tactical network optimization provide a combination of the minimization of carbon emissions with minimization of costs. Instead, all of them account for the carbon emissions costs in the single-objective function for cost minimization.

Operational Network Optimization: On the operational planning level, short-term and often real-time decisions are addressed. Usually, the routine operational decisions are guided by the strategic and tactical policies in place. However, constant replanning of transportation modes, routes and inventory levels are required as unplanned events, production delays and low inventory, among others, can affect the optimal choice defined on a higher level. The narrow window for decision-making considering requirements from all the parties involved in a specific delivery creates a level of dynamicity that make these problems extremely complex to be dealt with on a simulation or an optimization environment, as the variables are even more unpredictable. For that reason, relatively few studies have been dedicated to mathematically reproduce this specific level of supply chain planning.[11]

Adherence to a sustainable business model can be achieved by following the guidelines previously identified during tactical and strategic planning, as well as by applying operational strategies that can help reduce the carbon emissions from already defined production and transportation plans.

Carbon Emissions Calculation Models — As explained previously, the multi-objective optimization models rely on carbon emissions measurements. Although companies still lack knowledge on the measurement of environmental impacts and carbon footprint to provide reliable information to supply management strategic decisions, institutions are working on developing tools to analyze and measure the impacts of integrated supply chains on the environment by means of estimating carbon emissions.[12]

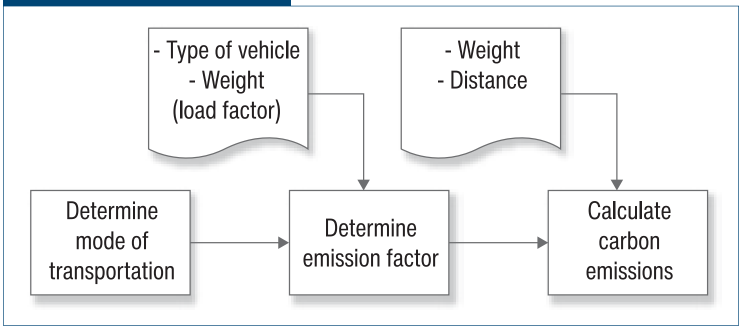
A few models based on actual registered emission measurements have been developed to estimate the carbon footprint specifically associated with transportation. These models provide valuable information on whether it is economically and environmentally attractive to invest in new technologies and in infrastructure, make a route change, or choose a different transportation modality.

The basis for the models' development is the greenhouse gas (GHG) protocol. This protocol is a partnership between non-governmental organizations, governments and the World Business Council for Sustainable Development that provides guidelines and standards for CO_2e emissions estimation. Two methods are proposed by the protocol, a fuel-based and a distance-based approach.[13] Other institutions such as Network for Transport Measures (NTM), CE Delft and Institut für Energie – und Umweltforschung (IFEU) developed specific models that adapt the calculation by including factors such as weight and vehicle life cycle.

One such model has been developed by the NTM, which is a Swedish non-profit organization that has established a database and a platform that provides tools, methods and a knowledge information center with the objective of simplifying environmental impact assessment from transport operations, with the final aim to support the development of sustainable transport.[14] The NTM methodology is largely used as it is a relatively simple and straightforward method, with explicit formulas for the calculation, based on parameters which are usually registered by companies, such as weight, type of vehicle and distance. The reviewed literature several times refer to having used the NTM methodology, such as in the cases of Hoen, Tan, Fransoo and Houtum,[9] and Loo.[15]

The method includes the carbon footprint associated with the fuel from well to tank, meaning that the entire life cycle of the fuel is evaluated, since its extraction until the use at the vehicle engine. The model establishes common values that can be used to compare the environmental impact from each transportation mode.[14] The steps used to calculate carbon footprint with the NTM methodology are summarized in Fig. 2.

Figure 2



Network for Transport Measures method simplified calculation steps.

Methodology

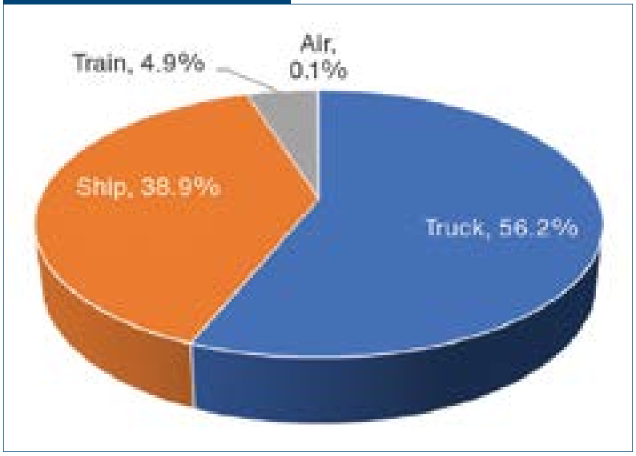
The company provided recent transportation data consisting of all transportation transactions registered in its system within a year to form the data basis for the current carbon emissions calculations. Each entry represents one movement of finished goods from a certain point (a manufacturing plant, a raw material plant, a consolidation point or a port) to another (a customer, a manufacturing plant, a consolidation point or a port), using one individual mode of transportation. These data, supplied in Microsoft Excel format, include departure and destination points, mode of transport used in the route, and weight of the cargo.

A calculation routine based on the NTM method was then applied to the received data to determine the company's carbon footprint associated to its supply chain. The calculation steps and factors used depend on the transportation mode, which can be by road, rail, water or air. The obtained results were also used to assess specific examples of supply chain activities within the company. In these cases, optimizations related to all the different decision-making levels of supply chain management were then proposed. Afterwards, the calculation routine was once again applied in order to illustrate the potential carbon emission savings that could be achieved in these new proposed conditions.

Results and Discussion

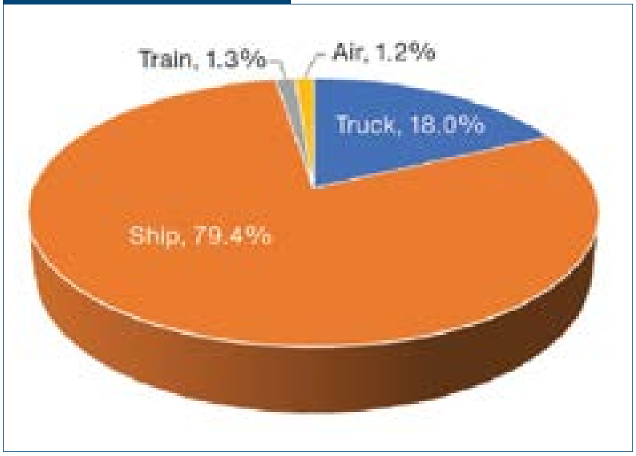
Transportation Figures — The graphs in Fig. 3 and Fig. 4 show the relative tonnage transported and the relative distances covered by each transportation mode in the registered

Figure 3



Weight transported by modality.

Figure 4



Distance traveled by modality.

data, respectively. The figures show that most of the tonnage is transported by road, whereas the highest distances are covered by water transportation. The contribution of air and rail shipping are almost insignificant to the total amount of water and road.

Calculated Emissions — The relative carbon footprint calculated per transportation mode is given in Fig. 5.

It can be noted that the major contributor of the carbon footprint of the company's logistics operations is water transportation, with over 71.6% of the CO_2e emissions, followed by road transportation with 23.9%. Interestingly, even though truck is responsible for more than 70% of the number of transports in the data provided and over half of the tonnage transported, it accounts for just under one quarter of the total carbon emissions. On the other hand, 20% of the registers are of water transports, but the emissions related to this modality are as high as 71.6%. This indicates that the traveled distance is the largest contributor of the company's carbon footprint.

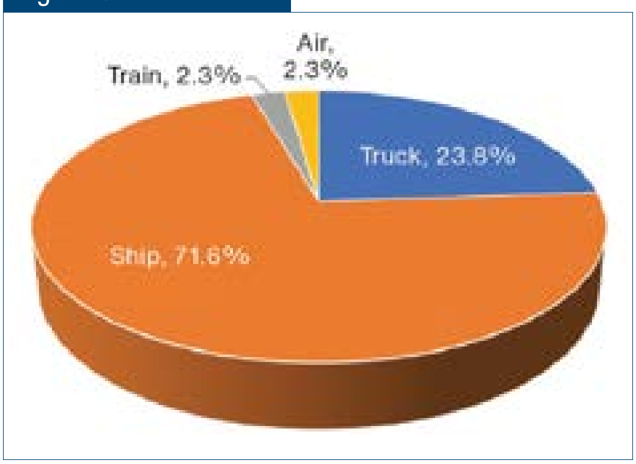
Also worth noting are the small contributions of air and rail freights in the overall carbon emissions calculated. As there are few entries in the data that used either air or rail transportation, the overall emissions contribution is considerably small. However, as air freight is an energy-intensive modality, its proportional contribution is significant, even though the absolute carbon emissions are small compared with road and water transportation.

The emission intensity of a transportation mode is closely related to the energy intensity, especially considering most of the vehicles run on fossil fuels. Emission intensities are given in grams of CO_2 emitted per kilometer traveled and per ton of the cargo transported (g/t.km). Average emission intensities are known and can be used as a basis for comparison between the different transportation modes. Fig. 6 presents average emission intensity numbers obtained in the literature[16] and how they compare with the company's calculated value.

It can be observed that the studied company is close to what would be the ideal number in terms of CO_2/t.km, which is the one for shipping. This confirms that the company makes high use of one of the least energy-intensive transportation modes, indicating a good positioning in terms of total carbon emissions. This indication can be misleading, however, as water transportation is often related to long traveling distances, such as in the case of intercontinental exports, which lead to high carbon emissions in absolute terms. This information directs the focus of any initiatives to reduce carbon footprint of the outbound transports in the company toward reducing the traveling distances, rather than shifting from one transportation mode to another, although shipping over shorter distances may require a transportation modality switch.

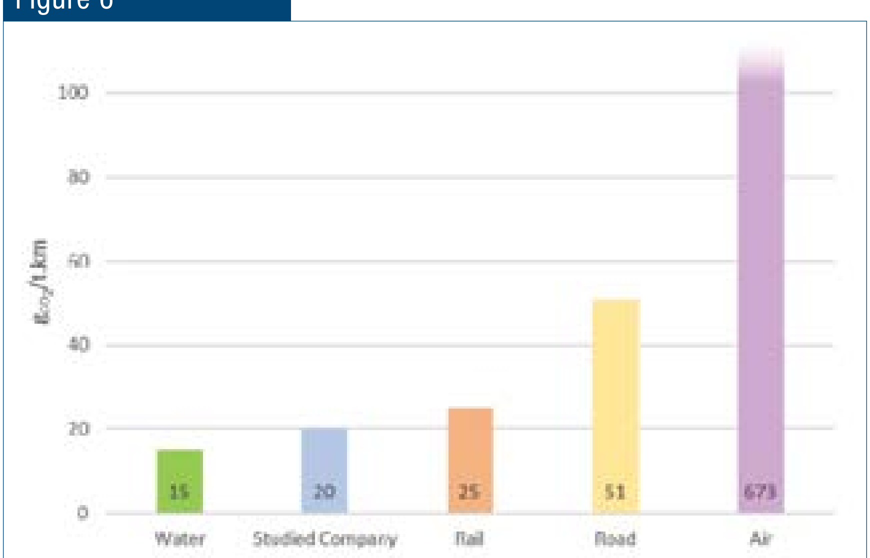
Distribution Network — The company under study owns and operates production plants spread around the world and distributes its products to many different countries. This complex distribution network clearly poses a challenge to planning production, purchasing, and transportation to meet customers and environmental

Figure 5



Carbon emissions division by transportation mode.

Figure 6



Energy intensity by transportation mode.

demand. The importance of using mathematical models to reach optimal strategic, tactical and operational distribution configurations in this case becomes even more significant. The following subsections illustrate examples of possible optimizations to be applied in each network level of the company. Some of the locations real names were suppressed, substituted by representative letters.

Strategic Network Optimization: The studied company's sales volume to the North American market in the analyzed period was achieved by both local production plants and imported goods from other plants around the world. The amount imported from other parts of the globe accounted for 51% of the company's consumed products in the region. This implies that the current production capacity in North America is nearly half of the total demand. Most of the 51% is derived from the company's production plants in Europe.

One usual route of products is from a production plant to Port A, in Europe, and then to Port B, in North America, followed by the distribution from the port to the customer. This last portion is usually outside of the company's scope, but still contributes to the total carbon emissions from this transport. If the company was to supply this demand from somewhere in North America, the carbon emissions would be significantly reduced as the sea transportation portion of the route would be eliminated. Additionally, economic savings in transportation would be obtained. The road or rail transportation shipping from somewhere in North America to the customer is assumed to be equal to the current distribution from the port to the customer site.

A reference freight rate from Port A to Port B was obtained in a freight calculator[17] and equals EUR 2,111.40 for a 20-ton container. This cost was used to extrapolate the total cost for intercontinental shipments to North America in a year. In a hypothetical trade-off to evaluate the potential of opening a new production facility to supply this external demand in North America, the savings with transportation costs (assuming the road transportation sections of the usual route would balance out when compared with the distribution from the new plant to customers) would represent an NPV of 205 MEUR in 20 years, at 7% discount rate. In addition to that, the atmosphere would be spared of 13% of the company's CO_2e yearly emissions.

On a single-objective function model, the carbon emissions savings could also be considered by applying a price to the CO_2. Current carbon credit prices in Europe are on the order of EUR 25–26/ton of CO_2.[18] This is a relatively low value and is expected to increase in the future with the establishment of new measures from the European Union. Considering a

Table 2

Calculation of NPV for New Facility in North America

Parameter	Value
Port of departure	A (Europe)
Port of destination	B (North America)
Cargo weight (t)	20
Sea freight (EUR)	2,111.40
NPV 7%, 20 years (MEUR)	205
Emissions savings (%)	13
Carbon price (EUR/tCO_2)	30
NPV 7%, 20 years, considering emissions cost savings (MEUR)	217

EUR 30/ton of CO_2e carbon price, the NPV would increase from 205 to 217 MEUR. A summary of the calculations is given in Table 2.

The cost of installing a new facility at this capacity is unknown and was not considered in this study, but if the NPV remains positive after the incorporation of these costs, the strategic decision should be to take on the new investment.

On an optimization model with two objective functions (one being carbon emissions minimization), the decision for the investment could be further supported. The example given is for the North American market, which showed to be more significant in terms of income flow of products and, therefore, more economically feasible for regionalization. However, the same thinking can be applied to other regions, looking toward shorter production (origin) to destination distances and thus reducing carbon emissions.

Tactical Network Optimization: A common route observed in the company data is the transportation from Asia to Europe. The choice for producing in Asia, given the company's infrastructures with several producing plants located in Europe, is usually a trade-off favorable to lower labor costs despite transportation costs. This option results in higher carbon emissions associated with the shipping from the eastern country to Europe.

When considering carbon costs in the trade-off, using the reference EUR 30/ton of CO_2e and the shipping distance from Port A, in Asia, to Port B, in Europe, an additional EUR 10.70/ton of the product is to be taken into account in addition to the freight costs. This is more than 11% of the transportation costs and can be representative when deciding where to allocate a certain demand to existing plants.

To illustrate the impact on the transportation versus labor trade-off, the average number of man-hours necessary to produce one ton of the product have been calculated based on literature data and was

Figure 7

(a) (b)

Common (a) and alternative (b) route from European plants to Middle East and Asia-Pacific regions.

estimated to be 12.5 Mh/ton. From that, the impact of the carbon costs on the labor rate can be calculated. This exercise shows that the carbon cost is equivalent to EUR 0.85/Mh that would have to be added to the comparison between Asian and European labor rates. The total potential emission savings for not transporting the cargo from Asia to Europe would be of 2.5% of the company's CO_2e yearly emissions.

Operational Network Optimization

Route Optimization: Since the studied company provides intercontinental shipping departing from Europe plants, a theoretical route was selected for this analysis, as shown in Fig. 7a. In this route, the product is transported from hypothetical plants located in Central Europe to a North European port, where it is then shipped to Middle East, Asia or Oceania.

As proposed in Fig. 7b, an alternative route is to use a South European port, such as Genoa, Italy, or Koper, Slovenia. Even though the road distances become higher due to the locations of the plants, a much shorter water distance needs to be covered by not contouring the Western European seas. The routes from one of the North European ports to Asia is 4,300 km longer than the route from the Port of Genoa to Asia.

As an illustration, routes from two theoretical facilities in Central Europe were selected: Plant A and Plant B. In both routes, Port A, in Northern Europe, was used to ship the cargo to Port B, in Asia. The costs associated to these transportation routes and the carbon emissions comparison is given in Table 3. With the current carbon price, the cost trade-off is not always favorable for using the South European, as in the case of Plant B, but the numbers are close enough to justify a choice for the most environmentally friendly route. The potential emission savings with this initiative applied to all

Table 3

Common vs. Alternative Route From Europe to East Comparison

Departure	Plant A	Plant B	Plant A	Plant B
Port of departure	A (Northern Europe)	A (Northern Europe)	Genoa	Genoa
Port of destination	B	B	B	B
Cargo weight (t)	20	20	20	20
Road freight to port (EUR)	791	604	1,496	1,824
Sea freight (EUR)	1,880	1,880	969	969
Total cost (EUR)	2,671	2,484	2,465	2,793
Road emissions (kgCO_2)	582	450	916	1,120
Sea emissions (kgCO_2)	4,139	4,139	2,825	2,825
Total emissions (kgCO_2)	4,721	4,589	3,741	3,945
Emissions savings (kgCO_2)	–	–	980	644
Emissions savings (EUR)	–	–	29.40	19.32
Total cost w/CO_2 (EUR)	2,671	2,484	2,436	2,774

similar routes in the year is estimated to be of 1% of the company's CO_2e yearly emissions.

Change in Transportation Modality: As shown before, most of the cargo in terms of weight within the company is transported by truck. This is also true for the internal European flow of products, despite the extensive and effective rail transportation network in the continent.

An exercise has been made to evaluate the potential savings in carbon footprint for the company if rail was used to partially substitute road, in a multi-modal transportation configuration, in the transports within Europe. In order to do so, a minimum distance of 1,000 km was established for the multi-modality use. It has also been considered that the product would leave the facility by truck and travel 100 km before reaching a rail terminal for modality switch. The product would then be transported by rail until a destination terminal, where it would again be transferred to trucks for final delivery, 100 km far from the terminal. The carbon footprint savings with this configuration for all road transports above 1,000 km in Europe would be of 4% of the company's CO_2e yearly emissions.

To financially evaluate the modality switch, estimated rail and road freight rates were obtained from online calculation tools and references.[17,19] With the current carbon price at EUR 30/ton, considering a 20-ton shipment, the financial breakeven for using multi-modality would be from 1,950 km. Therefore, the same exercise was repeated for all road transports above 1,950 km in Europe, with estimated savings of 1% of the company's CO_2e yearly emissions.

Road Factor Optimization: An additional calculation was performed to understand the impact of improving the utilization of trucks in the carbon footprint of the company's supply chain. Average truck load factors for the registered transports at the company in the analyzed year were 45%. A simple calculation was performed assuming that the load factor for every road transport would be maximized. The total CO_2e savings with 100% load factor would be 4% of the company's CO_2e yearly emissions.

This optimization could be partially achieved by collaborating with other players in the supply chain or from other industries. Additionally, transportation routes can be slightly changed to have one fully loaded vehicle delivering products to two clients instead of having two half-loaded ones traveling to a near destination. A good production planning and inventory management system can also ensure that products for the same customer reach the end of the production line within a reasonable timeframe. In a complex distribution network such as the one for the studied company, these initiatives can only be effectively implemented by the aid of a computational optimization tool.

Conclusion

A calculation framework for carbon footprint associated to supply chain activities was successfully developed and applied to the studied company's case. Most of the emissions derived from intercontinental shipping via sea freight with more than 70% of the emissions, followed by road transportation, with over 20% of the emissions. This indicated that one of the largest contributors to the company's carbon footprint in the supply chain was the distance traveled. Reduction in the distances would have a high potential to minimize this impact.

The result of applying models that include carbon footprint calculation would be of great potential CO_2 emission savings. In the examples that have been used in this case study to illustrate the potential reduction in the carbon footprint, savings were estimated at more than 15% of the yearly emissions associated to the company's supply chain activities, as a result of changes in the distribution network infrastructure (on the strategic level), optimized allocation of production/demand to plants (tactical level) and modality choice (operational level).

Obtaining a balance between transportation distances, carbon emissions and costs is a trade-off performed at different levels of supply chain planning. The calculation methodology developed in this study offered numerical data that can be used to support these decisions, making the entire process more efficient and accurate. Similar frameworks could be applied by other players inserted in the metallurgical industry, strengthening their available database and making possible considerable reductions of carbon footprint related to supply management activities.

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