MANAGEMENT, TECHNOLOGY
AND ENTREPRENEURSHIP

GenLots

EPFL

Incorporating carbon emissions as an optimization criterion in order planning:

Developing the business case for a B2B Software-as-a-Service, machine learning, supply chain startup

Master Thesis
of
Andres ENGELS

August 26th, 2020

Academic Supervisor
Kenneth Younge
Chair of Technology and Innovation Strategy
Dept. of Management, Technology, and Entrepreneurship (MTE)

Company Supervisor
Simon Schenker
Co-CEO GenLots

Abstract

Order planning, the process of determining the size and date to place an order, represents an important and highly complex operational decision within companies' production and supply chain management functions. In practice, it has been primarily concerned with trading-off between various economic considerations, such as quantity discounts, order costs, and inventory costs, thus overlooking or underestimating the environmental dimension. Greenhouse gases (GHGs) are emitted in each of the value chain processes that order planning touches as a result of the fuel and electricity consumed as well as the refrigerant leakage that may take place during the transportation, warehousing, and waste-treatment of inventory. Interest from manufacturers to reduce their GHG inventories from their logistics operations has increased in recent years driven by a combination of variables such as changing consumer and investor preferences towards sustainable products and companies, the threat from climate risk related supply chain disruptions, and the possibility of gaining a competitive advantage, among others.

GenLots is a machine learning software company that today optimizes order planning and safety stocks for manufacturing companies' inbound materials based on economic factors. As it already helps to reduce the number of orders and inventory, it consequently also contributes to reducing its client's carbon emissions. Nevertheless, neither the resulting environmental and financial impact from reducing them has not been quantified, nor has GenLots explored the potential to generate further carbon emission savings by introducing them as a parameter into its total cost of procurement (TCO) based model.

This paper evaluated whether a business case for GenLots to develop such product extension exists. As a result, the commercial and technical viability were researched which led to the development of a Greenhouse Gas Protocol compliant model for GenLots to incorporate GHG emissions into its lot sizing algorithm. The model was then applied in a case study, which helped to confirm that GenLots should move forward with investing further resources into performing the calculation and reporting of GHG emissions based on its current algorithm. However, the overall research suggested that GenLots is still 1-2 years early before it may become commercially viable to incorporate GHG emissions as a parameter into its algorithm.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

API	Application Programming Interface
CDP	Carbon Disclosure Project
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DEFRA	UK Department for Environment, Food, and Rural Affairs
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
ETS	Emissions Trading System
EU	European Union
FCL	Full Container Load
FTL	Full Truck Load
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
HFCs	Hydrofluorocarbons
ICP	Internal Carbon Price
IMO	International Maritime Organization
INCOTERMS	International Commercial Terms
IPCC	Intergovernmental Panel on Climate Change
IWT	Inland Waterway Transport
KML	Keyhole Markup Language (a human-readable computer markup language used for expression geographic annotations and visualizations in 2D maps and 3D Earth browsers)
KPI	Key Performance Indicator
LCL	Less than Container Load
LTL	Less than Truck Load
OECD	Organization for Economic Cooperation and Development
PFCs	Per fluorinated compounds

SAP	“Systemanalyse und Programmentwicklung” - German for Systems Analysis and Program development. It is the name of the German ERP software company SAP AG headquartered in Walldorf, Germany.
SBTi	Science Based Targets initiative: “A collaboration between CDP, the United Nations Global Compact, WRI and WWF defining and promoting best practice in science-based target setting. Companies serious about sustainability may have their scope 1 and 2 reduction targets — and eventually, scope 3 — approved by the SBTi”
SPP	Sustainable Procurement Pledge
TCE	Transaction Cost Economics
TCO	Total Cost of Ownership
TEU	Twenty-foot Equivalent Unit
tCO_2e	Tonnes of Carbon Dioxide Equivalent
tonne	A non-SI metric unit of mass equivalent to 1,000 kilograms, also referred to as metric tonne (MT).
UNFCCC	United Nations Framework Convention on Climate Change
WRI	World Resources Institute
XML	Extensible Markup Language (a human-readable computer markup language used for encoding documents via a set of rules)

1. Introduction

1.1. Motivation

Order planning in production, the process of determining the size and date to place an inbound material order represents an important and highly complex operational decision within companies' production and supply chain management functions. In practice, decision making and optimization models around order planning have primarily been concerned trading-off between various economic considerations such as quantity discounts, order costs, and inventory costs. However, an additional and just as critical dimension has been overlooked or underestimated: the environmental aspect. According to a report from the United Nations' Secretary General, between 1998–2017, an estimated US$3 trillion in direct economic losses and 1.3 million lives were claimed resulting from climate related and geophysical disasters (United Nations Secretary General, 2019). Global warming, climate change, and natural resource depletion are evidently also contributing to the economic equation, but they are rarely considered. In fact, they pose a severe risk to economic profits, and especially threaten present-day globalized supply chains in many ways.

When it comes to order planning, greenhouse gases are emitted across each of the value chain processes that order planning touches. Fuel and electricity are consumed in the transportation, warehousing, and disposal of scrap, while refrigerant leakage may also occur. Every order planning decision involves trading off between cost factors, most notably the order cost and inventory holding cost. As we increase the number of orders to reduce inventory holding costs, we increase the number of transports and hence also the emissions from transportation. On the other hand, as we increase inventory levels and reduce the number of orders energy resources are consumed during the warehousing process. Then, there is the third cost component, the cost of scrap. When a company orders too much and materials extend their shelf-life or become obsolete, emissions are also created in the transport and disposal of the materials, and one may also need to account for the emissions created from the extraction and assembling of the resources used to make the scrapped material.

Over the past decades, companies have directed their attention towards emission reduction opportunities mostly within their *direct* operations. This has mainly been driven by cost saving opportunities, increased efficiencies, financial penalties, public opinion, or government compliance. Additionally, companies encounter fewer difficulties concerning traceability, measurement, and reporting of their emissions within their direct operations in comparison to their supply chain. It is perhaps for these reasons that too few companies today actually include their supply chain in their emission's inventory which is often responsible for "70 to 80 percent of all lifecycle emissions [especially] in most manufacturing industries" (Dahlmann, 2020).

Despite the challenges in collating carbon emissions data from the supply chain and putting it to good use, translating carbon emissions into economic terms and incorporating them into the total cost equation can represent a major barrier to its implementation. Carbon pricing is an instrument that assigns an economic cost to greenhouse gas (GHG) emissions with the goal of encouraging companies to reduce their amount of emissions and of offsetting the external costs to society from climate change and pollution. In practice, carbon pricing is usually enforced through a carbon tax or an Emissions Trading System (ETS). Nevertheless, today there exists no consensus or unified price across country, ETS, industry, or company for one tonne of CO_2 emissions; in fact, carbon pricing covers only a fraction of the world's GHG emissions. Some of the more advanced companies when it comes to sustainability have utilized carbon pricing as a mechanism for strategic decision making, such as in deciding where to locate their facility or which supplier to select, however this carbon price has merely functioned as a virtual price that is not financially captured anywhere.

Given the shortcomings of traditional order planning models in addressing the pressing concerns around climate change and CO_2 emissions, over the past ten years great interest has emerged from the research community to develop new models. These models have studied the potential effects from different environmental regulation mechanisms such as carbon taxes, ETS systems under various mechanisms, and carbon offsets when factoring in the transport, warehousing, and/or scrap emissions into the total cost equation. Nevertheless, all of the relevant models that were studied were either based on simple or static order planning models and/or were merely theoretical and not suitable for real-world application. An effective and functional heuristic suitable for the real-world should be flexible and adaptable enough to handle different parameters and constraints across different companies and industries, as well as the differences in the data available within a company.

As more and more regulators worldwide mandate publicly listed companies to include measurements of their greenhouse gas emissions in their annual reports, the number of companies measuring and reporting their CO_2 emissions is only expected to increase. For example, in 2019, the UK introduced “streamlined energy and carbon reporting”, which includes supply chains” (Keaveny, 2020). Measuring and reporting are an essential first step in enabling emissions regulation and taxation, while also serving as a benchmark upon which to improve. But due to the complexity and high volumes of data and data sources involved in the measurement, reporting, and optimization of carbon emissions in the supply chain, we are seeing technology companies leading the way in this respect. One particular technology company aiming to take the lead in optimizing order planning sustainably is the Swiss startup, GenLots, the industry partner together with which this master thesis has been developed.

1.2. Industry Partner: GenLots

Founded in 2017, GenLots is a machine learning, software-as-a-service startup that helps industrial companies to optimize their inbound material production order plans as well as their safety stock levels based on a Total Cost of Ownership (TCO) approach. The TCO concept will be explored in further detail throughout this paper, while the terms order planning and lot sizing will be used interchangeably. Order planning can also be understood as the process immediately after material requirement forecasting has taken place, and immediately before the inbound logistics process, as illustrated in Figure 1.

Figure 1. Locating order planning in the value chain

GenLots has developed a proprietary algorithm that provides optimal order planning recommendations using reinforcement learning across a 52 to 78-week period. Reinforcement learning is one of three overarching machine learning algorithm types, which is unique in the sense that it does not rely on (large amounts of) historical data and which is highly effective for optimization problems with extraordinarily large solution spaces. Such an algorithm intelligently generates various scenarios to create a large solution space, and depending on the goal, whether to maximize or minimize, in GenLots’ case to minimize the TCO, the algorithm is rewarded or punished while accounting for whether constraints have been maintained. It iteratively explores new possibly good solutions until it has found an optimum. In comparison to most static lot sizing formulas, GenLots is capable of dynamically and flexibly handling the real-world trade-offs, and unique parameters and constraints encountered across a wide range of manufacturing-oriented industries and companies. Along with the client's material forecasts, these constraints and parameters are extracted from the client's Enterprise Resource Planning system and include supplier lead times and quantity constraints, quality control lead times and costs, shelf-life, quantity discounts, safety stocks, among others. In addition to extracting this data, GenLots also defines together with the client the appropriate business parameters for the algorithm, which include the fixed cost per order as well as the inventory holding cost rate. An example of a resulting optimized order plan created by GenLots is shown in Figure 2.

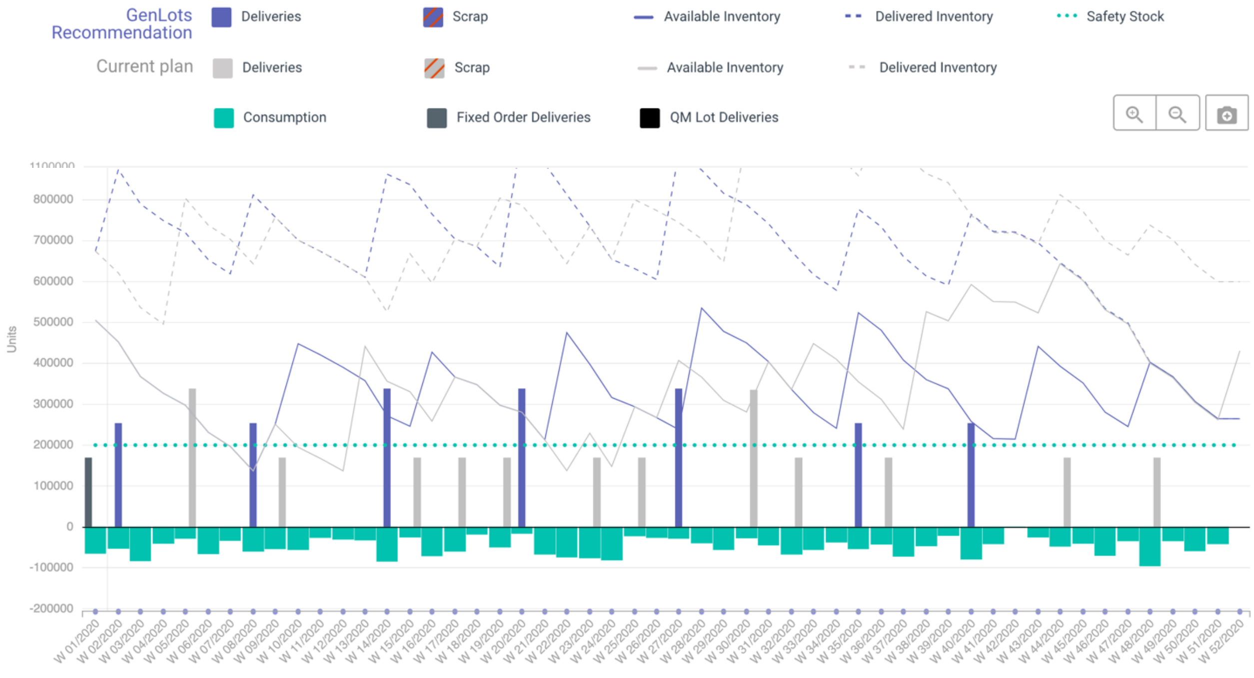


Figure 2. Example of an optimized order plan by GenLots

GenLots' technology has demonstrated to reduce inventories as well as the number of orders and scrap, which not only has a direct effect on a company's financial savings, but also a quantifiable impact on a company's carbon footprint by reducing the number of shipments, average inventory, and scrapped material. Figure 3 illustrates the projected reductions in inventory and in the number of orders associated with the order plan shown in Figure 2, which is included to provide necessary context for the rest of this paper. Curious to learn whether GenLots could help further reduce their CO_2 emissions, one of GenLots' clients in the food and beverage industry approached GenLots. Like many other companies, in recent years, this company had publicly pledged a very ambitious CO_2 emissions reduction plan. Similarly, like many others, its supply chain and sustainability practices have increasingly come under the spotlight from consumers, the media, governments, and NGOs, while the COVID-19 crisis has only exacerbated the situation. Conscious that GenLots' software has the potential to make both environmentally and economically optimal decisions to help companies become more sustainable beyond merely saving them millions, its founders decided to incorporate what they call a CO_2 Emissions Optimizer into its product roadmap.

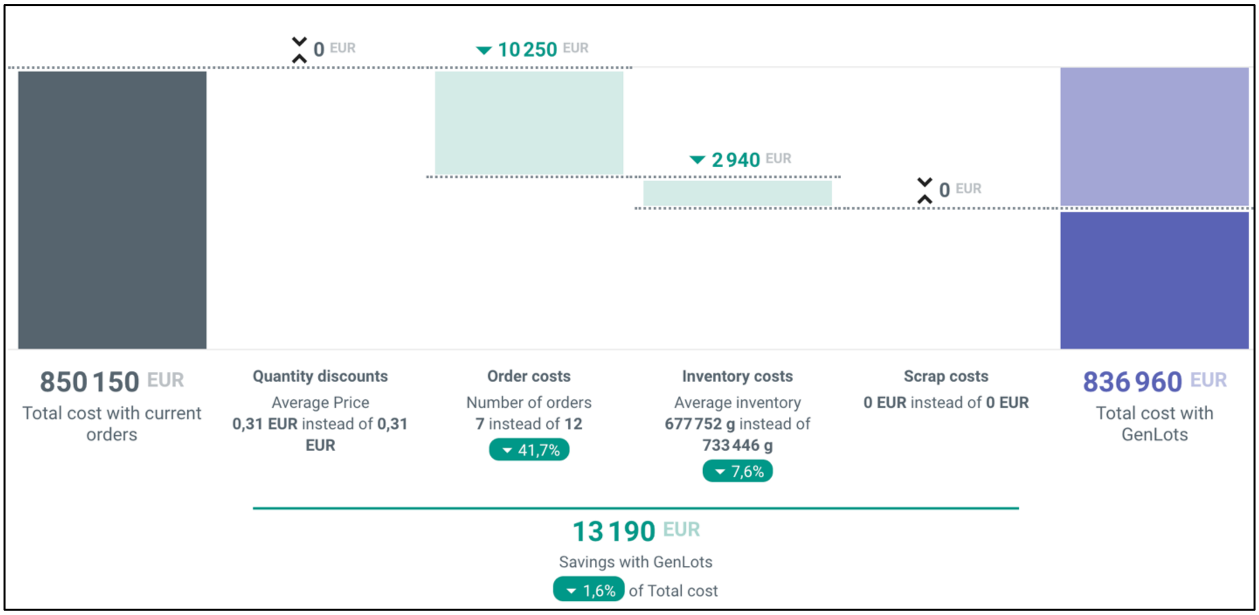


Figure 3. Comparative metrics from the optimized order plan in Figure 2.

1.3. Problem Definition and Structure of the Thesis

Today, GenLots does not have the knowledge, capabilities, nor the data from its clients to measure and report the carbon emission savings that its software generates concerning inbound logistics. More importantly, GenLots' algorithm does not consider the cost of carbon emissions as a parameter contributing to the TCO. Incorporating such capabilities into its software might help GenLots stand out as a socially and environmentally conscious company and drive more business towards it. However, building a CO_2 Emissions Optimizer product merely based on the "Let's build it and they will come" premise represents a very large opportunity cost in terms of deployed resources especially for a startup where resources can be very limited. This gives rise to the main research question undertaken in this paper: Should GenLots invest further resources in the short or medium term into fully developing and integrating a CO_2 Emissions Optimizer into its value proposition for its current and future clients, and if so, what steps should it take?

To answer this complex question additional questions must be answered:

1. Is there a need and interest for such a product in the market?
2. What is the job to be done?
3. What will the impact be?
4. Which types of companies and industries should GenLots target that would benefit most?
5. How should the product be offered and what features should it include?

The objective of this thesis will be to evaluate the commercial and technical viability and propose a model for GenLots to develop and integrate carbon emissions savings into its value proposition and optimization criteria. In the first section following this introduction, the design and process that was followed for this research is discussed. Next, an in-depth technical background covering the complexities and actualities of CO_2 emissions and CO_2 pricing in the context of a company's logistics and transportation is provided. Then a commercial and technical analysis is presented to evaluate the market readiness and go-to-market strategy as well as the technical viability. In the final section, a business case is presented, enabling the research question to be responded.

2. Research Design

The research subject lies at the intersection of logistics, supply chain management, economics, and environmental sustainability. It aims to develop the business case presented in three parts, the commercial viability, technical viability, and a case study, for whether GenLots should invest further resources into developing a CO_2 Emissions Optimizer in light of the present and evolving landscape. For this purpose, the practical considerations are strongly emphasized over the theoretical ones in designing this research.

Optimizing lot sizing by taking a TCO approach in which GHG emissions are accounted for first requires calculating the cost for those emissions. In its simplest form, calculating the total cost generally consists of multiplying a quantity by its unit price. In this case it is no different; we need the number of tonnes of GHG emitted and the price per tonne. The number of tonnes of GHG emitted can be found through carbon accounting, while determining the price per tonne, concerns the subject of carbon pricing. Learning whether companies actually have the data to measure and/or report their inbound logistics emissions as well as whether they are setting a price on those GHG emissions and what that price is based on, hence concerns this research. With this information we can then determine whether GenLots should perform any carbon accounting and/or carbon pricing calculations in-house or externally.

We must also situate carbon accounting and carbon pricing in the present-day context of this thesis. Thus, we must examine the internal and external stakeholders influencing the current and maturing outlook and their impact over it. Given the segments targeted by GenLots in the short-term and medium-term, additional emphasis has been placed on the European market, multinationals, and manufacturing-oriented companies in industries such as healthcare, chemicals, and fast-moving consumer goods. However, since the targeted companies all have a global supply chain and manufacturing footprint, an international view has also been offered.

In developing the business case for GenLots' CO_2 Emissions Optimizer, secondary research has been conducted in parallel with primary research. Secondary sources of research include carbon accounting and carbon pricing handbooks, reports, dashboards and calculators from authoritative sources such as the World Bank, the Carbon Disclosure Project (CDP), the European Union, among many others. Lot sizing models that incorporate GHG emissions have also been reviewed, as well as Annual (Sustainability) Reports from various public companies. These annual reports typically contain information regarding sustainability pledges for GHG emission reduction commitments including executed or pipeline projects; one can then induce whether such a company would have a need for or interest in GenLots' CO_2 Emissions Optimizer.

Primary research mainly consisted of interviews with professionals, academics, and experts covering a diverse range of roles, industries, and geographies. For the most relevant and specific insights, executives involved in one or more of the domains of sustainability, digitalization, supply chain, and logistics were contacted and interviewed for between 30 to 75 minutes. The public companies represented include Barry Callebaut, Coty, Henkel, Johnson and Johnson, Novartis, and Songwon Industrial Group. Additional interviews with representatives from the non-profit the Carbon Trust and from two technology companies that have developed CO_2 emissions calculators, CO_2 Monitor and EcoTransit World, complemented this research.

A comprehensive technical grounding about carbon emissions and carbon pricing is necessary to give meaning to this research, which is provided in the next section. This will set the stage for the discussions on the commercial and technical viability as well as for the case study.

3. Technical Background for the Research

This section lays out the technical background specific to the context of lot sizing and inbound logistics that is necessary to follow the rest of this thesis. Subjects covered range from the TCO to the classification, measurement, and pricing of carbon emissions in the industry.

3.1. Lot Sizing's Contribution to GHG Emissions

Lot sizing decisions directly influence the GHG emissions created by the logistics and transport sector, a sector which was estimated by the World Economic Forum in 2009 to contribute 5.5% of the global emissions (World Economic Forum, 2009). This figure is likely to be much greater today given that transportation emissions represent the fastest growing source of emissions (Wang & Ge, 2019). Despite the great improvements in vehicle efficiency to reduce emissions, these are being more than offset by the large volume increase in transports. Road transport represents 72% of global transport emissions, and while in Europe trucks represent fewer than 5% of all road vehicles, they account for about 25% of road transport GHG emissions (Wang & Ge, 2019). On the other hand shipping and aviation both represent 2+% of global emissions each and approximately 13-14% of the EU's transport emissions, both of which are only expected to increase due to rising consumer demand and international trade. This is also reflected by the fact that in 2019 a shipping (Mediterranean Shipping Company) and an airline company (Ryanair) made Europe's top ten list of CO_2 emitters based on a report by Transport and Environment. (Transport and Environment, 2020).

When it comes to the carbon footprint contribution by logistics buildings very little data is still available. The same report from the World Economic Forum estimated that their emissions represented 13% of the logistics sector's emissions. Other figures have estimated them to be as high as 30% for some countries, but these percentages may vary widely across countries due to differences in the "average size, age, design, and energy efficiency of the buildings, the degree to which material handling operations are mechanized and the carbon intensity of the electricity used" (McKinnon A. , 2018). Evidently, the magnitude of GHG emissions that lot sizing can influence is not trivial, but in order to influence lot sizing decisions based on GHG emissions a Total Cost of Ownership approach is necessary.

3.2. Defining the Total Cost of Ownership for Lot Sizing with CO_2 Emissions

The Total Cost of Ownership is defined as the value obtained from the financial analysis of a capital purchase or investment, such as a product or system, across its entire life-cycle. This includes accounting for every direct and indirect cost across acquisition, operation, and replacement. TCO is very versatile in that it can be applied across numerous contexts and industries, specifically when it comes to benchmarking and making decisions where trade-offs are involved.

In the context of order planning TCO can easily be understood by comparing two common ordering strategies: just-in-time (JIT) ordering and bulk ordering. In just-in-time inventory the goal is to minimize the carrying cost, increase efficiency and reduce waste. Nevertheless, this strategy may undermine the costs associated with placing an increased number of orders, ignoring the potential cost savings from quantity discounts and bulk ordering and failing to consider unpredictable supply chain disruptions. On the other hand, bulk ordering also has its setbacks as it ties additional working capital and carries other risks associated with it such as scrap. Somewhere in the middle of these two policies we can find the optimal order quantity that minimizes the TCO, as illustrated in Figure 4.

Minimizing the TCO means achieving the right balance between the purchase price and purchase quantities, the order cost, defined as the cost for placing an order, and the inventory holding cost, also known as the carrying cost. We can thus define the Total Cost of Ownership as follows in accordance with how GenLots applies it:

TCO = Purchasing Cost + Order Cost + Carrying Cost + Cost of Scrap

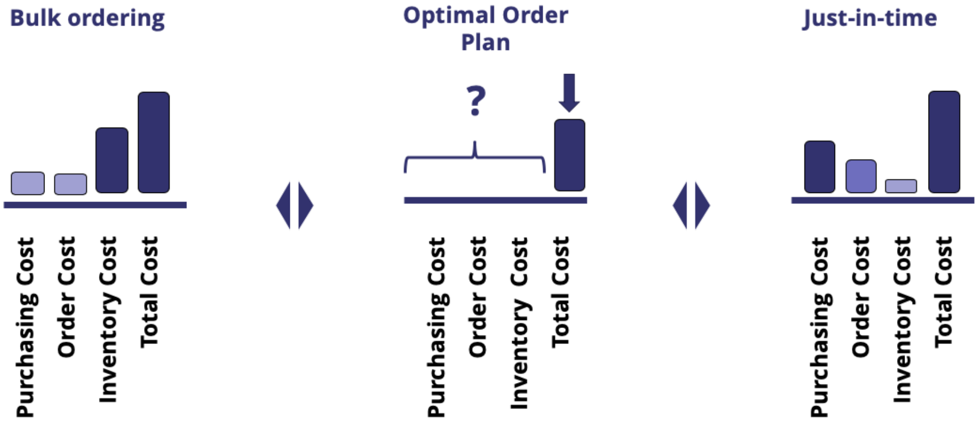


Figure 4. Total Cost of Ownership without CO_2 emissions

The problem with this formula is that it misses the environmental cost resulting from the CO_2 emissions emitted in getting the materials into the warehouse, in storing the materials, and in disposing of any scrapped materials. Figure 5 illustrates how CO_2 emissions relate to each of the previously described costs, while Figure 6 illustrates the trade-offs involved when the cost of CO_2 emissions is introduced into the total cost equation.

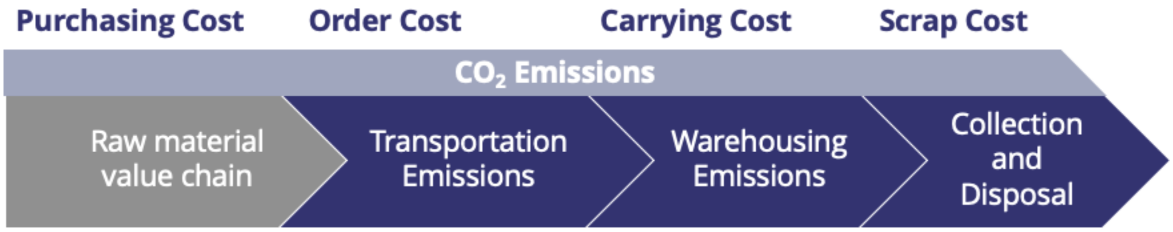


Figure 5. CO_2 emissions from order planning considering the product lifecycle

On a company's financial statement this environmental cost could be represented in different ways such as a carbon tax, the traded carbon price, or the voluntary price paid to offset those CO_2 emissions; these concepts will be disambiguated in the coming subsections. Ideally, these prices reflect the cost to eliminate the same amount of carbon from the atmosphere and/or to compensate for the potential cost that one additional unit of CO_2 emitted will cause to society. This burden to society is often referred to as a negative externality.

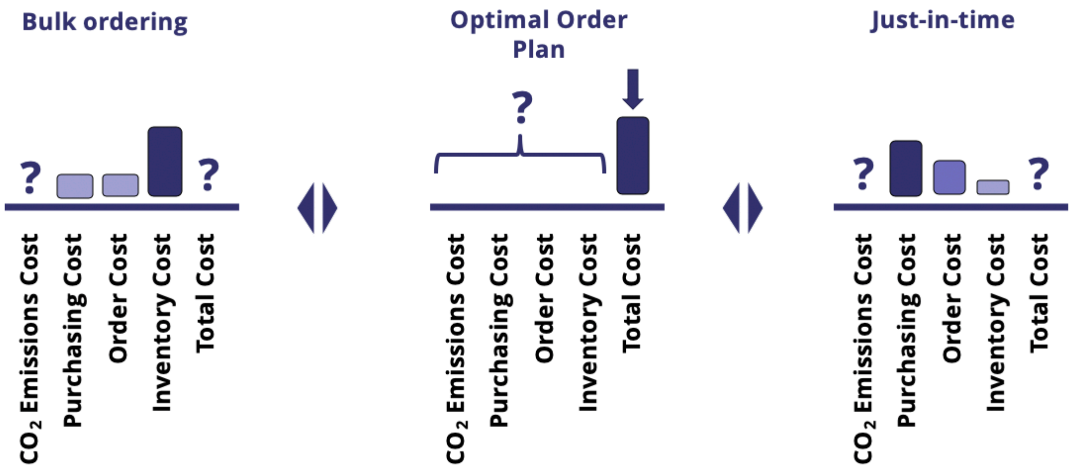


Figure 6. Total Cost of Ownership with CO_2 emissions

3.3. Externalities of GHG Emissions

Externalities or external costs to society result from the social or economic activities of one (group of) person(s), when their impact is not fully accounted for or is not compensated for by such individual or group. To identify externalities, the entire lifecycle of the emitted GHGs should be taken into account (i.e. from the moment that the fossil fuel was extracted or the electricity was generated to the long-term effects of the emitted emissions). Hence, this will include all external effects such as climate change, droughts, wildfires, acid rain, cyclones, floods, air quality deterioration, habitat damage, accidents, congestion, noise, among others.

Each of these effects has other repercussions on society across many dimensions including the economic, health, political, and social dimensions. Modeling, measuring, and monetizing some of these impacts, such as local noise and health effects, is routine and standardized in practice, especially at the local level. However, this becomes much more difficult for some of the other externalities such as climate change, especially when evaluated at an international level. In a report developed for the EU Commission by the independent research and consultancy organization CE Delft, the total external costs of transport in the EU28 during 2016 were estimated at €987 billion.[1]

---

[1] "This figure only includes congestion costs for road transport, as it was not possible to estimate congestion costs for other modes. In general, the most important cost category is accident costs equating to 29% of the total costs, followed by congestion costs (27%). Overall, environmental costs (climate change, air pollution, noise, well-to-tank and habitat damage) make up the remaining 44% of the total costs. However, large differences exist between transport modes."

"Road transport (largely due to passenger cars) was the largest contributor with €820 billion, rail transport and inland waterway transport (IWT) amounted to €18 billion and €3 billion, respectively, while aviation and maritime transport totaled an estimated €48 and €98 billion respectively (Schroten, van Essen, van Wijngaarden, Sutter, & Andrew, 2019). In practice, there is wide variation in the values used to measure the carbon costs across countries, but also across industry sectors even within a single country. Moreover, scientists and policy makers agree that such values will increase over time, at least conceptually, due to the marginal increase in the impact of one extra tonne of CO_2 as the concentration of CO_2 in the atmosphere increases (International Transport Forum, 2015).

3.4. Understanding GHG Emissions: Types and Categories

Greenhouse gases absorb heat or infrared radiation emitted from Earth's surface and reradiate it back creating a greenhouse effect. When we refer to GHGs we generally refer to carbon dioxide (CO_2) which makes up the grand majority of emissions, approximately 81% of all US GHG emissions came from CO_2 in 2018 (Environmental Protection Agency, 2018). Other most common GHG gases include methane (CH_4), nitrous oxide (N_2O), fluorinated gases such as HFCs and PFCs, and sulfur hexafluoride (SF_6). In order to report the carbon footprint from all of these GHGs as a single number, the standard unit CO_2 equivalent (CO_2e) is utilized. All other GHGs are converted to the equivalent CO_2 emissions using standard ratios based on the impact or Global Warming Potential (GWP) of each of the other GHGs; for example, the impact of 1 tonne of NO_2 comes in at 298 tonnes of CO_2.

In the past two decades, non-governmental institutions, governments, industry associations, and enterprise, among others have come together in what is today the Greenhouse Gas (GHG) Protocol to establish a "comprehensive global standardized framework to measure and manage greenhouse gas (GHG) emissions" across the private and public sector (Greenhouse Gas Protocol, 2020). The GHG Protocol has published best practices and guidelines for conducting GHG accounting, in other words measuring CO_2 emissions within an organization. It identifies three different

---

categories of GHG emissions based on whether these emissions result from the direct or indirect activities of an organization:

a. **Scope 1 emissions** are those that result from one's direct activities such as fuel consumed for the operation of vehicles and facilities owned or controlled.
b. **Scope 2 emissions** consist of emissions generated indirectly, off-site, such as through the generation of purchased electricity for activities like powering data centers, lighting, steam, heating, cooling, etc.
c. **Scope 3 emissions** include all other indirect sources of emissions within a company's value chain, resulting from other entities such as material suppliers, third-party logistics providers, waste management suppliers, travel suppliers, lessees and lessors, franchisees, retailers, employees, and customers" (Bhatia, et al., 2011).

Emissions are defined in this way in order to avoid having two or more companies double counting the same emissions accounted for within Scope 1 and 2. For the purpose of this research we are mainly concerned with Scope 3 emissions, more specifically with Scope 3 emissions arising from upstream transportation and distribution activities. Scope 3 emissions often exceed Scope 1 and 2 emissions by far, and for most sectors comprise over 70% of a company's total emissions. However, as Scope 3 emissions are found outside the boundaries and control of one's organization, they are usually the most difficult to influence. Notwithstanding, multiple leading companies especially within the consumer goods sector are already setting targets and taking steps to reduce their Scope 3 emissions. For example, Walmart announced its Project Gigaton initiative which aims to reduce its supply chain GHG emissions by 1 billion tonnes by 2030 (Supply Chain Solutions Center, 2020).

3.5. Carbon Accounting and CO_2 Reporting

Companies, states, and individuals measure their carbon dioxide equivalents through the process of carbon accounting. This enables them to understand and act upon their climate impact, but also to comply with government regulation through mandatory carbon reporting and participation in carbon markets. For example, in the UK, reporting is mandatory for all publicly listed companies, as well as for certain large companies and limited liability partnerships, while it is encouraged for all other companies to do so voluntarily. Governments must then consolidate and report this information at a national level to evaluate and report their progress against international climate agreements such as the Paris Climate Agreement ratified in 2016 and to inform future climate policy.

Besides governments, institutional investors are increasingly requiring this type of information as they seek to build resilient portfolios against climate change and climate change regulation by investing into low-carbon companies and/or carbon resilient companies. Climate risk is identified as a non-diversifiable risk, and when it comes to certain resources and raw materials, but also to logistics it poses a significant threat to company operations and profits. Research from the Sustainability Accounting Standards Board demonstrates that 72 of 79 industries will be greatly affected by climate risk, amounting to 93% of US equities by market capitalization; these 79 industries were classified into a Sustainable Industry Classification System based on shared sustainability risks and opportunities (Sustainability Accounting Standards Board, 2016). Consequently, the Carbon Disclosure Project (CDP) today provides a framework for the climate risk disclosure on behalf of 515 institutional investors with US$106 trillion in assets totaling over 8,400 companies. It does the same for more than 800 cities and 120 plus states/regions (CDP, 2020).

A domino effect in the number of companies reporting is also materializing. Companies required to report emissions in their supply chain, both upstream and downstream, are putting pressure on their suppliers and clients to provide such information and to attain a certain level of environmental sustainability performance. Companies like Verizon in the US have invited 448 of their key suppliers to the EcoVadis platform since 2013 (Johnson & Johnson, 2018). EcoVadis, in partnership with CDP is one the leading providers of business sustainability ratings, which helps assess corporate social responsibility and sustainable procurement across environmental, fair labor practices, ethics and fair business practices, and supply chain matters. Thanks to the evolving CO_2 reporting requirements, companies are starting to develop the mechanisms and tools to not only collect the necessary data for measuring their emissions in-house, but also throughout their supply chain.

3.6. Carbon Pricing

According to the World Bank, as of April 2020, 61 carbon pricing initiatives taking the form of a carbon tax or an Emissions Trading System have been implemented or are scheduled for implementation. These cover 46 national jurisdictions and 32 subnational jurisdictions (cities, states, and/or regions) and represent approximately 22.3% of global GHG emissions corresponding to 12 $GtCO_2e$. Across these initiatives, there is a vast price difference; prices range from as low as US$0.07/$tCO_2e$ in Poland to as high as US$119.43/$tCO_2e$ in Sweden, with the bulk of carbon prices set between US$5 and US$25 (The World Bank, 2020). These prices are significantly below the US$40-US$80/tCO_2e carbon prices estimated by the High-Level Commission on Carbon Prices that will enable the achievement of the 1.5ºC Paris Agreement temperature goal (Carbon Pricing Leadership, 2019). It is important to keep in mind that these carbon prices are generally only reflected across a subset of economic sectors and/or fossil fuel types depending on the initiative and pricing mechanism.

We can be certain nevertheless that carbon prices will increase in the future in parallel to the gradual or ambitious GHG emission reduction targets influenced by policy-makers, institutional investors, and company self-determination. However, carbon pricing is a highly complex topic, which bears many economic, political, social, and environmental implications, especially when we refer to carbon leakage. If a company in one jurisdiction such as the European Union suddenly faces increased costs from climate policies, carbon leakage may occur in the situation that such company decides to transfer its production to a different country with more relaxed GHG emission standards or policies. To avoid carbon leakage, the EU has engaged in discussions over the possibility of introducing a Carbon Border Tax on products produced abroad to make up for the difference between the domestic carbon tax and the respective carbon tax abroad (Horn & Sapir, 2019).

Depending on the carbon pricing mechanism in place at a particular jurisdiction and particular time, a company may not be directly affected by a carbon tax or be required to participate in an ETS. Nevertheless, such a company may choose to factor environmental costs into its economic analysis for various reasons and in a variety of ways such as through carbon offsetting, carbon insetting, and internal carbon prices. In the next subsections the different external and internal carbon pricing mechanisms are disambiguated.

3.6.1. Carbon taxes and Emissions Trading Systems (ETS)

Carbon taxes and Emissions Trading Systems have different means to the same end. They both lead to tCO_2e reductions by motivating companies to invest in clean technologies and low carbon approaches, and they also generate public revenue that can be used to "invest in climate and energy measures, finance tax reforms, pay down public debt, support social programs, or compensate households" (International Carbon Action Partnership, 2019). A carbon tax is the simplest form of carbon pricing, by setting a fixed price per tonne of CO_2e emitted within a national or subnational jurisdiction. On the other hand, an ETS is much more complex to implement and manage by creating a market-based instrument based on the supply and demand of permits for each CO_2e emitted.

Two main types of Emissions Trading Systems exist: a 'cap and trade' and a 'baseline-and-credit' system. The most common ETS type is the cap and trade system, which unlike a carbon tax fixes an upper limit or cap on the number of total allowed emissions and establishes a market price for each tCO_2e emitted. Under this system, each company is distributed GHG emission allowances or permits equal to the individual firm's cap either for free (typically on the basis of their past emissions) or through auctions. They can then trade their emission permits to satisfy their emission targets. Over time the cap is reduced, and the price is pushed up as the number of permits in the market diminishes. Companies are hence incentivized to implement emission abatement measures not only to meet future requirements, but also because they can sell any unused permits in the market. However, as technology improvements reduce the costs to lower one's GHG emissions, the opposite may occur, hence increasing the supply of permits, driving down the market price.

Alternatively, depending on the costs of abatement versus purchasing more permits, companies may choose to purchase additional permits to cover their excess emissions. In the EU ETS if a company fails to comply by surrendering enough permits corresponding to their emissions at the end of the trading period, they must face significant fines: €100/tCO_2 and rising with EU inflation since 2013 (European Commission, 2015). Additionally, such company receives fewer allocations in the next period. In contrast, under the baseline-and-credit system, no fixed limit on emissions is set, but credits are issued to companies that succeed at reducing their emissions to a level below a baseline emissions level; these credits can then be sold to excess polluters.

An ETS is much more flexible than a carbon tax as it is possible to extend it across national borders by linking it to other trading systems. Linking two or more systems leads to a larger carbon market in terms of the permit trading possibilities and the emission reduction options. As of January 1st, 2020, Switzerland's ETS, which includes approximately 90 companies, mainly energy producers, was linked to the EU ETS, which includes over 11,000 power plants and manufacturing installations. This has multiple benefits as it allows market prices across ETSs to converge as well as creates additional liquidity and reduces price volatility from large players (International Carbon Action Partnership, 2015).

Currently, there are 28 ETSs operating across five continents. The EU ETS launched in 2005 is the oldest and largest of all, and today includes the EU28, Norway, Iceland, and Liechtenstein. Since the beginning of its third phase which started in 2013 its cap has been linearly reduced by 38M tCO_2 per year down to 1,818M tCO_2 in 2020. New guidelines for its fourth phase beginning in 2021 are in the development process, which should lead to a more ambitious emissions reduction plan. During the period 2013-2016 EU members States generated nearly € 15.8 billion from the auctioning of EU ETS allowances, of which 80% has been used or is planned to be used for climate and energy purposes (European Commission, 2015). Other major ETSs include the California Cap and Trade system, the Regional Greenhouse Gas Initiative (RGGI) linking 10 northeastern US states, the Korean ETS, and New Zealand's ETS. After running 8 pilot ETSs at the city level, China is presently preparing to introduce a nationwide system that will overtake the EU ETS as the largest ETS. Around the world ETSs and carbon taxes are increasingly being adopted, with more sectors being incorporated into existing ones, helping to *reduce* or *prevent* carbon emissions. When it comes to those emissions that can no longer be prevented, especially in the case of sectors such as aviation that find it very difficult to reduce their emissions, complementary carbon pricing mechanisms aiming to *compensate* or *offset* emitted carbon emissions exist.

3.6.2. Carbon Offsetting and Carbon Insetting

Carbon offsetting is a mechanism that aims to *remove* GHG emissions by paying other sectors to reduce their emissions through *external* projects or program-based activities outside of a company's own value chain whether domestically or abroad; while it may be more appropriate to implement offsets for Scope 1 and 2 emissions locally, the opposite may be true for Scope 3 emissions. Carbon insetting on the other hand is no different except for the fact that the GHG emission removals take place within the company's value chain. Typical carbon offsets and insets may include reforestation, renewable energy, energy efficiency, waste management, or agricultural projects. They both aim to reduce CO_2e ex-post and hence serve as a corrective or compensatory action. Some ETSs may allow for offsets in some sectors as a way to earn carbon credits sometimes referred to as Greenhouse Gas Removal (GGR) certificates. However, offsets are also commonly used by companies or governments to move towards carbon neutrality, meaning releasing net zero emissions, even when some or none of their emissions are not taxed or accounted for in an ETS. In the case of Switzerland, grocery stores Coop and Migros have incorporated offsets on all of the emissions resulting from the air shipment of their goods (my M climate fund – CO_2 compensation in the value-creation chain , 2019) (MyClimate, 2019).

3.6.3. Internal Carbon Pricing

Internal Carbon Pricing (ICP) is a mechanism used to inform investment or operational decisions and/or to influence behavior by embedding a theoretical or assumed carbon price in overall procurement decisions or supply chain analyses. It is also often referred to as shadow pricing, as these prices are usually not represented by any financial flows or transfers and do not necessarily reflect the market. Most commonly it is used as a strategic risk management tool to account for hidden risks and opportunities within operations and the supply chain such as energy price forecasts, changes in customer demand, and existing or emerging carbon pricing regulations (i.e. mandatory compliance costs and carbon price increases). In some cases, a range of carbon prices may even be adopted in response to the different prices across jurisdictions. ICP will generally incentivize companies to reallocate budgets and resources towards low-carbon products or emission reduction activities such as energy efficiency and renewable energies. Its optimal application especially requires the support from upper management, having insights into suppliers' and their offerings' carbon footprint, as well as insights into climate policy developments at the procured locations.

According to the CDP, as of 2017 there were nearly 1,400 companies worldwide, and five of the top ten OECD GHG emitting countries implementing ICP. The prices that companies reported to be using were extremely wide ranging, going from US$0.01 per tCO_2e to US$909 per tCO_2e. The same could be observed for countries across a diverse set of years and sectors: US$5 per tCO_2e to US$400+ per tCO_2e (The World Bank, 2017). In many cases the ICP price levels disclosed were not surprisingly consistent with the price levels set through regulation, especially in the face of clear carbon price signals. In order for ICP to influence innovation, investment decisions, and market signals in line with the 1.5ºC-2ºC target, the United Nations Global Compact has called for companies to set a minimum internal carbon price of $100/$tCO_2e$ (Kingo, 2016). While in theory internal carbon prices may sound very promising, in practice they face many challenges and limitations arising from their complexity to implement as well as their intangibility and irrelevance on a company's Profit and Loss statement.

4. Commercial Viability

To evaluate the commercial business case of the CO_2 Emissions Optimizer, fourteen experts across ten different organizations from the industry, academics, and the non-profit sector were successfully contacted and interviewed for between 30 and 75 minutes, while Annual Sustainability Reports from public companies in the target industries were reviewed. Based on this research, in this section we analyze the perceived potential functional and economic value, determining whether there is a need and interest from clients and whether the value it would bring is something that companies have the budget for and/or would be willing to pay for. Depending on the company and the stakeholders, the budget for a software like GenLots may come from one of various departments within a company such as supply chain, procurement, innovation (and digital transformation), among others. It is important to assess whether the CO_2 Emissions Optimizer could open an untapped channel for GenLots to gain new clients by accessing environmental sustainability budgets, and if not whether it would still be an attractive secondary value proposition for existing and prospective clients.

We will review the different trends that could point towards its commercial viability as well as the various challenges and obstacles that could point away from it, offering a detailed outlook on the landscape concerning GHG emissions in logistics and transportation. It covers the future development of GHG emissions regulation and prices specific to the logistics domain as well as how industrial companies are being affected by and adapting to them. Also, it incorporates the different internal and external operational, technological, societal, cultural, and economic forces influencing the incorporation of GHG emissions into the Total Cost of Ownership framework within an organization.

4.1. Evaluating Potential Interest and Budget

Initial potential interest by companies in the CO_2 Emissions Optimizer was determined by evaluating where sustainability stands in terms of companies' priorities, particularly when it comes to logistics and transportation. To do so, several aspects were looked at:

1. What is the existing or expected impact from climate change on industrial companies' supply chains, and could this increase their interest? This was assessed based on the

information included in company websites and reports and collected from the interviews that were conducted.

2. Are companies already undertaking or planning to undertake any actions or investments to optimize their GHG emissions in their logistics and in general?
3. To what degree is sustainability becoming a priority and embedded within organizations? Public sustainability commitments and pledges as well as companies' organizational structure and job titles using LinkedIn were reviewed for this respect.

The conducted research evidenced that climate-related supply chain disruptions are on the rise being identified by companies as representing a serious threat, while setting off upward cost pressures. For example, in its 2019 Sustainability Report the chemicals company BASF describes how the low water levels on the Rhine River due to the hot and dry summer impacted a significant number of its shipments. 40% of the volumes for one of its sites in Germany which are transported directly to it by ship had to be transported by truck instead (BASF, 2020). This is just one example of many, where climate change related drought, extreme rainfall, and flooding can have great consequences. But perhaps one of the most concerning cases is the imminent effect on the Panama Canal, one of the most important shipping waterways in the world which reduces international maritime shipping times by several weeks (Timperley, 2020). In contrast, to the benefit of some companies and countries, the melting of the ice caps along the Arctic Ocean due to climate change has opened up new routes or maintained routes open for a longer period throughout the year. However, despite shipping being the most efficient transportation mode, given that the fuel used by ships is among the dirtiest of all transports, the ecology in the region is being greatly threatened (Transport and Environment, n.d.).

The realization of the urgency to accelerate climate risk mitigation efforts has brought stakeholders together to implement voluntary and/or mandatory reporting and disclosing of carbon footprints. In turn, this has driven many organizations to set very ambitious environmental sustainability goals and to start mapping their emissions along their entire value chains, down to the individual product level. For example, the pharmaceutical company, Novartis, has publicly committed to reduce its CO_2 emissions across its supply chain by 50% and across its entire value chain by 35% by 2030 with respect to 2016 levels (Novartis, n.d.). To make their sustainability targets more concrete and to spur innovation and collaboration, numerous cross-industry and industry-specific coalitions and initiatives have been launched, such as the Science-Based Targets initiative (SBTi) or Together for Sustainability coalition (formed by 26 chemicals companies). These initiatives are also helping to set and develop new standards and targets for organizations to follow. Nearly 1,400 companies have today joined SBTi, many setting targets not only for their Scope 1 and 2 emissions, but also for Scope 3 emissions across their entire value chain, including the upstream sourcing of raw materials (SBTi, 2020). These trends not only point towards potential interest, but also to a growing potential market.

All of this has also led to the emergence of the green finance movement, a movement which has led to companies' issuance of green bonds. Green bonds allow companies to raise funds to meet these ambitious targets by implementing climate and environmental related projects and could potentially enable an organization to create the budget for a solution like GenLots'. The green bond market is estimated to reach 1 trillion in 2020, and we can see that companies like Verizon have issued as much as US$1 billion in green bonds (Johnson & Johnson, 2018) (Brohé, 2018).

We were able to validate increased investment by companies into optimizing their logistics costs and GHG emissions. For example, most interviewed companies mentioned working with consulting companies to develop internal processes and tools, while others mentioned being currently in the process of deciding whether to purchase an existing solution from providers such as Llamasoft or RiverLogic. Both solutions were mentioned to have carbon accounting integrated into their platform, and thus offer indirect competing solutions to GenLots. It was also found that companies were already trying to or were interested in optimizing the capacity utilization in transportation to reduce the number of transports, such as by reducing the volume of their product packaging.

Another common denominator found across most companies was an increasing shift towards low-carbon transportation modes and low-carbon logistics providers. First of all, firms are adopting more intermodal transportation routes, while also transitioning as much as possible from air to sea and from road to rail. While this may certainly reduce their costs and environmental impact this of course may translate into longer lead times and hence a reduced agility to respond to demand fluctuations or supply chain disruptions. Secondly, some companies are beginning to introduce CO_2 disclosures and expectations into their logistics provider contracts. Nevertheless, while those companies may be ready to punish poor performing suppliers when it comes to sustainability, they are not necessarily ready to reward good ones by paying premiums, especially if these premiums are purposed for carbon offsets. In that case it opens the debate of whether the provider or the contracting company can offset its emissions at a lower cost, as well as what the nature of the selected offset project is, since the contracting company may prefer to inset its emissions within its own supply chain rather than offset them in project not in connection to its organization. These investments and initiatives demonstrate that there is interest and budget to optimize GHG emissions from logistics, especially when cost savings also follow, however this also means that GenLots would be indirectly competing for budget and the promise of cost savings against other initiatives that claim to also reduce GHG emissions.

Lastly, we were able to confirm first-hand using LinkedIn, company reports, and through the interviews conducted that environmental sustainability is being taken more seriously, slowly transitioning from being managed from a marketing, communications, or Human Resources domain, into an organization-wide responsibility with accountable leaders in each department. Not only have new positions such as the Chief Sustainability Officer or Head of Climate been created over the past decade, but also many existing roles are being redesigned to integrate sustainability. Specific titles include Sustainable Supply Chain Manager, Sustainable Procurement Manager, Procurement and Sustainability Controller, Digital and Environmental Lead, among many others. Companies further along in their sustainability journey have also started publishing standalone Sustainability Annual Reports rather than coupling sustainability into their all-encompassing Annual Report. Despite this transformation, sustainability still largely remains an activity that is looked at on a strategic, compliance, and marketing basis, rather than on an operational basis where information is available to inform real-time decision-making, signaling both an opportunity for GenLots, but also the fact that the timing might be too early.

4.2. The Functional Value of the CO_2 Emissions Optimizer

Based on the input from various interviewees the CO_2 Emissions Optimizer could provide significant functional value to companies by allowing material planners and supply chain and logistic managers to conduct simulations and sensitivity analyses considering GHG emissions in conjunction with the TCO to inform their decisions. This would allow them to easily compare the resulting effects on the GHG emissions from changing any one parameter. For example, it could help managers simulate different real and internal carbon pricing scenarios and find out what the break-even carbon price that influences decision-making is. According to them, it would prove especially useful if it were capable of supporting strategic decisions such as in determining whether to produce a particular product in Plant A or Plant B, or in using transportation supplier A or B. However, supporting strategic decisions like these, could be categorized as a product extension to the original basic purpose of the CO_2 Emissions Optimizer.

4.3. The Economic Value of the CO_2 Emissions Optimizer

Companies will typically purchase a new product if it will allow them to derive economic value either directly or indirectly by increasing their revenue, reducing their costs, or both. The CO_2 Emissions Optimizer has the potential to accomplish both. In order to increase the revenues of GenLots' clients, it would need to drive increased demand and/or an increased willingness to pay from their customers for a product or from a company with a lower relative carbon footprint. Over the past years a whole new industry has emerged around CO_2 certification and labeling as consumers increasingly pay attention to the carbon footprint of the companies and the goods that they purchase, especially in the food and beverage industry. Consequently, many organizations are starting to pay attention to climate and environmental sustainability even in the cases where short or medium-term cost savings may not be possible. Although this trend favors GenLots, based on the input from interviewees, it would be imperative for GenLots to help its clients make credible, product-specific reduced carbon footprint claims. GenLots should thus be capable of accurately and credibly measuring and reporting carbon emission savings by implementing globally accepted carbon accounting standards. Additionally, the emission savings it generates must be substantial relative to a product's or a company's emissions.

On the cost-saving side, even if GenLots can save a company substantial GHG emissions without also increasing their other costs, for real financial savings to take place, lot sizing-related GHG emissions need to be attached to either a tangible internal or external GHG emission price that gets reflected on a company's Profit and Loss (P&L) statement. Tangible internal carbon pricing may be implemented in response to current mandatory compliance and reporting measures or to the anticipation and proofing against such measures that could result in an increase to a company's operational costs. Similarly, it may be the result of a company's personal commitment to a selfimposed sustainability target. Given that Barry Callebaut has committed to becoming carbon positive across its entire value chain by 2025, this means that they will inset or offset all of their emissions beyond 2025 (Barry Callebaut, n.d.; UK Government, 2020). Today, typical offset prices range between \$5 and \$25 per tCO_2e, and hence represent a tangible internal carbon price in this case.

Externally set carbon prices on the other hand are created by the government and other regulatory bodies. They can affect a company directly by leading to increased operational costs, or indirectly such as by leading to increased supplier pricing. As most lot sizing-related emissions fall under Scope 3 emissions, which are presently not taxed nor included in an ETS, its regulatory outlook across the globe needs to be considered.

Emissions legislation within the transportation industry is fast-changing both globally, but is generally being led by Europe, which launched its New Green Deal aiming to become the first carbon neutral continent by 2050. As a resource-poor continent which is inherently looking abroad to gain access to materials and energy resources to meet the demands of its economy and citizens, it is clear that Europe is not only leading the way, but is also far ahead in comparison to the rest of the world when it comes to GHG emissions regulation and to transitioning into a low-carbon economy. In Europe aviation has been part of the EU ETS since 2012, whereas shipping was only recently decided to be included starting from 2021, while road transport has not been included yet (Strauss, 2020). It is worth mentioning that early this year the United Nation's regulatory body for maritime transport, the International Maritime Organization, introduced IMO 2020, a mandate aimed at reducing by 77% the emissions of highly polluting Sulphur oxides found in ship's fuel oil by lowering the maximum Sulphur quota from 3.5% to 0.5% (International Maritime Organization, 2020). Cleaner fuel standards for road vehicles were also announced this year within nine European countries, increasing the petrol grade standard from E5 to E10, allowing for up to 10% ethanol. Moreover, Germany has announced that as of 2021, it will put a price on the carbon emitted from those sectors not covered by the EU ETS – buildings, transport, and agriculture – through the creation of a separate national ETS with prices increasing from 25 €/tonne in 2021 up to 55 €/tonne in 2025 (Mohr, 2020). In a last example, Europe may soon set mandatory sales targets for emissions-free trucks, following the US state of California's decision to require each new truck sold in California by 2045 to be zero-emission (California Air Resources Board, 2020).

Evidently, emissions regulation concerning Scope 3 emissions around logistics and transportation particularly in Europe is catching up and tightening up. But as we can see we are only at a very premature phase of its implementation, also a signal that GenLots might be too early. If we take a look at other countries or regions, the CO_2 Emissions Optimizer might not even be viable in the next 3-5 years. In the medium-term, China and South East Asia could become the next most viable, given that the imminent threat from running out of water and land to cultivate, as well as air pollution levels are forcing the governments and corporations to adopt a rapid shift towards a low-carbon economy. Other countries like Japan and Korea are mainly treating environmental sustainability as a business opportunity, observing first what others are doing before taking any action. Then there are the fossil fuel rich countries whose high dependency on fossil fuels leave them no other choice than to continue to push for a fossil fuel economy. These countries could be dismissed, just as most all other countries whose reality is that they are far behind and today lack the leadership to follow quickly in the steps of Europe per say.

4.3.1. Discussion of the Economic Value from Cost-Savings

To evaluate the potential economic value under the assumption that tangible carbon pricing exists, we first need to consider the magnitude and share of the GHG emissions from companies' upstream transportation and distribution activities. Absolute GHG emission quantities from the upstream transportation and distribution activities of industrial companies with globalized supply chains are quantitatively very relevant in general, but they vary heavily across companies. While in some cases their share of emissions in comparison to the absolute emissions across all scopes may seem very small, they may still be quantitatively significant. Taking a few examples, we can see that Johnson & Johnson's (JnJ) upstream transportation and distribution emissions for 2019 totaled 2,201,590 tCO_2e, representing nearly 16% of their emissions across all scopes (Verizon, 2020). On the other hand, the 2019 upstream transportation and distribution emissions for Unilever and Givaudan amounted to 240,376 tCO_2e and 31,296 tCO_2e respectively, representing only around 1% of their entire product life-cycle-based GHG footprint (Unilver plc, 2020) (Johnson & Johnson, 2020). These variations may be based on a great number of factors such as the industry, turnover, transportation and storage condition requirements, supply chain network, among others.

If GenLots could measure the emission savings it generates and hence prove to save even just 1% of such emissions, for JnJ, this would amount to 22,015 tCO_2e. Under the assumption that JnJ were looking to be carbon positive across its entire value chain, at a carbon emission offset price of US\$25/tCO_2e, this would amount to an astounding US\$550,397.50 in savings, or US\$110,079.50 at a price of US\$5/tCO_2e. In contrast, for Givaudan, such savings would only range between a meager US\$1,564.80 and US\$7,824. From the above analysis we could infer that for commercial viability to exist, the upstream transportation and distribution emissions of a company may need to be at least in the several hundreds of thousands. This analysis, however, does not distinguish between the GHG emissions that GenLots is capable of saving today with and without incorporating GHG emissions as a parameter into its algorithm. Hence, it is important to carry out a case study to compare the results and evaluate the cost-benefit to incorporating it.

4.4. Challenges and Obstacles to Commercial Viability

Throughout the interviews, multiple challenges and obstacles were brought up, which could further point to GenLots being too early. These can be categorized into data and economic related factors.

4.4.1. Data Related Factors

Many large companies are starting to measure and report their Scope 3 emissions, but accurate measurement requires that companies have the right systems, calculation methodologies, and processes in place so as to obtain and store specific and granular data. However, modern-day ERP systems are not designed to handle and store carbon accounting data and hence companies are finding themselves developing their own internal tools (i.e. Excel spreadsheets) and/or using other systems which do not interact with their ERP system. Often these tools are not dynamic as well as intuitive enough for anyone who has never worked with carbon accounting. Thus, in order to drive decision-making it is necessary to make the data more accessible throughout the organization.

Another important challenge is the lack of granular data that most managers face, which leaves them relying on assumptions and generic database values. This makes it difficult for managers to influence the results following any improvements or changes they were responsible for. Even when specific and granular data is available, there is still the problem that the data is not always comparable as the data often comes from multiple suppliers and each supplier may work with different databases, assumptions, tools, and methodologies. Once all of the data has been collected, there is also a lot of work and a lead time involved in putting the data together as well as in interpreting it to understand the different drivers influencing a change in the carbon footprint. Consequently, organizations are ending up with lagging indicators, finding themselves reviewing environmental sustainability matters typically on a yearly basis and making decisions top-down as opposed to bottom-up.

To avoid this and to also steer a cultural change, companies like Barry Callebaut have moved away from annual carbon accounting towards quarterly carbon accounting. More frequent reporting will help its organization improve visibility around carbon accounting and with getting managers to become used to seeing the numbers, such that when receiving the additional sustainability target, they are less overwhelmed by all the existing targets that they are already responsible for hitting. This is especially important given that drawing precise conclusions from a change in the carbon footprint is extremely challenging due to the many factors that come into play, such as putting it into perspective with changes in business growth, suppliers, innovation, among others.

4.4.2. Economic Related Factors

When a company introduces sustainability considerations into its operational decisions and none of its competitors are doing the same, then they become faced with the problem of losing their competitive advantage. Even though there is a growing trend among consumers (in some industries) for more sustainable products and among investors for low-carbon investments, the reality is that lower prices continue to dominate consumer purchasing behavior and larger returns no matter the cost investment decision-making. As a result, when companies implement more sustainable alternatives, they want to understand the ROI of such decisions in terms of how they are going to create value. But that value may be difficult to determine as it is often dependent on figuring out which narrative will appeal more and have a stronger impact on the consumer and brand perception. For example a company may consider a strategy of achieving major emission reductions across its product portfolio but focus its emissions reductions on a particular product so as to market only that product as carbon neutral. Conversely, it may simply focus on achieving 50% or 100% of its emissions reductions across the entire value chain.

Perhaps one of the most important obstacles is that only a fraction of companies is implementing carbon pricing; carbon pricing not only requires high-level stakeholder support, but also reaching a consensus in regard to what the carbon price should be set at. On one hand there is the real cost of carbon, which is based on a market scheme or a carbon tax. On the other, is the fully burdened cost of carbon, which considers all the negative externalities, and internal carbon prices such as the internal price of $100 per tonne of CO_2e recommended by the UN Global Compact. However, when the carbon price is not tied to the real cost of carbon, companies run the risk of their analysis merely becoming an academic exercise. As the acceptance and ubiquity of carbon prices within an organization increase, multiple carbon prices may come into play, such as a shadow price for long-term capital investment, a short-term internal price for influencing how a company operates, and a real P&L carbon price that considers what companies do to operate.

4.5. Commercial Viability Discussion

In this section we have pointed out how GHG emissions in logistics and transportation is increasingly drawing the attention of regulatory bodies, industrial companies, logistics providers, software providers, and the innovation ecosystem, resulting in a rapidly changing landscape. Nevertheless, as has been hinted several times, we are undoubtedly at a very early stage in the maturity life cycle for GenLots CO_2 Emissions Optimizer to be commercially viable. One of the most critical factors is the lack of specific and granular carbon accounting logistics data as well as the low adoption of carbon pricing in inbound logistics. Further evidence pointing to this is the fact that only at the start of 2020, the ERP company, SAP, announced at the World Economic Forum that they are co-innovating with leading companies across various industries to launch a new program they call Climate 21; Climate 21 will allow its customers to understand, monitor, and optimize their carbon footprint across their supply chain operations and their products, both within their organizations and beyond it (SAP, 2020). Although the timeline for this rollout is not known, this will likely help accelerate adoption and innovation in this space as companies develop the ability to integrate all their carbon emissions data with their ERP system. Given the subject's complexity and unique situation of each industry and company, if there proves to be technical viability, and a business case, GenLots will likely need to adopt a similar innovation strategy to SAP's.

Part of GenLots' growth and funding strategy has included co-innovation and grant funding, two strategies that should be considered for the CO_2 Emissions Optimizer. Co-innovation usually entails finding early adopters, which in this case should include European companies, which have made ambitious Scope 3 supply chain emission reduction commitments. Such a company would also need to have already invested into upstream logistics emissions data collection, accounting, and/or modeling, hence signaling that they are serious about the subject and have their money where their mouth is. Additionally, GenLots should target firms that would likely benefit the most from the product; companies with energy-intensive logistic operations such as from short lead time requirements and from special transportation and storage conditions leading to high shipping costs and emissions would fall under this category. To validate a company's readiness, GenLots should review a company's sustainability and assurance report in addition to briefly researching the company's organizational structure and employee titles (e.g. on LinkedIn) in connection to sustainability.

GenLots has also applied to and participated in several accelerator and grant programs, such as the European Commission's Horizon 2020 program. Programs like Horizon 2020 focus their funding on some the major global challenges such as "climate action, environment, resource efficiency and raw materials" (European Commission, n.d.). Today the reduction of GHG emissions is not central to GenLots' value proposition despite the imminent GHG emission reductions associated with decreasing inventories and transports in upstream logistics. While GenLots was successful in receiving funding from Horizon 2020's first phase, it was unsuccessful with the second phase; having had the CO_2 Emissions Optimizer as a central value proposition may have potentially increased its success possibilities. Hence, by introducing GHG emissions measurement, reporting, and optimization into its core product or into a new product, it could possibly increase its grant funding possibilities in the near future.

5. Technical Viability

To evaluate the technical viability of the CO_2 Emissions Optimizer it is first important to understand what the globally accepted GHG emission calculation methods are as well as what kind of data is needed for those methods. We then review previously developed lot sizing models that incorporate CO_2 emissions, and benchmark them against the globally accepted standards, while comparing and evaluating their strengths and shortcomings. We then review what kind of data is available today within companies as well as whether companies are calculating their emissions themselves and if so how. Upon evaluating whether technological viability exists today, we then propose a methodology and model for GenLots, including how GenLots should perform the behind-the-scenes calculation and communicate the results to the end-user.

5.1. The Three Sources of GHG in Lot Sizing and their Global Calculation Standard

Measuring, reporting, and optimizing emissions in logistics and transportation requires having access to very detailed data. Unfortunately, this data is not always easy to acquire or manipulate, especially in the case of inbound transportation where companies may employ tens or hundreds of third-party logistics providers. In 2011, the GHG Protocol released its Scope 3 Technical Calculation Standard, which provides the only internationally accepted method for calculating Scope 3 emissions, such as those from upstream transportation and distribution activities including warehousing (WRI & WBCSD, 2013). These methodologies are explained and contextualized to this thesis in this section.

5.1.1. Emissions in Transportation

When calculating emissions from transportation, the goal is to calculate fuel and electricity consumption per mode of transport including fugitive emissions such as those from refrigerant loss and air conditioning. These emissions resulting from the direct consumption of energy in the transport operation are referred to as the Tank-to-Wheel (TTW) emissions. However, as illustrated in Figure 7, additional emissions from the extraction (generation), refinement (power plant operation), and distribution of fuel (electricity), are generated in the process of getting the fuel (electricity) into the vehicle's tank (battery); these emissions must also be accounted for and are referred to as Well-to-Tank (WTT) emissions. This complete chain of activities can then be referred to as Well-to-Wheel or as Cradle-to-Gate emissions. Further emissions resulting from the construction of infrastructure and the vehicles themselves could be considered, but estimating them can be nearly impossible, hence they are usually ignored. Lastly, it is also important to consider energy consumption emissions occurring during the period after which a delivery has been completed where a vehicle might return or continue its journey either empty or partially empty; this is referred to as the empty trip factor.

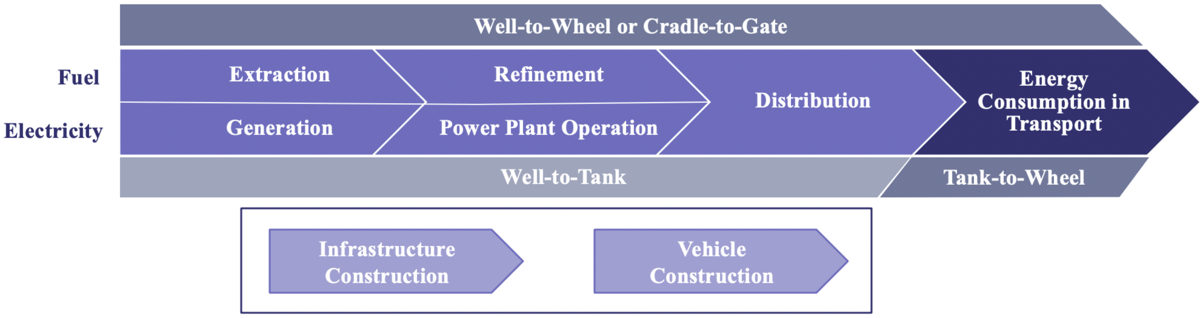


Figure 7. Well-to-Wheel vs Well-to-Tank emissions

Depending on the granularity of data, which a company is able to collect or obtain, different methods are recommended and used in the industry. The three methods outlined by the GHG Protocol include the fuel-based, the distance-based, and the spend-based methods. Using one over the other has trade-offs in terms of the level of accuracy and the ease of implementation based on the available data and complexity of calculation as shown in Figure 8. An overview of the type of data and the calculation formulas is provided in Table 1, followed by a more detailed discussion on when and how to use each.

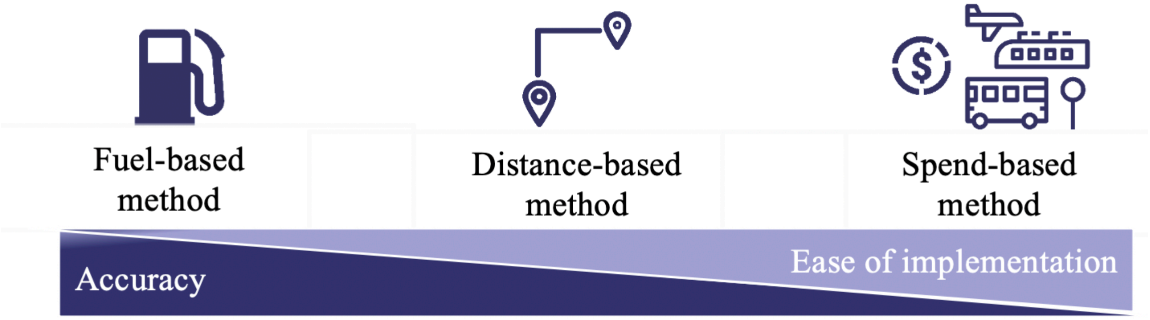
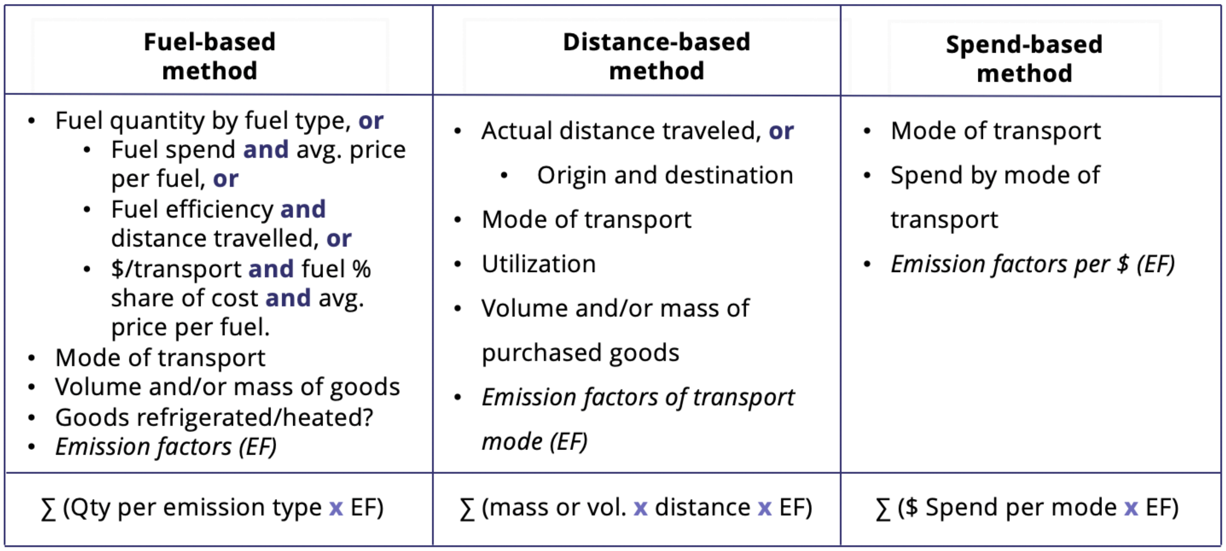


Figure 8. Methods for calculating CO_2 emissions from transportation

A vital piece of data to all three methods and to any GHG emission calculation is an emission factor. Emission factors are coefficients that allow us to relate an activity associated with the release of GHG emissions to the quantity of emissions released (based on a pollutant's weight). This enables us to answer the questions such as how many kilograms of CO_2e are emitted per kWh, per liter of fuel type, per mass or per volume traveled, or per amount spent on transportation type. Ideally, these emission factors, which have been scientifically calculated through testing and analysis would already account for Well-to-Wheel emissions. Data sources for these emissions will typically include government agencies, transportation carriers, industry associations, or other online databases and tools.



Fuel-based method	**Distance-based method**	**Spend-based method**

• Fuel quantity by fuel type, **or**
  • Fuel spend **and** avg. price per fuel, **or**
  • Fuel efficiency **and** distance travelled, **or**
  • $/transport **and** fuel % share of cost **and** avg. price per fuel.
• Mode of transport
• Volume and/or mass of goods
• Goods refrigerated/heated?
• *Emission factors (EF)*
	• Actual distance traveled, **or**
	  • Origin and destination
	• Mode of transport
	• Utilization
	• Volume and/or mass of purchased goods
	• *Emission factors of transport mode (EF)*
		• Mode of transport
		• Spend by mode of transport
		• *Emission factors per $ (EF)*

∑ (Qty per emission type **x** EF)	∑ (mass or vol. **x** distance **x** EF)	∑ ($ Spend per mode **x** EF)

Table 1. Data and formulas by method for calculating transportation GHG emissions

<u>The fuel-based method</u>

Because fuel or electricity consumption are directly related to GHG emissions, estimating these consumptions is necessary for calculating CO_2e emissions. But if we actually know how much fuel or electricity was consumed rather than having to estimate it, the resulting accuracy would end up being the greatest. Alternatively, fuel consumption can be derived by multiplying the amount spent per fuel type by the average price per fuel, multiplying the distance traveled by the vehicle's fuel efficiency, or multiplying together the amount spent per transportation service, the percentage share of the fuel's cost on the transportation service cost, and the average price per fuel.

In order to calculate how much fuel was consumed per product it is necessary to make an allocation based on the product's weight, volume, or both (including packaging) depending on whether the vehicle's capacity is limited by weight (i.e. truck, rail, air), volume (i.e. vessel), or a combination of both. Additionally, allocation by distance in the case of multiple transport legs would be necessary. However, when data is unavailable to estimate the fuel consumption or conduct the proper allocations, the distance-based or the spend-based methods should be used. Otherwise the calculation proceeds in a straightforward manner by summing the product of all the actual or estimated emission quantities from fuel, electricity, and fugitive emissions by the corresponding emission factors for each of the applicable quantities.

The distance-based method

In the absence of actual consumptions or the data to estimate the consumptions, the distance-based method provides a reasonable, yet less precise approach for calculating the GHG emissions per product. If the actual traveled distance is not known (from the transportation provider) it may be calculated by knowing the point of departure and the end destination using online maps, online calculators, and/or port-to-port published travel distances. The distance can then be multiplied by the mass or volume as well as by the corresponding emission factor. The emission factor expressed in GHG units by unit of mass or volume traveled should already incorporate the average fuel consumption for the specific transport mode, the utilization rate, and the associated GHG emissions.

The spend-based method

The spend-based method may be used as a last resort in lieu of the fuel and distance-based methods, and although it is not recommended due to uncertainty purposes it is better than not measuring at all. In this method, the amount spent by transportation type can be collected from supplier bills or invoices and multiplied accordingly by the corresponding EEIO (Environmentally-extended input output data) emission factors, which are specific to units of economic value. Generally, data for this method is readily available as it does not require interfacing with a third-party logistics provider. Although this method is useful for understanding one's carbon footprint at a broad level and making transportation mode change decisions, it is not very effective at all for optimization purposes, especially in the context of this thesis.

5.1.2. Emissions in Warehousing

In some supply chains, emissions from warehousing should not go unnoticed, especially when heating or refrigeration are involved leading to heavy energy consumption. Otherwise, energy will nevertheless be consumed in the processes of material handling (from equipment such as industrial trucks, conveyors, fork-lifts, rack feeders, lifts, cranes), lighting (indoor and outdoor), IT infrastructure, and offices. The GHG Protocol identifies two methods for quantifying these emissions depending on whether warehousing contributes significantly to emissions and whether fuel, electricity, and fugitive emissions data specific to each site is available, hence the methods' names: site-specific method and average-data method.

The site-specific method

This method estimates GHG emissions generated by a storage site based on the fuel and electricity consumed by both buildings and mobile vehicles using the corresponding fuel/electricity emission factors. Such data may be obtained through utility bills, purchase records, meter readings, or other internal systems. Emissions by product can then be allocated using different methods: based on the volume of the product with respect to the total volume of goods stored, based on the storage method (i.e. refrigerated vs ambient temperature), and/or based on the amount of time that the goods spend in storage. While the site-specific method yields the most accurate result, in practice it may be very cumbersome and time-consuming, or the data may not be available.

The average-data method

In this method, warehousing emissions are calculated by multiplying the volume of the stored goods per site (e.g. square meters, cubic meters, pallets, TEU) by the average number of days a good is stored as well as the average emission factors by volume for a storage facility (kg CO_2e/m^3 or pallet or TEU/day).

$$tCO_2e = \text{Volume}*\text{Average days stored}*\text{Emissions Factor}$$

5.1.3. Emissions from Scrapped Materials

The GHG Protocol also provides a standard for calculating emissions for the treatment of waste resulting from a company's operations, in this case the raw materials or components (and their packaging) being scrapped that exceeded their shelf life or became obsolete. Besides the emissions generated in the handling and transportation of these materials, emissions are generated in each of the different waste treatment activities which may include: landfilling, incineration, recycling, composting, wastewater treatment, waste-to-energy, among others. Companies treating such waste within their own facilities will most likely already be reporting such emissions within their Scope 1 and 2 emissions, and hence this information would already be known. Otherwise, in the case where a third-party waste treatment company is used, such emissions would fall under Scope 3 emissions. Three different methods are identified as well by the GHG Protocol for this purpose.

The supplier-specific method

This method simply involves directly requesting the Scope 1 and Scope 2 emissions from the waste-treatment company and ensuring the proper allocation to the material under consideration.

The waste-type-specific method

The quantity of emissions that is generated is not only dependent on the treatment activity, but also on the type of waste itself. When the actual emissions cannot be obtained from the supplier, a company may calculate the waste treatment emissions by multiplying the mass or volume of the waste by the specific emission factor corresponding to the waste type and waste treatment method in kg CO_2e per tonne or per m^3. These emission factors may also already include the emissions from the transportation of such waste.

The average-data method

The average-data method is the least accurate of the three methods. The calculation proceeds by multiplying the total mass of the scrapped waste by the emission factor for the corresponding waste treatment method in kg CO_2e per tonne. If different waste treatment methods are used, then the proportion of the total waste being treated per treatment method must be introduced.

5.1.4. Summary of Calculation Standards by GHG Emissions Source

Table 2 below summarizes the different calculations standards available for each source of GHG emission concerning the lot sizing decision. The ranked by decreasing accuracy and by increasing ease of implementation from top to bottom.

Transportation Emissions	Warehousing Emissions	Waste-Treatment Emissions
1. Fuel-based method 2. Distance-based method 3. Spend-based method	1. Site-specific method 2. Average-data method	1. Supplier-specific method 2. Waste-type specific method 3. Average-data method

Table 2. Summary of calculation standards by GHG emissions source

5.2. An Overview of Existing Order Planning Models with CO_2 Emissions

Researchers have adapted existing lot sizing models to incorporate carbon emissions as an additional parameter within the cost minimization objective function and/or as a constraint to such function. While some of these models are very simple and purely theoretical as the title of the published paper in which they appear indicates, others are more complex and aim to incorporate more real-life parameters. While some take on the perspective of a retailer, others take on that of a manufacturer. The most relevant models among these will be discussed.

5.2.1. Modeling Carbon Emissions Under Regulatory Emission Control Policies

In their paper "Carbon footprint and the management of supply chains: insights from simple models," Benjaafar, Li, and Daskin (2013) analyzed how integrating carbon emission parameters and parameters from four different regulatory emission control policies could be integrated into a traditional multi-period lot sizing model to support operational decision-making as a means to influence carbon emission reductions. (Benjaafar, M, & Daskin, 2013) The four carbon policies considered include a strict carbon cap, a carbon tax on the amount of emissions, a cap-and-trade system, and a carbon cap with the possibility to invest in carbon offsets. Below we discuss each of the four policies, where we purposefully ignore all variables and parts of the equation irrelevant to the carbon emissions discussion.

$\widehat{f}_t$	Fixed amount of CO_2e from the placement and transportation of each order
$\widehat{c}_t$	Variable amount of CO_2e per unit due to the handling and transportation per order
$\widehat{h}_t$	Amount of CO_2e per unit of inventory stored per period
y_t	Split-wise function where $y_t = 1$ if an order is placed and $y_t = 0$ otherwise
I_t	Amount of inventory carried from period t to period $t+1$

q_t	Order quantity in period *t*
C	Fixed cap on the number of emissions allowed
α	Carbon unit tax
p	Price per unit of CO2e

Table 3. Decision variables and parameters in Benjaafar et al. (2013)

Under the *strict carbon cap* scenario outlined by Benjaafar et al. emissions must be maintained below a certain level no matter what, and unlike an ETS, any unused carbon credits are simply surrendered without the option to trade them. Although the model does not incorporate GHG emissions into the objective function, it does incorporate them as a constraint. In contrast to the next three scenarios that will be presented the price of carbon is irrelevant in this one.

$$\sum_{t}^{T}\left(\widehat{f_t} * y_t + \widehat{c_t} * q_t + \hat{h}_t * I_t\right) \leq C$$

Under the *carbon tax* scenario, Benjaafar et al. simply incorporate the left-hand side of the above constraint into the total cost objective function by multiplying the total emissions by the carbon unit tax.

$$\text{Minimize: Total cost} = \cdots + \alpha * \sum_{t}^{T}\left(\widehat{f_t} * y_t + \widehat{c_t} * q_t + \hat{h}_t * I_t\right)$$

The *carbon cap-and-trade* scenario resembles an ETS by incorporating the possibility of buying or selling carbon credits in the carbon market. The constraint under the *strict carbon cap* model is modified by incorporating e_t^- to account for the unused carbon credits sold in the market at period *t* as well as e_t^+ to account for the excess emissions for which carbon credits must be purchased in the market at period *t*. The traditional objective function is also modified to incorporate the cost or profit from trading carbon credits using: $p * (e_t^+ - e_t^-)$.

$$\sum_{t}^{T}\left(\widehat{f_t} * y_t + \widehat{c_t} * q_t + \hat{h}_t * I_t + e_t^-\right) \leq C + \sum_{t}^{T} e_t^+$$

The fourth scenario, which considers a *cap with carbon offsets* is very similar to the *cap-and-trade* model except that it eliminates the possibility of selling unused carbon credits, and the price of an offset is not based on a market price, but rather on the price offered by suppliers of offset projects. The constraint and objective function are adjusted accordingly, simply eliminating e_t^-, while keeping all else the same. Hence, the objective function only uses $p * e_t^+$, while the constraint becomes:

$$\sum_{t}^{T}\left(\hat{f}_t * y_t + \hat{c}_t * q_t + \hat{h}_t * I_t\right) \leq C + \sum\nolimits_{t}^{T} e_t^+$$

All four of these models are very logical and easy to follow. They incorporate GHG emissions from transportation and warehousing, however they fail to include the emissions related to scrap material. Similar to the next models that will be presented, these four models consider a fixed and a variable cost when it comes to transportation emissions. This is reasonable given that fixed emission quantities arise from the energy consumption from the transport, independent of the quantity of goods being transported. On the other hand, variable emission quantities are present due to the additional energy required to move the additional load created by the goods being transported; depending on the quantity of transported goods, the allocation of GHG emissions per unit will be greater or smaller. If we follow the distance-based method for calculating transportation emissions as outlined in the GHG Protocol, we would realize that we do not need to make this distinction between fixed and variable transportation costs. In fact, emission factors already take into account the average fuel consumption for the specific transport mode, the average utilization, and the associated GHG emissions. These are then multiplied by the mass or volume and by the distance to obtain the total transportation emissions.

We can also observe that the three models that consider a carbon cap are in practice rather useless in this context, as carbon caps are set for companies for a specific site or region as a whole, rather than on a product basis. Companies would otherwise need to set their own internal carbon caps on a product-specific and a period-specific basis. Because Scope 3 emissions are not accounted for in a company's regulated emissions inventory employing a carbon cap is also irrelevant. Only the *carbon tax* scenario would thus be relevant, but we could substitute the carbon tax for the carbon price in the ETS market, the offset cost, or even an internal carbon price.

5.2.2. The Sustainable EOQ Model (S-EOQ)

The next model to be presented extends the carbon tax model by adapting the Economic Order Quantity (EOQ) lot sizing model. The Economic Order Quantity (EOQ) formula, also known as Andler's Formula in Germany and Wilson's Formula in France was developed in 1913 by Ford W. Harris in order to mathematically compute how much to buy based on a static average inventory, order cost, and carrying cost. Due to its relative simplicity EOQ is still one of the most widely taught models in universities, and it is also applied across many companies. In 2013, Battini, Persona, and Sgarbossa developed what they call the Sustainable EOQ model (Battini, Persona, & Sgarbossa, 2014).

The S-EOQ model not only introduces additional variables that provide additional granularity to the transportation and warehousing GHG emissions calculation, but it also incorporates obsolescence costs. It defines the Total Cost objective function as a function of five different cost factors: the variable purchasing cost $(p * D)$, the ordering cost excluding transportation $(\frac{D}{Q} * O)$, the holding cost $(\frac{Q}{2} * (h + c_{eh} * b))$, the inventory obsolescence cost $(\frac{Q}{2} * \beta * [(p - p') + a * c_{eo}])$, and the transportation cost $(\{\sum_j [(c_{int-fj} + c_{ext-fj}) * d_j * \sum_i n_i + (c_{int-vj} + c_{ext-vj}) * d_j * DP_k]\} * \frac{D}{Q})$. It also includes a constraint, $\min \sum_i n_i$, based on minimizing the total number of containers or vehicles used such that the total capacity of all containers used exceeds the number of units purchased.

$$C_S(Q) = p * D + \frac{D}{Q} * O + \frac{Q}{2} * (h + c_{eh} * b) + \frac{Q}{2} * \beta * [(p - p') + a * c_{eo}]$$

$$+ \left\{ \sum_j \left[(c_{int-fj} + c_{ext-fj}) * d_j * \sum_i n_i + (c_{int-vj} + c_{ext-vj}) * d_j * DP_k \right] \right\} * \frac{D}{Q}$$

Table 4 below describes each of the notations, decision variables, and input parameter used in the above formula, for purposes of the forthcoming discussion.

i	Container or vehicle type
j	Transportation mode
Q	Decision variable [units/purchasing order]
$C_s(Q)$	Total average annual cost of replenishment [\$/year]

D	Annual demand [units/year]
p	Unit purchase cost
p'	Unitary scrap price
h	Holding cost
c_{eh}	Average carbon emission cost coefficient of a warehouse [\$/m^3]
b	Space occupied by product unit [m^3/unit]
a	Weight of an obsolete unit stored in the warehouse [ton/unit]
ß	Average inventory obsolescence annual rate [%]
c_{eo}	Average CO_2 cost coefficient of inventory waste for collection and disposal [\$/ton]
O	Fixed ordering cost per order
d_j	Distance traveled by transportation mode j [km]
n_i	Number of full load-vehicles or containers i
N	Set of n_i
y_i	Capacity of full load-vehicle or full-load container i
k	Range of order quantity Q_s between the two discontinuity points DP_k and DP_{k+1}
DP_k	Discontinuity Point for range k, defined as $\sum_i n_i * y_i$
S	Freight vehicle utilization ratio in %
C_{int-fj}	Fixed internal cost coefficient for transportation mode j [\$/km]
C_{int-vj}	Variable internal cost coefficient for transportation mode j [\$/km m^3]
C_{ext-fj}	Fixed external cost coefficient for transportation mode j [\$/km]
C_{ext-vj}	Variable external cost coefficient for transportation mode j [\$/km m^3]

Table 4. Notations, decision variables, and input parameters in Battini et al.

Beginning with the formula to compute the cost associated with warehousing emissions, we can see that the volume of a product is multiplied by the average carbon emission cost coefficient of a warehouse. The average carbon emission cost coefficient essentially fulfills a similar role to using an Emission Factor which has the carbon price built-in. In their case study they apply a c_{eh} of €0.55/m^3, which they derive from DEFRA. However, this model proves inflexible if we want to quickly choose a different carbon price. As this model is also static, the average inventory *Q/2* is used to calculate the total emissions over the considered period. In contrast, the GHG Protocol utilizes the average days stored for the product, which would yield a much more accurate result.

In the case of the inventory obsolescence emissions cost we can observe that the material's mass is multiplied by an average carbon emission cost coefficient, as well as by the average inventory obsolescence annual rate. Their case study applies a c_{eo} of €13/ton, which they derive from the US Environmental Protection Agency's (EPA) WARM (Waste Reduction Model) software. As GenLots is based on dynamic lot sizing, it can calculate exactly how much scrap is generated per period, where each period is equivalent to a week, but will become a day in the future. Thus the average inventory obsolescence annual rate would need to be converted to an average inventory obsolescence weekly or daily rate. The same discussion as in the warehousing cost, would apply here with respect to the average inventory and the average carbon emission cost coefficient.

When it comes to the transportation emission cost, the first thing we can notice is that the cost coefficients are described as external cost coefficients rather than as carbon emission cost coefficients. This is because the costs to society from congestion, accidents, roadway facility costs, etc. are also considered. Unfortunately, these additional costs to society, which are specific only to certain transportation modes, can be highly intangible, hence it may be more difficult for a company to justify taking them into account for such an operational decision. If a company wanted to include these costs, perhaps they would like to see them separately, hence we would need two different prices, one pertaining only to carbon emissions and another to all the other negative externalities.

The transportation formula also distinguishes between the fixed costs which only depend on the distance traveled, and the variable costs which depend on both the distance and the quantity ordered. It also incorporates the physical constraints found in transportation related to vehicle capacity by introducing a discontinuity point variable that considers the fact that as the quantity ordered increases a different vehicle type with a different capacity and different cost may be more effective. This discontinuity point DP_k is obtained "after the accurate evaluation of all capacity saturation ranges of different kinds of container *i*" and is obtained from the formula $S_j = \frac{Q}{\sum_i n_i * y_i} = \frac{Q}{DP_k}$. Theoretically, this part of the equation makes a lot of sense, however in practice performing this evaluation across different vehicle types and transportation modes, would be highly complex and require having all the available information related to each transport possibility.

5.2.3. EOQ Model Linking Carbon Emissions and Defective Items

Daryanto, Christata, and Kristiyani (2020) proposed a revised EOQ model for retailers that takes into account defective items as well as a carbon emission tax (Daryanto, 2020). Table 5 shows the decision variables and parameters used in their model, which are referred to in its ensuing discussion.

y	Order quantity
α	Rate of defective items per lot y
$b*$	Optimum backorder quantity
d_1	Rate of customer demand for good quality items [units/year]
i	Rate of quality inspection
C_t	Carbon tax [\$/tCO_2]
l	Delivery distance [km]
F	Direct emissions from fuel usage [tCO_2/liter]
E	Indirect emissions from electricity usage [tCO_2/kWh]
w	Product weight [ton/unit]
a	Fuel efficiency for empty truck [liter/km]
b	Fuel efficiency from truckload [liter/km/ton]
c	Average electricity consumption per unit inventory [kWh/unit]
f_t	Fixed carbon emissions associated with each order
c_t	Variable amount of carbon emissions per unit in each order
h_t	Amount of carbon emissions per unit of inventory stored per period
y_t	y_t=0 if order is placed; y_t=1 otherwise
I_t	Amount of inventory carried from period to period t+1
l	Delivery distance [km]
F	Direct emission from fuel usage [tCO_2/liter]
E	Indirect emission from electricity usage [tCO_2/kWh]

w	Product weight [ton/unit]
a	Fuel efficiency for empty truck [liter/km]
b	Fuel efficiency from truckload [liter/km/ton]
c	Average electricity consumption per unit inventory [kWh/unit]

Table 5. Decision variables and input parameters in Daryanto et al.

When it comes to the warehousing cost, as shown in the formula below, this model subtracts defective units which do not clear quality control from the CO_2 warehousing cost calculation. It then *indirectly* applies the GHG Protocol's site-specific method by multiplying the average electricity consumption per unit of inventory by the electricity emission factor. But in order to obtain the average electricity consumption per unit of inventory it would likely be necessary to conduct an in-depth analysis concerning the product's volume, electricity spend, whether the product has special storage conditions and/or the average number of days it is stored. The set of data they use for a brief illustration uses E=0.005 tCO_2/kWh (note that CO_2e is not used).

$$(cEC_t)\left(\frac{1}{2} * \frac{(y - E[a]y - b^*)^2}{d_1} + \frac{E[a]y^2}{i}\right)$$

For the transportation carbon emissions calculation, we can observe the same logic used in previously discussed models, which introduces a fixed and a variable cost; however, in this model the fuel-based method is implemented by multiplying the fuel efficiency of the vehicle under the empty truck and truckload conditions, by the distance, as well as by the emissions factor in tCO_2 per liter of fuel (F=0.0026 tCO_2/liter is used in their brief example). The model requires that we obtain or estimate the values for the fuel efficiency of an empty vehicle for the fixed cost part as well as for a truckload in liters per kilometer per ton. It can also be observed that the fixed cost portion is multiplied by two in order to account for the empty return trip, however the truck may not return to its original location.

$$C = 2\mathrm{al}FC_t + blwFC_t y$$

5.2.4. Discussion and Comparison of Existing Models

Six different previously developed models across three different research papers which incorporate carbon emissions into the total cost equation have been presented thus far. While many others were reviewed there were only two additional ones that are worth mentioning without going into too many details. In 2015, Tang, Wang, Yan, Hao (2015) developed a model based on the periodic inventory review system (Tang, Wang, Yan, & Hao, 2015). Their proposed model however only considered items that do not require special storage conditions such as refrigeration or heating, hence it is only applicable to cases where transportation emissions predominate over warehousing emissions. Wang and Ye (2018) also developed a very simple model to compare lot sizing using a Just-in-Time strategy versus the EOQ method and implementing only the carbon tax rate and the unit product carbon emissions; both of these models assumed that the carbon emissions quantities are constant for any given order quantity, which make them unrealistic (Shijin & Ye, 2018).

As one can see, many of these models are based on the EOQ model, but it is important to keep in mind that although GenLots does not specifically implement EOQ or any such model, which recommends a static lot size, it does use some of the same underlying concepts. It is also evident that the sustainable lot sizing models presented ignore many of the real-world considerations and are also very difficult to adapt to incorporate new parameters and constraints especially due to the differences in the available data necessary to perform a calculation that may arise across companies and even products. However, of the six models that were presented, three were found to be relevant and are compared in Table 6, as useful insights can be extracted from this exercise for determining what kind of model to design and implement by posing several questions. How do we overcome the shortcomings identified in these models? How do we balance the trade-off between accuracy and model complexity? What data do we need for the new model and where do companies store it? Can this data be automatically extracted or does it need to be manually entered? And how do we design a flexible model based on the differences in available data that companies may have and that also follows the GHG Protocol standard so that companies accept and trust the methodology? These questions will be explored throughout the next sections.

Model(s)	Carbon Emissions Under Regulatory Emission Control Policies	S-EOQ	EOQ Linking Carbon Emissions and Defective Items
Transportation Emissions	• Incorporates a fixed and variable cost. • No particular method specified.	• Incorporates a fixed and variable cost. • Is a variation of the distance-based method. • Emissions factor is in \$/km m^3.	• Incorporates a fixed and variable cost. • Is a variation of the fuel-based method. • Emissions factor is in tCO_2/liter.
Warehousing Emissions	• Included. • No particular method specified.	• Included. • Is a variation of the average-data method, which is based on the volume. • Emissions factor is in \$/m^3.	• Included, and also singles out defective materials from the calculation. • Is a variation of the site-specific method; considers electricity consumption and allocates based on volume. • Emissions factor is in tCO_2/kWh.
Waste Treatment Emissions	Not included.	• Included. • Is a variation of the average-data method, but no waste treatment method (i.e. landfilling) is specified. • Emissions factor is in \$/ton. • Assumes an average obsolescence rate.	Not included.
Dynamic or static	Dynamic. Multi-period and varying demand.	Static. EOQ-based.	Static. EOQ-based.

Table 6. Comparison of previously developed lot sizing models

5.3. Important Considerations Concerning the Calculation of Transport Emissions

Significant differences in the available data across materials and companies make the GHG emissions calculation for transportation particularly challenging. This is mainly due to the fact that manufacturers rarely own the trucks, trains, ships, or planes used to transport the raw materials to their production sites and will instead rely on third-party logistics providers. Consequently, most of the transportation-related data is owned by the third-party logistics providers, raising the issues of whether these third-party logistics providers even have the data in the first place, or whether they are willing to share any of it at all. Based on the different annual company Sustainability Reports reviewed as well as the company interviews that were conducted for this research, a significant gap across companies was identified with respect to the available data and the granularity of the data being collected. Certain companies with very ambitious carbon emission reduction targets and with more years of experience carrying out GHG reporting were generally years ahead from most others.

When comparing the two extremes of companies, on one hand some companies only had data related to their spend by transportation mode. While this data can be used for applying the spend-based method, there is much uncertainty concerning this method's results that it may not be worth considering it at all. On the other hand, companies like Barry Callebaut have developed a refined tool for calculating the carbon footprint for some of their raw materials. Their tool combines specific data on the "distances, transported volumes, transport modes (i.e. ship, truck type, liquid/ solid, standard / solid cooled), and payload utilization of trucks, with GHG emission factors which are calculated for each specific transport situation" (Barry Callebaut, 2019). Barry Callebaut uses a "transport coefficient model", which allows the calculation of GHG emission factors for each specific truck, train, and ship situation linked to size, payload utilization, share of empty trips, and special transport conditions (i.e. heated or cooled).

Even if a company is not as advanced in collecting such data, it is very likely that a company could at least provide the minimal information needed for the calculation such as the transport mode, the start and end points of the transport, any special transport conditions, and the weight and volume of the products (including packaging). Moreover, if the transportation-related GHG emissions factors cannot be obtained directly from the client they could potentially be retrieved from a database such as EcoInvent version 3.4. or in the case of the chemicals industry from the European Chemical Industry Council (Cefic) (McKinnon & Piecyk, 2011). However, in fact, the calculation of GHG emissions from transportation can be extremely complex particularly because selecting the right emission factors is not trivial. The emission factors are dependent on a large number of variables including the transport mode(s), specific transport type(s) and size(s) (i.e. differences in trucks, trains, vessels, planes, etc.), fuel types, emission classes, fuel quality, among others, all of which are heavily influenced by the country to country differences and the desired transport route. Additionally, there are further considerations such as the Well-to-Tank emissions, the Empty Trip Factor, and the emissions resulting from a transshipment (intermodal transfer).

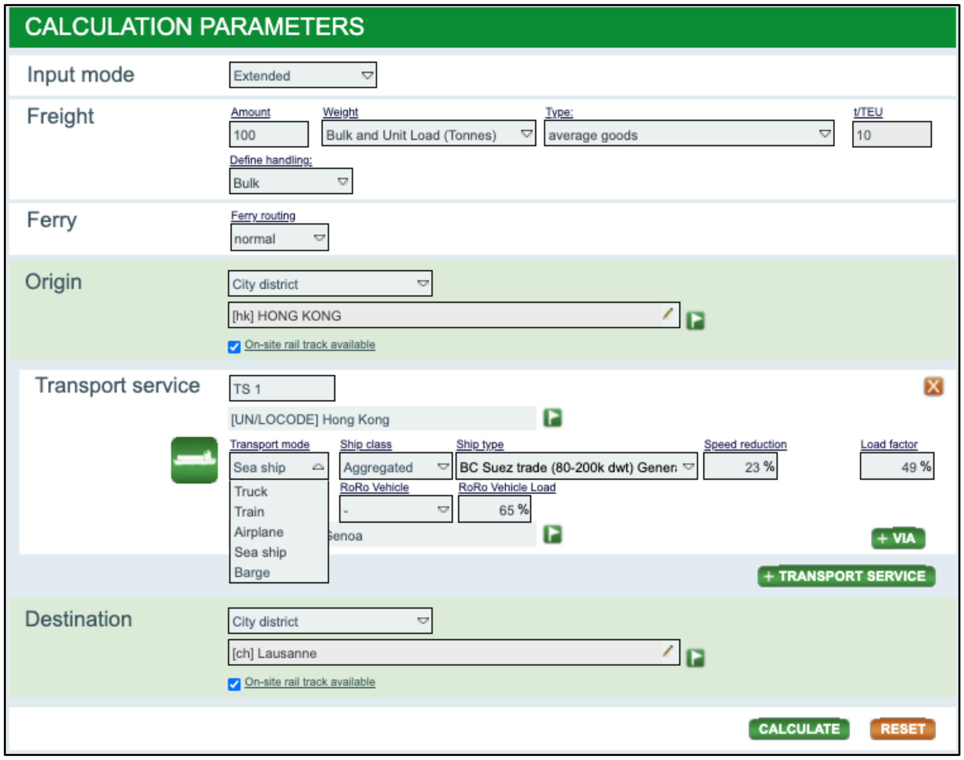
5.4. Discussion on the GHG Emissions Calculation from Transportation

Given GenLots' lack of prior experience and expertise with carbon accounting and the fact that the CO_2 Emissions Optimizer is not at the core of GenLots' product, raises the issue of *Transaction Cost Economics (TCE)*: whether GenLots should try to develop its own calculation engine from zero or whether it should transact over the market to gain access to such a calculation engine if one is available. The concept of a CO_2 emissions calculation engine also known as a CO_2 calculator is not new at all, especially when it comes to transportation. Such tools have been widely developed allowing anyone to estimate their carbon footprint for activities such as the regular commute to work, (business) air travel, and a handful of other lifestyle items and behaviors (CO2 Monitor, n.d.) (MyClimate, n.d.).

In the context of logistics multiple tools have been developed that calculate emissions from specific transport modes and/or for specific countries, however only two tools could be identified to combine all transport modes at a global scale, to incorporate each of the complexities described in the previous paragraph, and to also be compliant with the European Committee for Standardization's GHG emissions calculation and declaration standard, EN 16258 (EcoTransIT World, n.d.) (Bearing Point, 2020). These two products are LogEC developed by the Amsterdam-based management and technology consulting firm, BearingPoint and the Germany-based, EcoTransit World. EcoTransIT World is additionally accredited by the Smart Freight Centre as being in accordance with the Global Logistics Emissions Council (GLEC) Framework. The GLEC framework is "the only globally recognized methodology for harmonized calculation and reporting of the logistics GHG footprint across the multi-modal supply chain", and it is also in alignment with the GHG Protocol, CDP reporting, and the UN-led Global Green Freight Action Plan (Smart Freight Centre, n.d.). Its calculation method is based on the fuel-based method, as it uses the origin and destination points to estimate the traveled distance for a specific route, and in turn uses the distance to estimate the energy consumption.

One can observe that although most of EcoTransIT World's clients are logistics providers it also counts several industrial firms as clients in industries that GenLots is targeting, such as Henkel, Michelin, and AB InBev. These kinds of companies already trust the tool and are primarily using EcoTransIT World to calculate, report, and simulate the environmental impact from their internal and outbound transports. If GenLots were to pursue internally developing such a GHG calculation engine not only would it bear high development and maintenance costs (i.e. from updating emission factors and regulatory requirements), but also the opportunity cost and risk resulting from the time required to develop, accredit, and market the tool. For a client to derive any value from the tool they need to able to trust the calculation method and the outputs, such that they can confidently report any resulting GHG emission and cost savings or increases. That said, it would likely be more effective and efficient for GenLots to purchase a license that enables it to integrate with an existing solution for performing this calculation; GenLots could integrate via an Application Programming Interface (API) like the one offered by EcoTransit World using a Soap XML Web Service (WSDL).

Figure 9 shows a screenshot of the free web browser version of the EcoTransIT World solution available to the general public. It allows for the calculation of GHG emissions and other pollutants while providing a lot of flexibility and granularity options when it comes to the inputs. Its business solution offers even greater parameter possibilities (100+) and transportation types for each different mode (i.e. 250+ aircraft types). A calculation can be made within 0.1-0.3 seconds per transport service, and for a calculation to be performed, at a minimum, the cargo weight, the transportation mode, the origin, and the destination of the shipment must be provided; anything else missing gets filled up with default pre-defined values.



CALCULATION PARAMETERS

Input mode: Extended

Freight: Amount: 100; Weight: Bulk and Unit Load (Tonnes); Type: average goods; t/TEU: 10

Define handling: Bulk

Ferry: Ferry routing: normal

Origin: City district; [hk] HONG KONG

☑ On-site rail track available

Transport service: TS 1

[UN/LOCODE] Hong Kong

Transport mode: Sea ship; Ship class: Aggregated; Ship type: BC Suez trade (80-200k dwt) Gener; Speed reduction: 23 %; Load factor: 49 %

RoRo Vehicle: -; RoRo Vehicle Load: 65 %

Genoa

Destination: City district; [ch] Lausanne

☑ On-site rail track available

Figure 9. EcoTransIT World web browser interface: example input parameters

Based on an interview with and on information provided by an EcoTransit World representative, the business model and annual license cost for performing third-party calculations is based on the number of calculation requests submitted per year. To understand what this would mean for GenLots, we can consider the scenario where GenLots only compares the transportation emissions from its recommended optimal order plan against the original one, without integrating emissions into the TCO. Since each order may have a different order quantity, and hence also a different mass or volume, the number of API requests becomes equal to the total number of orders placed in the original order plan and in the optimized order plan. Because GenLots updates its calculation on a daily basis, the number of API requests for a single material could quickly grow to a few thousand.

In order to avoid this situation, it could be assumed that the route as well as the transportation mode and type remains the same unless a drastic difference in the recommended order quantity takes place; it may then be possible for GenLots' algorithm to learn and/or predict the resulting emissions from adjusting the single parameter, total mass or volume on a per unit, batch, or pallet basis. Under the scenario where the GHG emissions are added into the TCO, GenLots would have to also implement such a prediction model in order to iteratively identify the optimal order quantity based on the effect that the shipped volume or mass has on the total emissions quantity. If GenLots is able to develop such a prediction model, then undoubtedly, integrating with an existing SaaS solution like EcoTransIT World would represent the lowest economic and risk-taking implementation option. Alternatively, GenLots could try to negotiate different business model pricing conditions for its license.

5.5. Discussion on the GHG Emissions Calculation from Warehousing and Scrap

Calculating the GHG emissions for warehousing and scrap disposal is much simpler and could generally be carried out effortlessly by GenLots. For both calculations GenLots should follow the GHG Protocol standard. When it comes to the warehousing emissions implementing the site-specific method will likely be unfeasible due to the burden of collecting all the data and performing the allocation. However, the average-data method should be very straightforward for GenLots to apply. GenLots would need to obtain volume per unit from the client, as well as ideally the emission factor for the storage facility in order for it to be specific to the geographic location and site's energy mix, otherwise GenLots could retrieve a generic emission factor from a database. Using its existing algorithm GenLots could calculate the average days stored for the material.

In the case of the scrap disposal emissions GenLots should implement the supplier-specific method if its client already has the emission quantities. Otherwise, the company should implement the waste-type-specific method for which GenLots would need the mass or volume per unit and the emission factor corresponding to the waste type and waste treatment method. This emission factor should also come from the client, otherwise GenLots would need to obtain the waste type and the disposal method to obtain the emission factor from a database. Appendix 2 shows examples of waste-treatment emission factors taken from DEFRA, the UK's Department for Environment, Food, and Rural Affairs.

5.6. Model Recommendation

The previous discussions have outlined the methods that GenLots should use to calculate the emission quantities per unit. With the per unit GHG emissions it is then possible to integrate them into the TCO equation in line with how GenLots is currently calculating the optimal order plan dynamically using reinforcement learning. This can be done in the following manner, where:

Transportation emissions = $y_t * p_c$

Warehousing emissions = $p_c*(V*a*E_w)$

Scrap emissions = $p_c*(q_s*V*E_s)$

such that:

p_c	Carbon price: input parameter defined by client
y_t	Per unit transportation emissions – calculated using EcoTransit using the extracted data from the client's system
V	Per unit volume: extracted from ERP
a	Average days stored per unit: calculated by GenLots
E_w	Emissions factor for warehousing: provided by client or default value selected from database by GenLots
q_s	Planned scrap quantity of materials: calculated by GenLots in current algorithm
E_s	Emissions factor for scrap: provided by client or default value selected from database by GenLots based on

Table 7. List of variables for model recommendation

5.7. Technical Viability Discussion

Having reviewed the GHG Protocol calculation methods for transportation, warehousing, and waste, previously developed lot sizing models, and proposed a model for GenLots to implement we can conclude that technical viability exists. Nevertheless, it may only be technically viable for certain products where enough data is available to perform the GHG emissions calculation. If we map the process that an inbound material planner using the CO_2 Emissions Optimizer would follow, the first would be for them to set up a carbon price parameter using the company's real carbon price or a shadow price either across all products or on a case by case product basis. Next, if the necessary parameters for the calculation are not stored in the ERP system or in a different software to which GenLots could connect via an API, then these parameters will need to be manually configured for each product the first time. In such case, to avoid the burden of a manual configuration on thousands of products, a company may choose to only perform the environmental footprint optimization on certain strategic products or on those products identified to have the highest carbon footprint when it comes to the lot sizing decision. Finally, the optimized order plan is delivered along with the corresponding financial and environmental metrics, which could be made downloadable or exportable into a separate software or database used by the company to manage its environmental impact.

5.7.1. Reporting and Communicating the Results

Together with every optimal order plan calculation, GenLots visually and numerically communicates the operational and financial impact of its recommendation. With the CO_2 Emissions Optimizer, GenLots will need to also incorporate the environmental impact into the Optimal Order Plan results and into its Opportunity Dashboard. Doing so will entail adding a new reporting dimension and set of Key Performance Indicators (KPIs) to compare the original order plan against the optimized order plan. In order for the results to be operationally meaningful and for a material planner to understand and influence the environmental footprint of their lot sizing decision it will be important to breakout the GHG emissions by their corresponding emissions source: transportation, warehousing, and waste treatment.

For each source, not only could GenLots separately report the estimated financial impact from pricing the GHG emissions and the GHG emission quantities themselves, but also as applicable, the standalone CO_2 emissions, the energy consumed, the air pollutants, and other indirect GHG emissions not accounted for in the CO_2e emissions such as nitrogen oxides (NO_x), sulfur dioxides (SO_2), and non-methane hydrocarbons. In the case of the transportation emissions, we could also distinguish between WTT and TTW emissions. In Appendix 2-A, we can observe how EcoTransIT World provides all of these metrics as part of its output calculation results on a per transportation mode basis, in addition to the intermodal transfer if any occurs. Energy consumed is reported in kilowatt-hours, CO_2 and CO_2e emissions are reported in tonnes, while NO_x's and SO_2's and non-methane hydrocarbons are reported in kilograms. Furthermore, we can observe both numerically and graphically (in a 2D map or an exportable Google Earth KML file) the distances traveled per transport mode as well as on a per country basis, including international waters or airspaces. In order for these metrics to be useful and comparable across time and order plans GenLots must communicate them as a ratio. Identified ratios and KPIs commonly utilized in the industry include tonnes of CO_2e per kilometer, per kilogram or ton of material, per area or volume (m^2 and m^3), and per unit of sale or pallet. These KPIs can also be converted into financial KPIs by simply multiplying the GHG emissions price by the number of tonnes of CO_2e.

The KPI, tonnes of CO_2e per kilometer, is only applicable to the transportation emissions and can be useful for considering alternative transportation suppliers including transportation modes, vehicles, and fuels. If a company is sourcing the same product from two or more suppliers it could compare its environmental footprint resulting from transportation emissions as a result of its supplier location. Similarly, a company receiving the same product at two or more plants could quantify its environmental footprint based on their plant location with respect to its supplier location. The next three KPIs, tonnes of CO_2e per kilogram or ton of material, tonnes of CO_2e per area or volume (m^2 and m^3), and tonnes of CO_2e per unit of sale or pallet relate to the material properties themselves. These metrics can be useful to a company particularly when there is a perceived value by its clients or end-consumers for purchasing a low(er) carbon product; however such an interest may not necessarily represent a higher willingness to pay for a lower carbon product.

6. Case Study

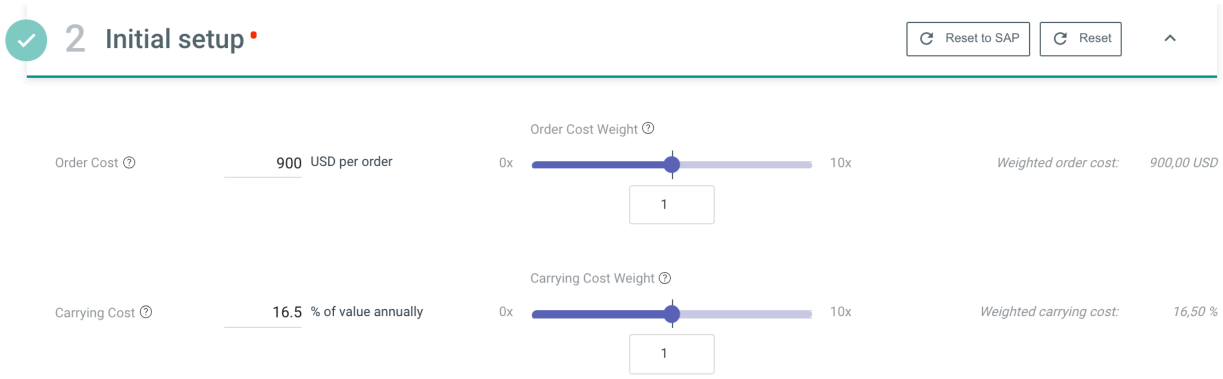
6.1. Context

The purpose for conducting a case study was to test the assumptions and the proposed model to evaluate whether there is a business case for incorporating GHG emissions into the TCO in lot sizing and finding out how or whether quantifying and pricing GHG emissions from transportation, warehousing, and scrap influence the order recommendation. We set out to devise a Minimum Viable Product (MVP) to test the proposed model for the CO_2 Emissions Optimizer and interpret the results under different scenarios; an MVP is a concept from the Lean Startup model for rapidly testing new ideas and learning as fast as possible with the least amount of effort. This meant designing a process for calculating and testing the incorporation of GHG emissions into GenLots' Order Planner. The process needed to enable conducting sensitivity analyses on different factors such as the weight of the material, the transportation mode, storage condition, distance, among other parameters.

Over 20 organizations including GenLots' existing clients were contacted in order to obtain an interview and potentially an anonymized dataset on at least one single product to perform this case study. Due to the complexity concerning the sharing of any information with a third-party within these large organizations it was not possible to gain access to such a dataset, and hence this presented itself as a limitation for the development of this case study. A work around was found by resorting to the demo data that GenLots uses for its prospective client demos, which is based on real-world anonymized data from previous Pilot projects. Appendix C-1 shows a snapshot of the first few weeks of data that was used. However, only having this data available still ended up presenting some important missing pieces of information that could not be overcome even with assumptions.

6.2. Method

The selected process for conducting this case study involved using MS Excel and EcoTransIT World to perform all GHG emission and/or GHG pricing calculations. GenLots' Order Planning software was also used in its current state without adding any line of code to extract the initial data set and to perform the lot sizing optimization calculations with and without considering the GHG emissions in the TCO. The existing setup made it possible to simulate adding the GHG emissions cost from transportation into the order cost and adding the GHG emissions cost from warehousing into the inventory carrying rate, however it was not possible to add the GHG emissions cost for scrap material. Figure 11 shows the second step in the Order Planner where the order cost and the carrying rate are specified for a given material based on client estimates. The order cost is defined as the fixed cost to place each order, while the carrying rate is defined as the annual holding cost for each $100 worth of material that is ordered. We could thus modify these two parameters accordingly based on the additional cost contribution resulting from the GHG emissions.



Order Cost: 900 USD per order

Order Cost Weight: 1

Weighted order cost: 900,00 USD

Carrying Cost: 16.5 % of value annually

Carrying Cost Weight: 1

Weighted carrying cost: 16,50 %

Table 8. Setup for the order cost and carrying rate in GenLots' order planner

Several real-world scenarios from existing clients were created for the simulation, four involving transportation, and two involving storage. The four scenarios involving transportation included air freighting Material X from Shanghai to Geneva, shipping Material X from Shanghai to Geneva, and trucking Material X from Aubonne to Vevey (both in Vaud, Switzerland) under ambient and under refrigerated temperature conditions. With respect to warehousing, ambient temperature and refrigerated storage conditions were considered for which average emissions factors had to be identified.

After extracting the data for Material X for the 52-week period, the first thing that was done was to compute the average order size across all periods and then use EcoTransIT World to calculate the average GHG emissions associated with placing an order under each of the four transportation scenarios. With that information it was then possible to compute the additional cost per order under various carbon pricing scenarios. Three scenarios were created: setting the price to $5, $25, and $100 per tCO_2e. $5 and $25 were selected for being the low-end and high-end carbon offset prices respectively, while $100 was selected for being the carbon price recommended by the UN Global Compact such that it influences decision-making.

In contrast, for warehousing, we first needed to identify adequate emission factors. After conducting extensive research, no average emissions factor for warehousing in terms of the material's volume could be obtained. Nevertheless, an average emissions factor for warehousing was identified, which was in terms of the materials' mass in kg CO_2e / tonne per year, as shown in Appendix A-3. This meant that an alternative yet less accurate formula to the one in the proposed model would be needed, such that only the mass of the material had to be multiplied by the emissions factor to obtain the GHG emissions. We then calculated the amount of material per $100 worth of material ($100 divided by the price of the material). The resulting GHG emissions could then be obtained by multiplying the emissions factor for each storage condition by the material quantity per $100 worth of material. Finally, by multiplying this result by each carbon price we could get the additional carrying rate percentage under each scenario.

Although it was not possible to include GHG emissions corresponding to scrapped material in the TCO calculation for the MVP, it was still possible to calculate the corresponding emissions from scrapping a given quantity of Material X. This was done by multiplying the avoided scrap quantity by the mass of one unit of material as well as by the emissions factor taken from a database such as the one shown in Appendix A-2.

6.3. Results and Discussion

Upon the obtaining our results the first thing that was noticed was that the GHG emissions from warehousing barely had an effect on the carrying rate. Even when refrigerated storage and a carbon price of $100 were considered not even a 0.1% change took place as shown in Appendix C-3. Furthermore, the 32,000 kg reduction in average inventory reduction over the course of the 52-week period resulting from GenLots' order plan recommendation only equated to between $0.87 and $37.51 in savings as shown in Appendix C-4; this depended on the selected inventory GHG emissions factor and the selected carbon price. These results indicated that GHG emissions from warehousing do not influence the carrying cost in meaningful way and can hence bring the model down to two factors, transport and scrap. Nevertheless, to be completely certain of this conclusion, in the absence of data, it would be necessary to perform the same calculation using the actual Average-data method based on GHG Protocol by obtaining the actual material volume and emission factors from the company.

Although it was not possible to test adding GHG emission costs from scrap in the TCO, it was still possible to calculate the GHG emission cost savings from the avoided scrap that GenLots' order plan recommendation yielded. As shown in Appendix C-5, the 79.7 tonnes of scrap material avoided, saved about 8 tCO_2e, equating to between \$40 (\$5/tCO_2e) and \$795 (\$100/tCO_2e) and depending on the carbon price selected when assuming the landfilling of commercial and industrial waste for the emissions factor. It is important to note that these results do not include the GHG emissions involved in producing the scrapped material, but rather only those resulting from its waste treatment. Hence, if such emissions were to be included, the resulting GHG emissions and cost-savings could be much larger.

When it came to the transport GHG emissions, after testing several scenarios, we noticed that under most circumstances it would make no sense to incorporate the cost of GHG emissions into the TCO. This was the case with the demo data, where the supplier of the material or the company ordering the material had imposed a rounding value equal to a full truckload. Thus, unless it was possible to not have full truck loads (i.e. no product consolidation was possible whether with the same material or a different one) then there would be no way to influence the GHG emissions. Moreover, EcoTransIT World automatically assumes a default utilization rate on the mode of transport, but since the utilization rate per order was not known, there was no way to influence the results either; no matter how much material was being ordered the resulting GHG emissions would simply be a multiple of the material ordered. Therefore, for viability to exist, as has previously been discussed specific data is needed; the utilization rate for the transport of each comparison order must be known, and this utilization rate must not be 100%.

Notwithstanding it was still possible to extract other valuable insights concerning the viability of the business case based on the results for in Appendix C-2 Material X and in Appendix C-7 Material Y. We can observe that the weight of the total order size can make very large difference determining whether the GHG emissions will influence the TCO or not at all. In the case of air freighting, GHG emissions were consistently 50 times greater while sulfur dioxide emissions were only 3 times greater than those resulting from shipping, despite the fact that nearly twice as much distance was covered by ship in the case of a trip from Shanghai to Geneva. At a carbon price of \$5/tCO_2e in the case of Material X, the \$1,553 cost of air freighting emissions already represented nearly 200% of the original order cost of \$900. In the case of shipping, larger carbon prices would be necessary to influence the TCO, while in the case of trucking long distances and heavy materials are a precursor for influencing the TCO. Having a refrigerated truck only resulted in an approximately 20% increase in GHG emissions in comparison to a truck under normal conditions. This case study calls for further research using an extended data set on multiple materials such that a complete data is available. This will allow for the warehousing and scrap emission findings to be validated, and for calculating the transport GHG emissions on each order size with the utilization rate. Although it was not part of the scope of this thesis, this research could be extended to evaluate whether it makes more sense to hold higher safety stocks than risking the need to air freight a product under a TCO approach with GHG emissions.

7. Conclusion: Recommendations for GenLots

This thesis has evaluated whether there is a business case for GenLots to pursue the development of its CO_2 Emissions Optimizer, which aims to incorporate GHG emissions into the Total Cost of Ownership for lot sizing decisions. The research consisted of reviewing the commercial and technical viability and providing a case study for it. For the commercial viability interviews conducted with sustainability, logistics, and supply chain experts as well as corporate Annual Sustainability Reports revealed that there is interest around reducing GHG emissions from logistics especially when it comes to European industrial companies. The company-specific degree of interest greatly depends on how ambitious a company's sustainability commitment are and the nature of the supply chain network. When it comes specifically to Scope 3 upstream transportation and distribution emissions, which concern this thesis, although the regulatory and data collation landscape is fast-changing it is still not mature enough for GenLots' CO_2 Emissions Optimizer to represent an attractive enough opportunity today, but it could become in the coming 2-3 years.

Technical viability was determined by researching previously developed lot sizing models that incorporated sustainability considerations and building upon them to propose a new model in compliance with the GHG Protocol emissions calculation standard. The proposed model consists of utilizing the certified online GHG emissions calculator EcoTransIT World for the transport emissions calculation and following the GHG Protocol's "Average-data method" and the "Waste-type specific method" for computing the warehousing emissions and waste treatment emissions respectively. The proposed model was then applied in a case study.

The case study revealed that the TCO equation could be reduced to only include GHG emissions from transportation and scrap as warehousing emissions did not appear to have a significant impact on the carrying rate parameter. Additionally, it demonstrated that the CO_2 Emissions Optimizer is only useful when material order quantities are not restricted to full truckload rounding values as trucks are necessary for the last mile in most cases unless direct delivery via rail or waterway is possible. Unfortunately, the extent of the findings from the case study were limited by the available data set, which was taken from GenLots demo data set as it was not possible for various reasons to obtain a real-world, specific and anonymized data set from any organization.

To conclude it would be advisable for GenLots to hold-off on incorporating GHG emissions as a parameter in its algorithm, such that lot sizing decisions can be both economically and environmentally optimal. Nevertheless, based on the commercially and technical viability discussion GenLots should pursue co-innovation with its clients to compute and report the GHG emission savings that it is capable of generating today. This will allow GenLots to improve its core-product's value proposition and its grant funding possibilities, while attracting and potentially retaining clients. Additionally, setting itself on this path may unveil new opportunities for further research such as in applying sustainability considerations in safety stock decisions or in supporting one of many other strategic and operational procurement and logistics decisions discussed in this paper.

8. Acknowledgements

I would like to start out by thanking Simon Schenker, co-CEO of GenLots for the opportunity to join the GenLots team for writing this thesis, as well as for the advice and guidance he provided throughout the process, pushing me to deliver my best work. I am also grateful to my colleagues at GenLots, especially Arnaud, Adrian Wildeis, Matthieu Dumont, and Vaibhav Kulkarni who provided their support throughout this thesis.

I would also like to thank Kenneth Younge, Chair of Technology and Innovation Strategy at EPFL for supervising this thesis. The knowledge I obtained from taking his Technology and Innovation Strategy course as well as his Data Science for Business course have greatly shaped the final result of this work.

This thesis would not have been possible either without the contributions from each and every one of the interviewees who provided their personal time to share their experiences and insight, and for which I am extremely thankful: Erica Mazerolle, Sascha Nick, Lisa Lafferty, Dave Howson, Astrid Bosten, Marianne Gries, James Goudreau, Andrej Szijjarto, Olivier Keisier, Theresa Fucks, Sabine Fortmann, Jakub Maciej Ferenc, Alena Schmidt, Veera Johnson. I am grateful to the Sustainable Procurement Pledge (SPP), for providing a space to exchange knowledge and network with professionals in procurement looking to make a difference in turning procurement into a more sustainable-minded practice. Furthermore, I am thankful to Anaïs Matthey, Enrique Alvarado, and Alp Katalan for connecting me to some of the interviewees for this thesis.

I'd like to extend a special thanks to Damien Jaton, Andreas Richardson, and Beatrice Scarioni for sharing relevant resources that propelled my research during the early phases.

Finally, I am immensely grateful to my parents, my family, and my friends who have supported me especially throughout this atypical and difficult times of coronavirus.

9. References

Barry Callebaut. (2019). *Forever Chocolate Thriving Nature*. Retrieved from Barry Callebaut: https://www.barry-callebaut.com/en/group/forever-chocolate/sustainability-reporting/forever-chocolate-progress-report-2018-19/forever-chocolate-thriving-nature

Barry Callebaut. (2019, November 4). *Independent Limited Assurance Report to the Directors of Barry Callebaut AG*. (PwC) Retrieved June 18, 2020, from Barry Callebaut: https://www.barry-callebaut.com/sites/default/files/2019-12/Barry%20Callebaut%20Forever%20Chocolate%20Progress%20Report%202018-19%20-%20Assurance%20Report.pdf

Barry Callebaut. (n.d.). *Forever Chocolate Strategy: By 2025 we will be carbon and forest positive*. (Barry Callebaut) Retrieved August 05, 2020, from Barry Callebaut: https://www.barry-callebaut.com/en/group/forever-chocolate/forever-chocolate-strategy/2025-we-will-be-carbon-and-forest-positive

BASF. (2020, February 28). *Transportation and Storage*. (BASF) Retrieved July 26, 2020, from BASF: https://report.basf.com/2019/en/managements-report/responsibility-along-the-value-chain/environmental-protection-health-and-safety/transportation-and-storage.html

Battini, D., Persona, A., & Sgarbossa, F. (2014). A sustainable EOQ model: theoretical formulation and applications. *International Journal of Production Economics, 149*, 145-153.

Bearing Point. (2020). *LogEC - Logistic Emissions Calculator*. (BearingPoint) Retrieved July 04, 2020, from Bearing Point: https://www.bearingpoint.com/en/our-expertise/innovations/digital-supply-chain-management/logec-logistics-emissions-calculator/

Benjaafar, S., M, L. Y., & Daskin, M. (2013). Carbon footprint and the management of supply chains: insights from simple models. *IEEE Transactions on Automation Science and Engineering, 10*(1), 99-116.

Bhatia, P., Cummis, C., Brown, A., Rich, D., Draucker, L., & Lahd, H. (2011). *Corporate Value Chain (Scope 3) Accounting and Reporting Standard*. (Greenhouse Gas Protocol) Retrieved May 14, 2020, from https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard-EReader_041613_0.pdf

Brohé, A. (2018, May 23). *How Accounting Can Save The Planet*. (TEDxColumbiaUniversity) Retrieved January 28, 2020, from YouTube TEDx Talks: https://www.youtube.com/watch?v=A-bJJlFALB0

California Air Resources Board. (2020, June 25). *California takes bold step to reduce truck pollution*. (California Air Resources Board) Retrieved July 04, 2020, from California Air Resources Board: https://ww2.arb.ca.gov/news/california-takes-bold-step-reduce-truck-pollution

Carbon Pricing Leadership. (2019, June). *Carbon Pricing in Action*. (Carbon PRicing Leadership Coalition) Retrieved May 04, 2020, from Carbon Pricing Leadership: https://www.carbonpricingleadership.org/who

CDP. (2020). *What we do*. (CDP) Retrieved July 12, 2020, from CDP: https://www.cdp.net/en/info/about-us/what-we-do

Chiodo, J. (2020, June 13). *What does a ton of CO2 look like?* (Cx Associates) Retrieved May 05, 2020, from https://buildingenergy.cx-associates.com/2012/06/what-does-a-ton-of-co2-look-like/

CO2 Monitor. (n.d.). *CO2 Monitor*. (CO2 Monitor) Retrieved June 01, 2020, from CO2 Monitor: https://www.co2-monitor.ch/en/

Dahlmann, F. (2020, January 05). *How to manage your supply chain's carbon footprint*. Retrieved from Warwick Business School: https://www.wbs.ac.uk/news/how-to-manage-your-supply-chain-s-carbon-footprint/

Daryanto, Y. e. (2020). Retailer’s EOQ model considering demand and holding cost of the defective items under carbon emission tax. *IOP Conf. Series: Materials Science and Engineering, 847*(012012).

Dobers, K., & Rüdiger, D. (2019, May). *Emission intensity factors for logistics buildings.* Retrieved from Fraunhofer IML: https://www.iml.fraunhofer.de/content/dam/iml/en/documents/OE%20310/Emission_%20intensity_factors_logistics_buildings_FraunhoferIML_052019.pdf

EcoTransIT World. (n.d.). *ETW at a Glance*. (EcoTransIT World) Retrieved July 04, 2020, from EcoTransIT World: https://www.ecotransit.org/about.en.html

Environmental Protection Agency. (2018). *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. (US Environmental Protection Agency) Retrieved July 10, 2020, from Environmental Protection Agency: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

Environmental Protection Agency. (2019). *Waste Reduction Model (WARM)*. Retrieved from Environmental Protection Agency: https://www.epa.gov/warm

European Commission. (2015). *EU ETS Handbook*. (European Commission) Retrieved March 20, 2020, from European Commission: https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf

European Commission. (n.d.). *Horizon 2020 - Societal Challenges*. Retrieved from European Commission: https://ec.europa.eu/programmes/horizon2020/en/h2020-section/societal-challenges

Greenhouse Gas Protocol. (2020). *About Us*. (Greenhouse Gas Protocol) Retrieved Jul 09, 2020, from Greenhouse Gas Protocol: https://ghgprotocol.org/about-us

Horn, H., & Sapir, A. (2019, August 29). *Border Carbon Tariffs: Giving Up on Trade to Save the Climate?* . (Bruegel) Retrieved July 22, 2020, from https://www.bruegel.org/2019/08/border-carbon-tariffs-giving-up-on-trade-to-save-the-climate/

International Carbon Action Partnership. (2015, January). *Linking Emissions Trading Systems: A Summary of Current Research*. Retrieved July 14, 2020, from International Carbon Action Partnership: https://icapcarbonaction.com/en/?option=com_attach&task=download&id=241

International Carbon Action Partnership. (2019, April). *Emissions Trading and Carbon Tax: Two Instruments, One Goal*. (International Carbon Action Partnership) Retrieved July 05, 2020, from International Carbon Action Partnership: https://icapcarbonaction.com/en/?option=com_attach&task=download&id=638#:~:text=Quantity%20certainty%20vs.,mitigation%20outcome%20of%20the%20policy.&text=On%20the%20other%20hand%2C%20a,mitigation%20outcome%20cannot%20be%20set.

International Maritime Organization. (2020). *Sulphur 2020 – cutting sulphur oxide emissions*. (International Maritime Organization) Retrieved July 15, 2020, from International Maritime Organization: http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx

International Transport Forum. (2015). *Carbon Valuation for Transport Policy*. (International Transport Forum (OECD)) Retrieved May 05, 2020, from International Transport Forum: https://www.itf-oecd.org/sites/default/files/docs/cop-pdf-02.pdf

Johnson & Johnson. (2018). *2018 Corporate Sustainability Report*. (Verizon) Retrieved January 28, 2020, from https://www.verizon.com/about/sites/default/files/corporate-responsibility-report/2018/supply/performance.html

Johnson & Johnson. (2020). *2019 Sustainability GRI Index*. Retrieved from Givaudan: https://www.givaudan.com/file/198276/download

Keaveny, P. (2020, January 23). *How to really hold business to account on their carbon footprint – include their supply chains* . (The Conversation) Retrieved July 1, 2020, from https://theconversation.com/how-to-really-hold-business-to-account-on-their-carbon-footprint-include-their-supply-chains-130402

Kingo, L. (2016, April 22). *Executive Update: Setting a $100 price on carbon* . (United Nations Global Compact) Retrieved July 15, 2020, from https://www.unglobalcompact.org/news/3361-04-22-2016

McKinnon, A. (2018). *Decarbonizing logistics: Distributing goods in a low carbon world.* New York: Kogan Page Ltd.

McKinnon, A., & Piecyk, M. (2011, March). *Guidelines for Measuring and Managing CO2 Emission from Freight Transport Operations*. Retrieved from The Chemical Logistics Association: https://www.ecta.com/resources/Documents/Best%20Practices%20Guidelines/guideline_for_measuring_and_managing_co2.pdf

Mohr, B. (2020, March 13). *A National ETS with a Moderate Price to be Introduced in Germany in 2021* . Retrieved July 15, 2020, from https://www.climatescorecard.org/2020/03/a-national-ets-with-a-moderate-price-to-be-introduced-in-germany-in-2021/

my M climate fund – CO_2 compensation in the value-creation chain . (2019, March 15). (myClimate) Retrieved July 15, 2020, from https://www.myclimate.org/information/news-press/news/newsdetail/detail/News/my-m-klimafonds-co2-kompensation-in-der-wertschoepfungskette-1/

MyClimate. (2019). *WWF Switzerland – Long-standing Partnership with myclimate*. (myClimate) Retrieved July 15, 2020, from MyClimate: https://www.myclimate.org/information/partners-in-climate-protection/partner-detail/detail/News/wwf-switzerland-long-standing-partnership-with-myclimate/

MyClimate. (n.d.). *MyClimate*. (MyClimate) Retrieved June 07, 2020, from MyClimate: https://www.myclimate.org/

Novartis. (n.d.). *CDP 2019 Climate Change Information Request Response*. Retrieved August 05, 2020, from https://www.novartis.com/sites/www.novartis.com/files/cdp-2019-climate-change-information-request-response.pdf

SAP. (2020, 06 01). *SAP to Help Customers Track Their Greenhouse Gas Emissions*. Retrieved from SAP: https://news.sap.com/2020/06/climate-21-track-greenhouse-gas-emissions/

SBTi. (2020, July). *Meet the companies already setting their emissions reduction targets in line with climate science*. (Science-Based Targets initiative) Retrieved August 05, 2020, from SBTi: https://sciencebasedtargets.org/companies-taking-action/

Schroten, A., van Essen, H., van Wijngaarden, L., Sutter, D., & Andrew, E. (2019, May). *Sustainable Transport Infrastructure Charging and Internalisation of Transport Externalities: Main Findings*. (CE Delft) Retrieved July 03, 2020, from European Commission: https://ec.europa.eu/transport/sites/transport/files/studies/internalisation-study-summary-isbn_978-92-76-03076-8.pdf

Shijin, W., & Ye, B. (2018). A comparison between just-in-time and economic order quantity models with carbon emissions. *Journal of Cleaner Production, 187*, 662-671.

Smart Freight Centre. (n.d.). *What is the GLEC Framework*. (Smart Freight Centre) Retrieved July 30, 2020, from Smart Freight Centre: https://www.smartfreightcentre.org/en/how-to-implement-items/what-is-glec-framework/58/

Strauss, M. (2020, July 07). *EU lawmakers agree to include shipping emissions in EU carbon market* . (Reuters) Retrieved July 15, 2020, from https://www.reuters.com/article/us-climate-change-eu-shipping/eu-lawmakers-agree-to-include-shipping-emissions-in-eu-carbon-market-idUSKBN2481UD#:~:text=Shipping%20companies%20are%20not%20yet,efforts%20to%20cut%20greenhouse%20gases.

Supply Chain Solutions Center. (2020). *Carbon accounting 101*. (Environmental Defense Fund - Supply chain Solutions Center) Retrieved Jan 28, 2020, from Supply Chain Solutions Center: https://supplychain.edf.org/resources/carbon-accounting/

Sustainability Accounting Standards Board. (2016, October). *Climate Risk Technical Bulleting*. (Sustainability Accounting Standards Board) Retrieved July 17, 2020, from Sustainability Accounting Standards Board: https://www.sasb.org/wp-content/uploads/2019/08/Climate-Risk-Technical-Bulletin-web.pdf

Tang, S., Wang, W., Yan, H., & Hao, G. (2015). Low carbon logistics: Reducing shipment frequency to cut carbon emissions. *Int. J. Production Economics, 164*, 339-350.

The World Bank. (2017). *Carbon Pricing Dashboard: What is carbon pricing?* (The World Bank) Retrieved July 15, 2020, from The World Bank: https://carbonpricingdashboard.worldbank.org/what-carbon-pricing

The World Bank. (2020, April 01). *Carbon Pricing Dashboard*. (The World Bank) Retrieved July 14, 2020, from The World Bank: https://carbonpricingdashboard.worldbank.org/

Timperley, J. (2020, January 15). *The Panama Canal is Running Out of Water*. (Wired) Retrieved August 05, 2020, from Wired: https://www.wired.co.uk/article/panama-canal-climate-change

Transport and Environment. (2020, July 03). *Top shipping polluter overtakes power plants as coal shuts down*. (Transport and Environment) Retrieved July 04, 2020, from Transport and Environment: https://www.transportenvironment.org/press/top-shipping-polluter-overtakes-power-plants-coal-shuts-down

Transport and Environment. (n.d.). *Arctic Shipping*. (Transport and Environment) Retrieved August 05, 2020, from https://www.transportenvironment.org/what-we-do/shipping-and-environment/arctic-shipping#:~:text=Shipping%20traffic%20in%20the%20Arctic,50%25%20between%202012%20and%202050.

UK Government. (2020, July 28). *Greenhouse gas reporting: conversion factors 2019*. Retrieved from UK Government: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019

Unilver plc. (2020). *Unilever plc - Climate Change 2019 CDP Report*. Retrieved from Unilver plc: https://www.unilever.com/Images/cdp-climate-2019_tcm244-542977_en.pdf

United Nations Secretary General. (2019, May 08). *Special edition: progress towards the Sustainable Development Goals*. (United Nations Economic and Social Council) Retrieved July 07, 2020, from https://undocs.org/E/2019/68

Verizon. (2020). *2019 Health for Humanity Report: Independent Assurance Statement*. Retrieved from Johnson & Johnson: https://healthforhumanityreport.jnj.com/_document/erm-assurance-statement-gm-emission-data?id=00000172-a90f-d872-a776-bb7f62dd0000

Wang, S., & Ge, M. (2019, October 16). *Everything You Need to Know About the Fastest-Growing Source of Global Emissions: Transport* . (World Resources Institute) Retrieved July 15 2020, from https://www.wri.org/blog/2019/10/everything-you-need-know-about-fastest-growing-source-global-emissions-transport

Wang, S., & Ye, B. (2018). A comparison between just-in-time and economic order quantity models with carbon emissions. *Journal of Cleaner Production, 187*, 662-671.

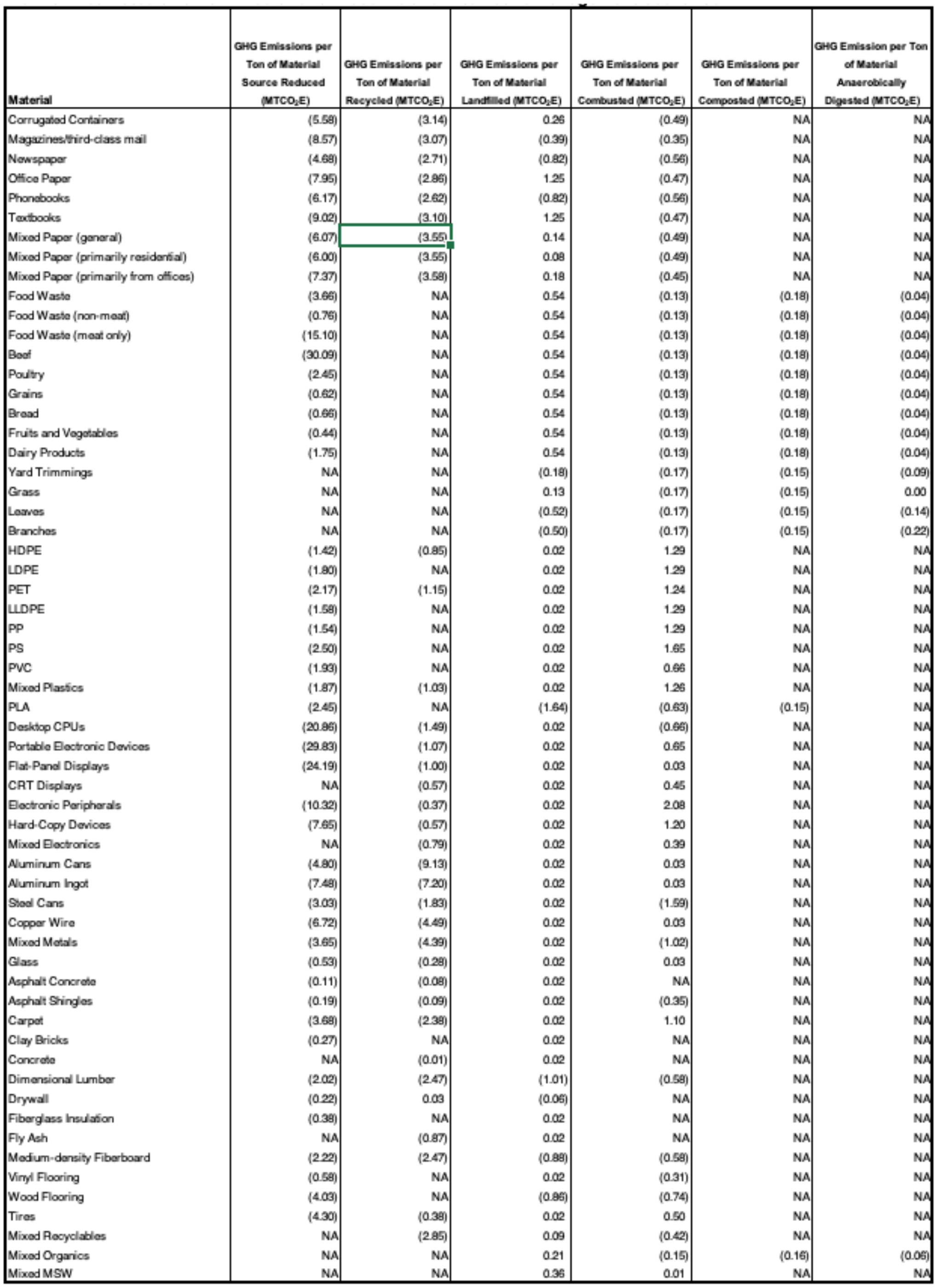
World Economic Forum. (2009). *Supply Chain Decarbonization: The Role of Logistics and Transport in Reducing Supply Chain Emissions*. Retrieved from World Economic Forum: http://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf

WRI, & WBCSD. (2013). *Technical Guidance for Calculating Scope 3 Emissions*. (Greenhouse Gas Protocol) Retrieved May 15, 2020, from https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf

10. Appendix

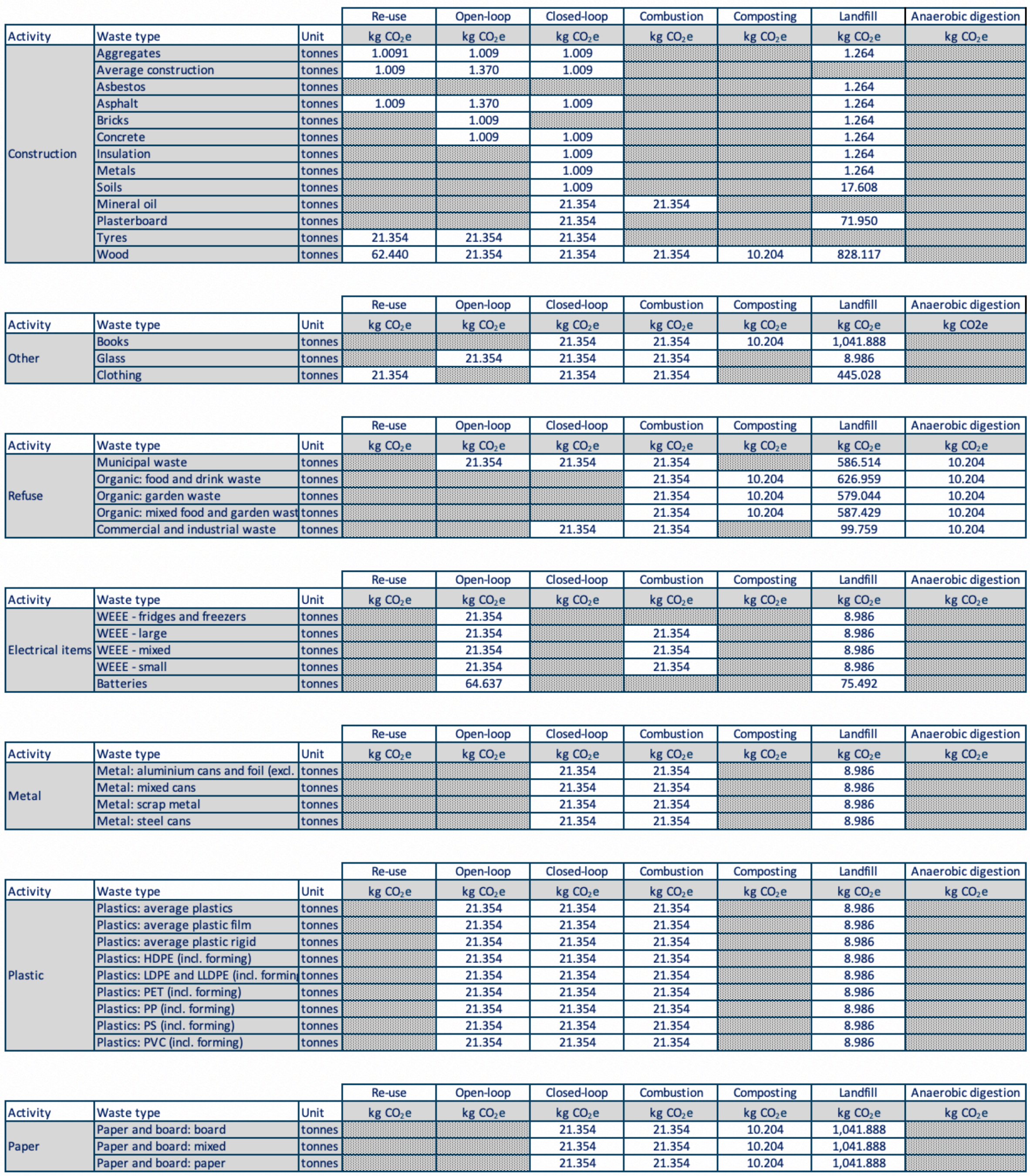
A. Sample Emission Factors

A-1. Per ton estimates of GHG Emissions for waste-treatment from WARM tool (Environmental Protection Agency, 2019)



Material	GHG Emissions per Ton of Material Source Reduced (MTCO$_2$E)	GHG Emissions per Ton of Material Recycled (MTCO$_2$E)	GHG Emissions per Ton of Material Landfilled (MTCO$_2$E)	GHG Emissions per Ton of Material Combusted (MTCO$_2$E)	GHG Emissions per Ton of Material Composted (MTCO$_2$E)	GHG Emission per Ton of Material Anaerobically Digested (MTCO$_2$E)
Corrugated Containers	(5.58)	(3.14)	0.26	(0.49)	NA	NA
Magazines/third-class mail	(8.57)	(3.07)	(0.39)	(0.35)	NA	NA
Newspaper	(4.68)	(2.71)	(0.82)	(0.56)	NA	NA
Office Paper	(7.95)	(2.86)	1.25	(0.47)	NA	NA
Phonebooks	(6.17)	(2.62)	(0.82)	(0.56)	NA	NA
Textbooks	(9.02)	(3.10)	1.25	(0.47)	NA	NA
Mixed Paper (general)	(6.07)	(3.55)	0.14	(0.49)	NA	NA
Mixed Paper (primarily residential)	(6.00)	(3.55)	0.08	(0.49)	NA	NA
Mixed Paper (primarily from offices)	(7.37)	(3.58)	0.18	(0.45)	NA	NA
Food Waste	(3.66)	NA	0.54	(0.13)	(0.18)	(0.04)
Food Waste (non-meat)	(0.76)	NA	0.54	(0.13)	(0.18)	(0.04)
Food Waste (meat only)	(15.10)	NA	0.54	(0.13)	(0.18)	(0.04)
Beef	(30.09)	NA	0.54	(0.13)	(0.18)	(0.04)
Poultry	(2.45)	NA	0.54	(0.13)	(0.18)	(0.04)
Grains	(0.62)	NA	0.54	(0.13)	(0.18)	(0.04)
Bread	(0.66)	NA	0.54	(0.13)	(0.18)	(0.04)
Fruits and Vegetables	(0.44)	NA	0.54	(0.13)	(0.18)	(0.04)
Dairy Products	(1.75)	NA	0.54	(0.13)	(0.18)	(0.04)
Yard Trimmings	NA	NA	(0.18)	(0.17)	(0.15)	(0.09)
Grass	NA	NA	0.13	(0.17)	(0.15)	0.00
Leaves	NA	NA	(0.52)	(0.17)	(0.15)	(0.14)
Branches	NA	NA	(0.50)	(0.17)	(0.15)	(0.22)
HDPE	(1.42)	(0.85)	0.02	1.29	NA	NA
LDPE	(1.80)	NA	0.02	1.29	NA	NA
PET	(2.17)	(1.15)	0.02	1.24	NA	NA
LLDPE	(1.58)	NA	0.02	1.29	NA	NA
PP	(1.54)	NA	0.02	1.29	NA	NA
PS	(2.50)	NA	0.02	1.65	NA	NA
PVC	(1.93)	NA	0.02	0.66	NA	NA
Mixed Plastics	(1.87)	(1.03)	0.02	1.26	NA	NA
PLA	(2.45)	NA	(1.64)	(0.63)	(0.15)	NA
Desktop CPUs	(20.86)	(1.49)	0.02	(0.66)	NA	NA
Portable Electronic Devices	(29.83)	(1.07)	0.02	0.65	NA	NA
Flat-Panel Displays	(24.19)	(1.00)	0.02	0.03	NA	NA
CRT Displays	NA	(0.57)	0.02	0.45	NA	NA
Electronic Peripherals	(10.32)	(0.37)	0.02	2.08	NA	NA
Hard-Copy Devices	(7.65)	(0.57)	0.02	1.20	NA	NA
Mixed Electronics	NA	(0.79)	0.02	0.39	NA	NA
Aluminum Cans	(4.80)	(9.13)	0.02	0.03	NA	NA
Aluminum Ingot	(7.48)	(7.20)	0.02	0.03	NA	NA
Steel Cans	(3.03)	(1.83)	0.02	(1.59)	NA	NA
Copper Wire	(6.72)	(4.49)	0.02	0.03	NA	NA
Mixed Metals	(3.65)	(4.39)	0.02	(1.02)	NA	NA
Glass	(0.53)	(0.28)	0.02	0.03	NA	NA
Asphalt Concrete	(0.11)	(0.08)	0.02	NA	NA	NA
Asphalt Shingles	(0.19)	(0.09)	0.02	(0.35)	NA	NA
Carpet	(3.68)	(2.38)	0.02	1.10	NA	NA
Clay Bricks	(0.27)	NA	0.02	NA	NA	NA
Concrete	NA	(0.01)	0.02	NA	NA	NA
Dimensional Lumber	(2.02)	(2.47)	(1.01)	(0.58)	NA	NA
Drywall	(0.22)	0.03	(0.06)	NA	NA	NA
Fiberglass Insulation	(0.38)	NA	0.02	NA	NA	NA
Fly Ash	NA	(0.87)	0.02	NA	NA	NA
Medium-density Fiberboard	(2.22)	(2.47)	(0.88)	(0.58)	NA	NA
Vinyl Flooring	(0.58)	NA	0.02	(0.31)	NA	NA
Wood Flooring	(4.03)	NA	(0.86)	(0.74)	NA	NA
Tires	(4.30)	(0.38)	0.02	0.50	NA	NA
Mixed Recyclables	NA	(2.85)	0.09	(0.42)	NA	NA
Mixed Organics	NA	NA	0.21	(0.15)	(0.16)	(0.06)
Mixed MSW	NA	NA	0.36	0.01	NA	NA

A-2. Per ton estimates of GHG Emissions for waste-treatment from DEFRA for 2019 (UK Government, 2020)



			Re-use	Open-loop	Closed-loop	Combustion	Composting	Landfill	Anaerobic digestion
Activity	Waste type	Unit	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e
Construction	Aggregates	tonnes	1.0091	1.009	1.009			1.264	
	Average construction	tonnes	1.009	1.370	1.009				
	Asbestos	tonnes						1.264	
	Asphalt	tonnes	1.009	1.370	1.009			1.264	
	Bricks	tonnes		1.009				1.264	
	Concrete	tonnes		1.009	1.009			1.264	
	Insulation	tonnes			1.009			1.264	
	Metals	tonnes			1.009			1.264	
	Soils	tonnes			1.009			17.608	
	Mineral oil	tonnes			21.354	21.354			
	Plasterboard	tonnes			21.354			71.950	
	Tyres	tonnes	21.354	21.354	21.354				
	Wood	tonnes	62.440	21.354	21.354	21.354	10.204	828.117	

			Re-use	Open-loop	Closed-loop	Combustion	Composting	Landfill	Anaerobic digestion
Activity	Waste type	Unit	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO2e
Other	Books	tonnes			21.354	21.354	10.204	1,041.888	
	Glass	tonnes		21.354	21.354	21.354		8.986	
	Clothing	tonnes	21.354		21.354	21.354		445.028	

			Re-use	Open-loop	Closed-loop	Combustion	Composting	Landfill	Anaerobic digestion
Activity	Waste type	Unit	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e
Refuse	Municipal waste	tonnes		21.354	21.354	21.354		586.514	10.204
	Organic: food and drink waste	tonnes				21.354	10.204	626.959	10.204
	Organic: garden waste	tonnes				21.354	10.204	579.044	10.204
	Organic: mixed food and garden wast	tonnes				21.354	10.204	587.429	10.204
	Commercial and industrial waste	tonnes			21.354	21.354		99.759	10.204

			Re-use	Open-loop	Closed-loop	Combustion	Composting	Landfill	Anaerobic digestion
Activity	Waste type	Unit	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e
Electrical items	WEEE - fridges and freezers	tonnes		21.354				8.986	
	WEEE - large	tonnes		21.354		21.354		8.986	
	WEEE - mixed	tonnes		21.354		21.354		8.986	
	WEEE - small	tonnes		21.354		21.354		8.986	
	Batteries	tonnes		64.637				75.492	

			Re-use	Open-loop	Closed-loop	Combustion	Composting	Landfill	Anaerobic digestion
Activity	Waste type	Unit	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e
Metal	Metal: aluminium cans and foil (excl.	tonnes			21.354	21.354		8.986	
	Metal: mixed cans	tonnes			21.354	21.354		8.986	
	Metal: scrap metal	tonnes			21.354	21.354		8.986	
	Metal: steel cans	tonnes			21.354	21.354		8.986	

			Re-use	Open-loop	Closed-loop	Combustion	Composting	Landfill	Anaerobic digestion
Activity	Waste type	Unit	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e
Plastic	Plastics: average plastics	tonnes		21.354	21.354	21.354		8.986	
	Plastics: average plastic film	tonnes		21.354	21.354	21.354		8.986	
	Plastics: average plastic rigid	tonnes		21.354	21.354	21.354		8.986	
	Plastics: HDPE (incl. forming)	tonnes		21.354	21.354	21.354		8.986	
	Plastics: LDPE and LLDPE (incl. formin	tonnes		21.354	21.354	21.354		8.986	
	Plastics: PET (incl. forming)	tonnes		21.354	21.354	21.354		8.986	
	Plastics: PP (incl. forming)	tonnes		21.354	21.354	21.354		8.986	
	Plastics: PS (incl. forming)	tonnes		21.354	21.354	21.354		8.986	
	Plastics: PVC (incl. forming)	tonnes		21.354	21.354	21.354		8.986	

			Re-use	Open-loop	Closed-loop	Combustion	Composting	Landfill	Anaerobic digestion
Activity	Waste type	Unit	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e	kg CO_2e
Paper	Paper and board: board	tonnes			21.354	21.354	10.204	1,041.888	
	Paper and board: mixed	tonnes			21.354	21.354	10.204	1,041.888	
	Paper and board: paper	tonnes			21.354	21.354	10.204	1,041.888	

Please note - factors that are: (a) not available, will be marked with an empty, light shaded cell: ░

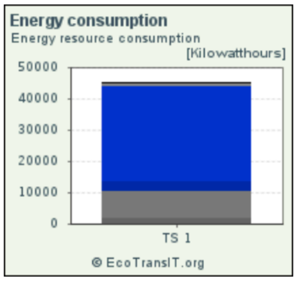
(b) have an invalid combination of criteria, will be marked with an empty, dark shaded cell: ▓

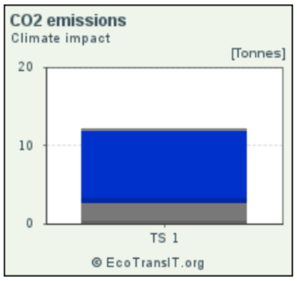
A-3. Per ton estimates of GHG Emissions for logistics sites in Europe from Fraunhofer IML study (Dobers & Rüdiger, 2019)

Type of logistics site	**Number of sites**	**Median**
Transshipment (ambient)	4	1.2 kg CO_2e/tonne
Storage + transshipment (ambient)	34	5.4 kg CO_2e/tonne
Storage + transshipment (refrigerated)	15	11.7 kg CO_2e/tonne

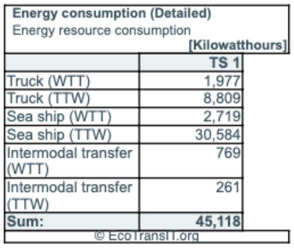
B. EcoTransIT World Web Interface Example Calculation Results

B-1. Results including Google Maps from EcoTransIT World





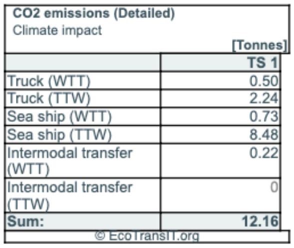
■ Truck well to tank
■ Truck tank to wheel
■ Sea ship well to tank
■ Sea ship tank to wheel



Energy consumption (Detailed)
Energy resource consumption
[Kilowatthours]

	TS 1
Truck (WTT)	1,977
Truck (TTW)	8,809
Sea ship (WTT)	2,719
Sea ship (TTW)	30,584
Intermodal transfer (WTT)	769
Intermodal transfer (TTW)	261
Sum:	**45,118**

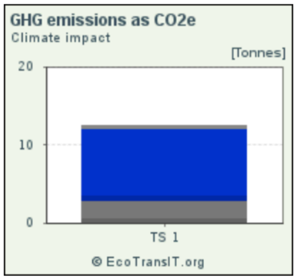
© EcoTransIT.org

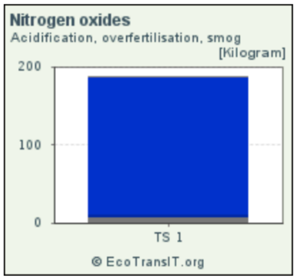


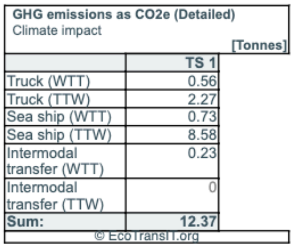
CO2 emissions (Detailed)
Climate impact
[Tonnes]

	TS 1
Truck (WTT)	0.50
Truck (TTW)	2.24
Sea ship (WTT)	0.73
Sea ship (TTW)	8.48
Intermodal transfer (WTT)	0.22
Intermodal transfer (TTW)	0
Sum:	**12.16**

© EcoTransIT.org



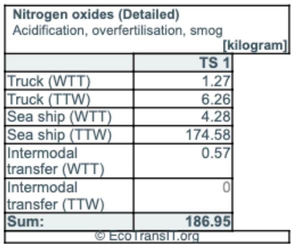




GHG emissions as CO2e (Detailed)
Climate impact
[Tonnes]

	TS 1
Truck (WTT)	0.56
Truck (TTW)	2.27
Sea ship (WTT)	0.73
Sea ship (TTW)	8.58
Intermodal transfer (WTT)	0.23
Intermodal transfer (TTW)	0
Sum:	**12.37**

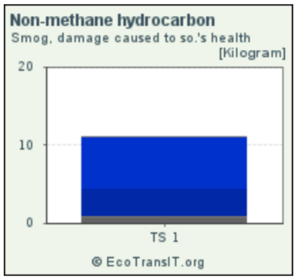
© EcoTransIT.org

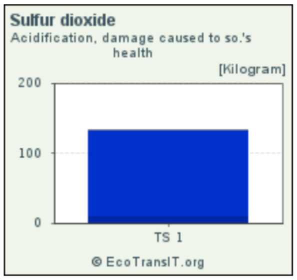


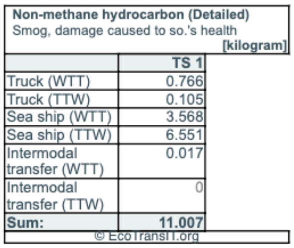
Nitrogen oxides (Detailed)
Acidification, overfertilisation, smog
[kilogram]

	TS 1
Truck (WTT)	1.27
Truck (TTW)	6.26
Sea ship (WTT)	4.28
Sea ship (TTW)	174.58
Intermodal transfer (WTT)	0.57
Intermodal transfer (TTW)	0
Sum:	**186.95**

© EcoTransIT.org



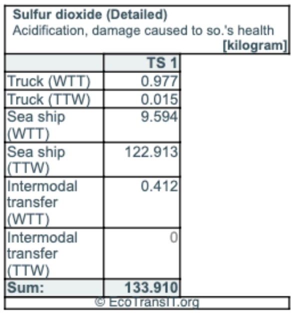




Non-methane hydrocarbon (Detailed)
Smog, damage caused to so.'s health
[kilogram]

	TS 1
Truck (WTT)	0.766
Truck (TTW)	0.105
Sea ship (WTT)	3.568
Sea ship (TTW)	6.551
Intermodal transfer (WTT)	0.017
Intermodal transfer (TTW)	0
Sum:	**11.007**

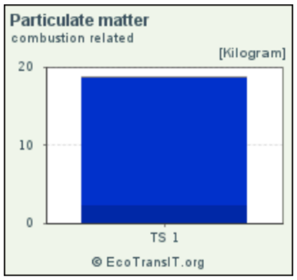
© EcoTransIT.org

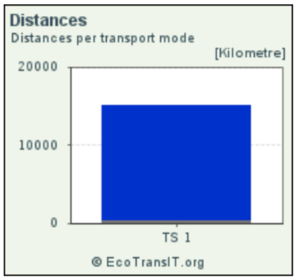


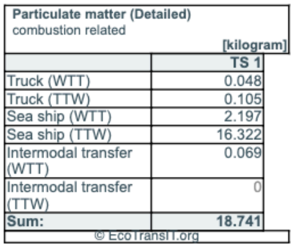
Sulfur dioxide (Detailed)
Acidification, damage caused to so.'s health
[kilogram]

	TS 1
Truck (WTT)	0.977
Truck (TTW)	0.015
Sea ship (WTT)	9.594
Sea ship (TTW)	122.913
Intermodal transfer (WTT)	0.412
Intermodal transfer (TTW)	0
Sum:	**133.910**

© EcoTransIT.org



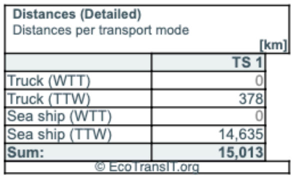




Particulate matter (Detailed)
combustion related
[kilogram]

	TS 1
Truck (WTT)	0.048
Truck (TTW)	0.105
Sea ship (WTT)	2.197
Sea ship (TTW)	16.322
Intermodal transfer (WTT)	0.069
Intermodal transfer (TTW)	0
Sum:	**18.741**

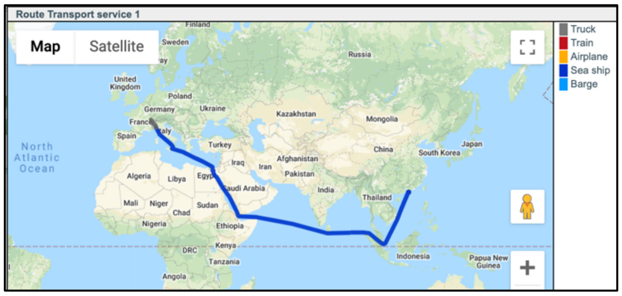
© EcoTransIT.org

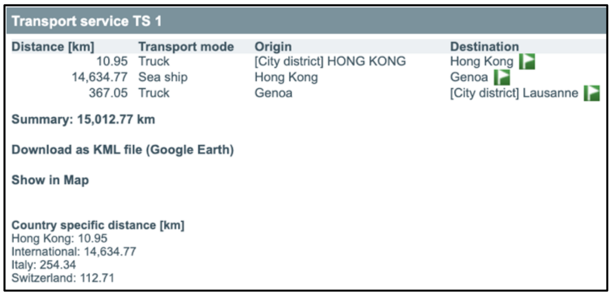


Distances (Detailed)
Distances per transport mode
[km]

	TS 1
Truck (WTT)	0
Truck (TTW)	378
Sea ship (WTT)	0
Sea ship (TTW)	14,635
Sum:	**15,013**

© EcoTransIT.org





Transport service TS 1

Distance [km]	Transport mode	Origin	Destination
10.95	Truck	[City district] HONG KONG	Hong Kong
14,634.77	Sea ship	Hong Kong	Genoa
367.05	Truck	Genoa	[City district] Lausanne

Summary: 15,012.77 km

Download as KML file (Google Earth)

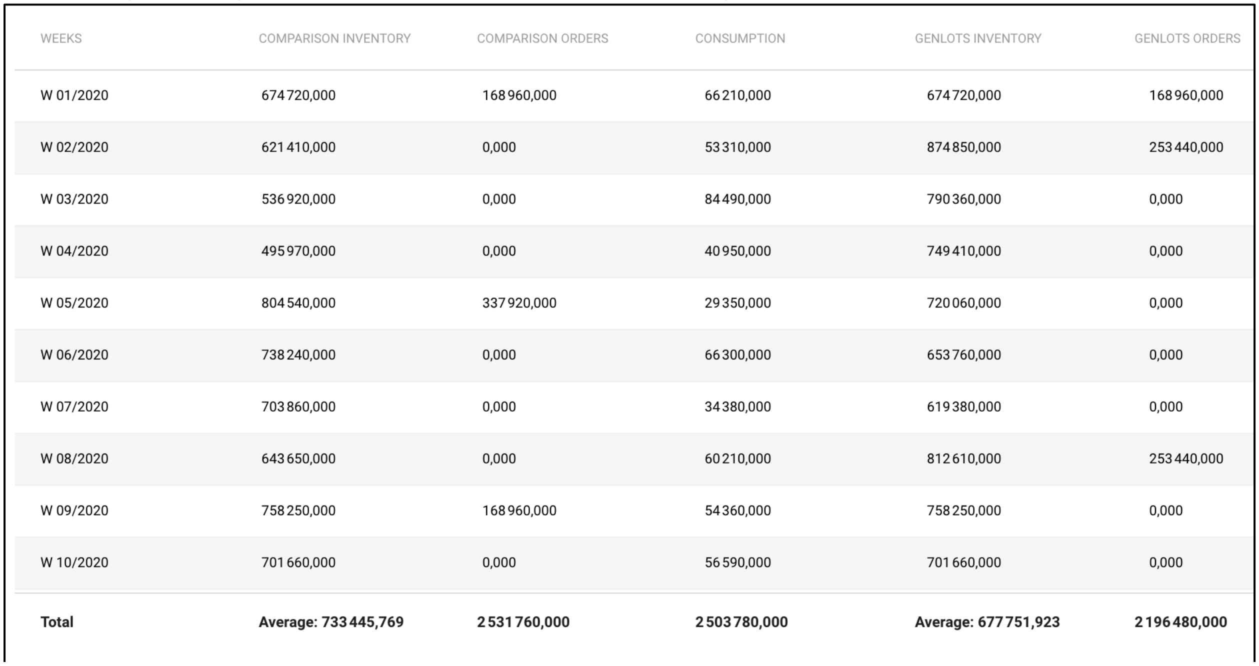
Show in Map

Country specific distance [km]
Hong Kong: 10.95
International: 14,634.77
Italy: 254.34
Switzerland: 112.71

C. Case Study Data and Results

C-1. Material X Consumption, Ordering, and Inventory Data

Units = kg. Average Comparison Order Size = 42,308 kg = 42.31 tonnes

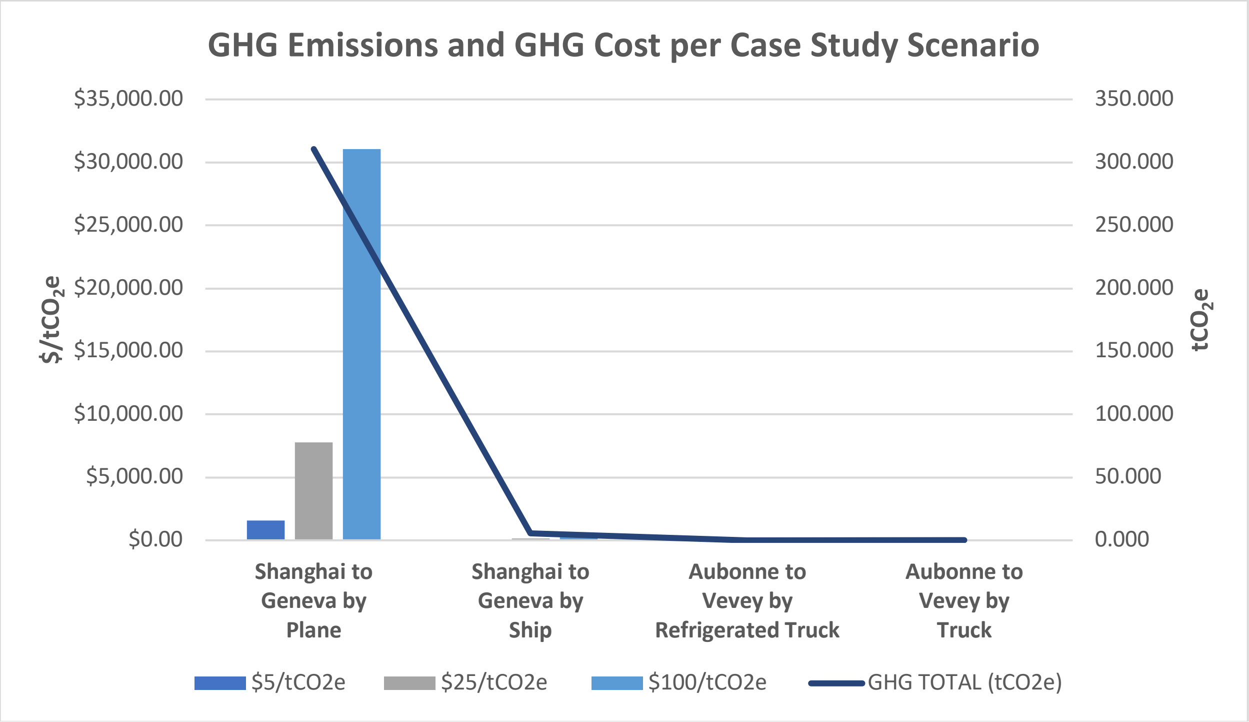


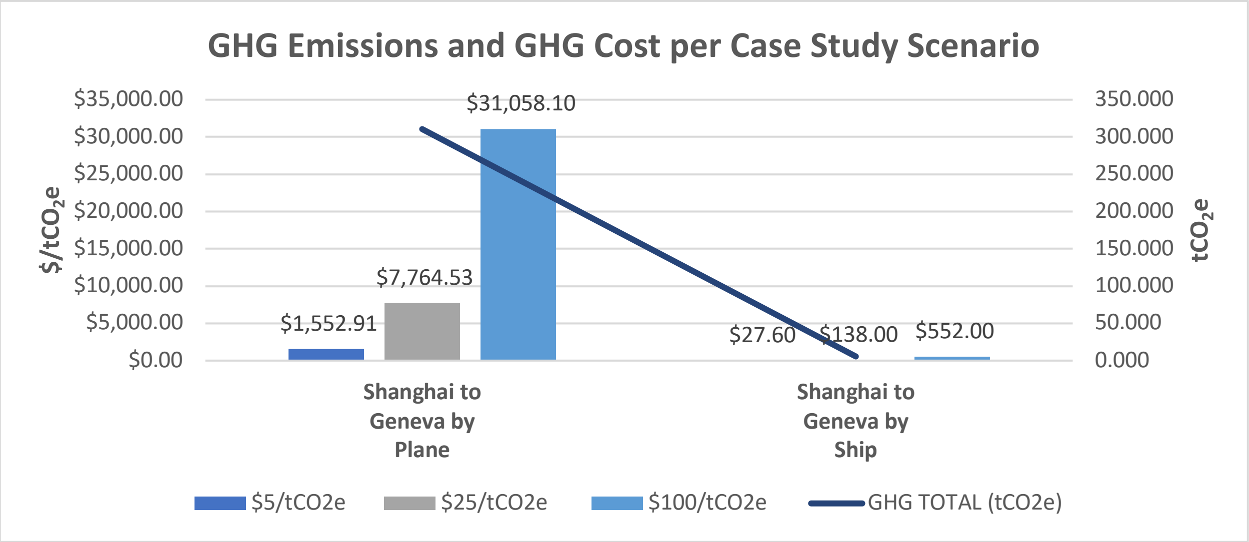
WEEKS	COMPARISON INVENTORY	COMPARISON ORDERS	CONSUMPTION	GENLOTS INVENTORY	GENLOTS ORDERS
W 01/2020	674 720,000	168 960,000	66 210,000	674 720,000	168 960,000
W 02/2020	621 410,000	0,000	53 310,000	874 850,000	253 440,000
W 03/2020	536 920,000	0,000	84 490,000	790 360,000	0,000
W 04/2020	495 970,000	0,000	40 950,000	749 410,000	0,000
W 05/2020	804 540,000	337 920,000	29 350,000	720 060,000	0,000
W 06/2020	738 240,000	0,000	66 300,000	653 760,000	0,000
W 07/2020	703 860,000	0,000	34 380,000	619 380,000	0,000
W 08/2020	643 650,000	0,000	60 210,000	812 610,000	253 440,000
W 09/2020	758 250,000	168 960,000	54 360,000	758 250,000	0,000
W 10/2020	701 660,000	0,000	56 590,000	701 660,000	0,000
Total	**Average: 733 445,769**	**2 531 760,000**	**2 503 780,000**	**Average: 677 751,923**	**2 196 480,000**

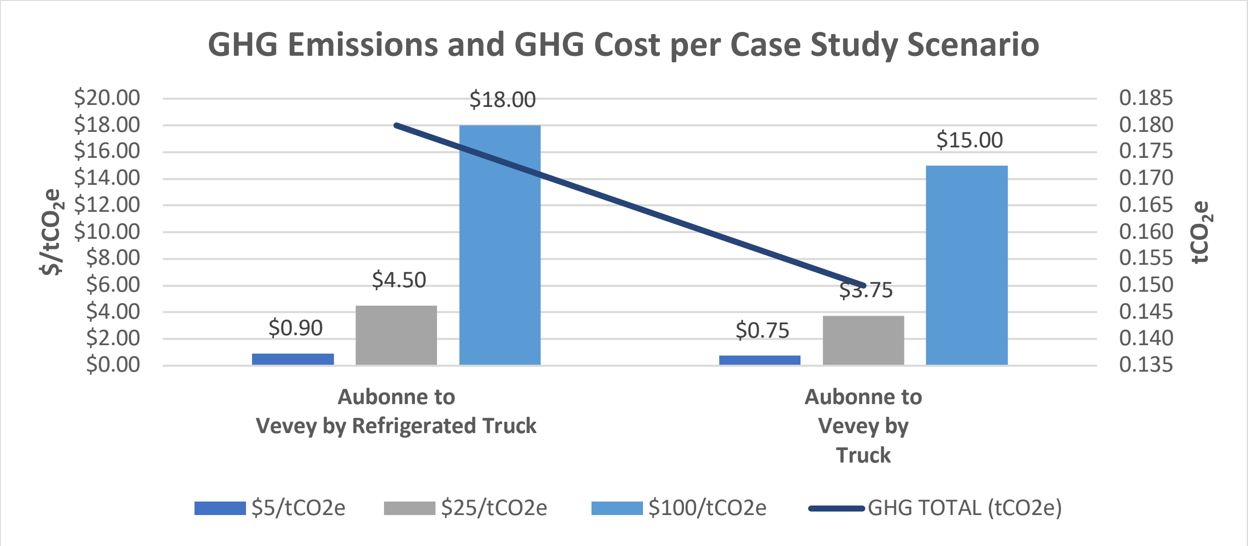
C-2. Material X Transportation Well-to-Wheel GHG Emission Results from EcoTransIT World for TCO Computation

Avg Comparison Order Size (tonnes)	42.31			
Origin Destination Mode of Transport	Shanghai to Geneva by Plane	Shanghai to Geneva by Ship	Aubonne to Vevey by Refrigerated Truck	Aubonne to Vevey by Truck
Distance Plane (km)	9,324	-	-	-
Distance Ship (km)	-	16,061	-	-
Distance Truck (km)	31	384	48	48
DISTANCE TOTAL	9,355	16,445	48	48
Energy Consumption Plane (Megajoule)	4,200,258	-	-	-
Energy Consumption Ship (Megajoule)	-	55,669	-	-
Energy Consumption Truck (Megajoule)	1,353	16,790	2,458	2,036
ENERGY CONSUMPTION TOTAL (Megajoule)	4,201,611	72,459	2,458	2,036
Sulfur dioxide Plane (kg)	176.089	-	-	-
Sulfur dioxide Ship (kg)	-	61.530	-	-
Sulfur dioxide Truck (kg)	0.036	0.420	0.064	0.053
SULFUR DIOXIDE TOTAL (kg)	176.125	61.950	0.064	0.053
GHG Plane (tCO2e)	310.483	-	-	-
GHG Ship (tCO2e)	-	4.320	-	-
GHG Truck (tCO2e)	0.098	1.200	0.180	0.150
GHG TOTAL (tCO2e)	310.581	5.520	0.180	0.150
GHG Emissions / Km	0.0333	0.000269	0.0038	0.0031
GHG Emissions / Tonne	7.3406	0.1305	0.0043	0.0035

Carbon Price	Order Cost Change			
$ 5.00	$ 1,552.91	$ 27.60	$ 0.90	$ 0.75
$ 25.00	$ 7,764.53	$ 138.00	$ 4.50	$ 3.75
$ 100.00	$ 31,058.10	$ 552.00	$ 18.00	$ 15.00







C-3. Material X Warehousing GHG Emissions Results for TCO Computation

Products per $100	35.21	**Current carrying cost per $100**	$16.50

Emissions Factor (from Appendix A-3)	**GHG Emissions per $100 (tonnes CO2e)**	**GHG Cost per $100**		
		Carbon price		
		$5.00	**$25.00**	**$100.00**
5.4	0.000190141	$0.00095	$0.00475	$0.01901
		16.501%	16.505%	16.519%
11.7	0.000411972	$0.00206	$0.01030	$0.04120
		16.502%	16.510%	16.541%

C-4. Material X Warehousing GHG Emissions and Cost Savings

Avg. Comparison Inventory (tonnes)	195.586
Avg. Inventory with GenLots (tonnes)	163.525
Δ Avg. Inventory (tonnes)	32.061
Δ Avg. Inventory	-16.4%

Inventory GHG Emission Factors (from Appendix A-3)	GHG Emissions Savings (tonnes CO2e)	GHG Cost Savings		
		Carbon price		
		$5.00	$25.00	$100.00
5.4	0.1731294	$0.86565	$4.32824	$17.31294
11.7	0.3751137	$1.87557	$9.37784	$37.51137

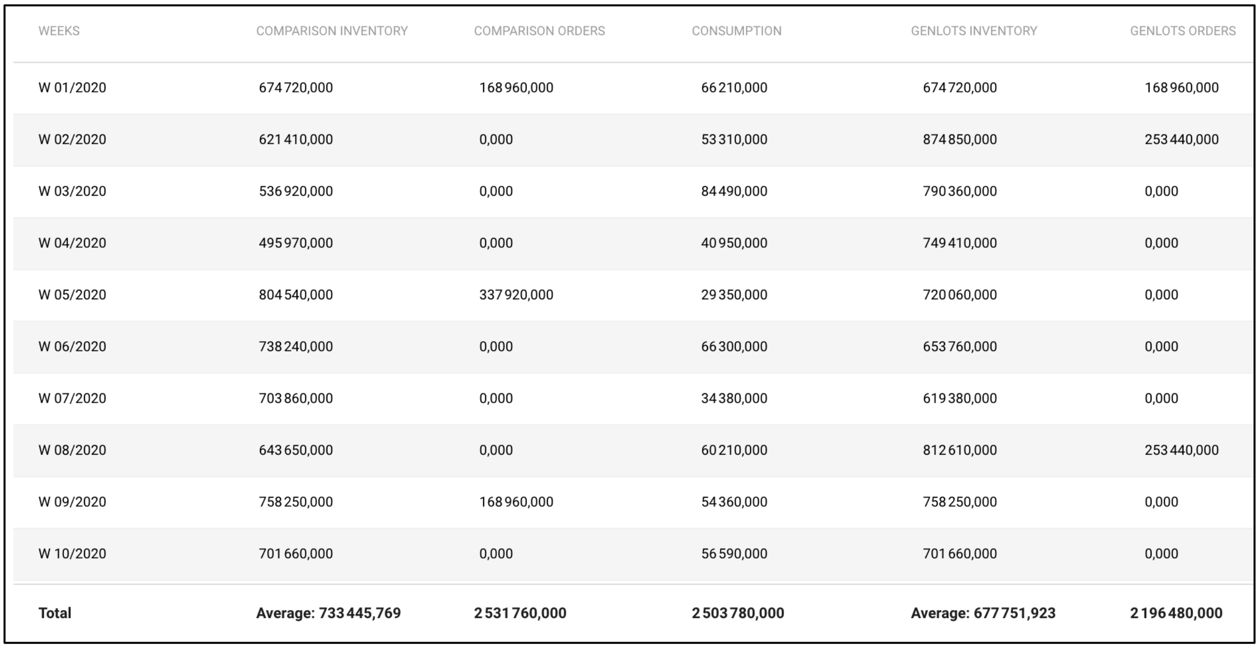
C-5. Material X Scrap GHG Emissions and Cost Savings for

Avoided scrap (tonnes)	79.7
Emissions factor for scrap (E_S) in kg CO_2e/tonne *Assuming commercial and industrial waste landfill*	99.759

Scrap Emissions Savings (tonnes)	**Scrap Emissions Cost Savings**		
	$5.00	**$25.00**	**$100.00**
7.951390854	$39.76	$198.78	$795.14

C-6. Material Y Consumption, Ordering, and Inventory Data

Units = grams. Average Comparison Order Size = 194,551grams = 0.195 tonnes



WEEKS	COMPARISON INVENTORY	COMPARISON ORDERS	CONSUMPTION	GENLOTS INVENTORY	GENLOTS ORDERS
W 01/2020	674 720,000	168 960,000	66 210,000	674 720,000	168 960,000
W 02/2020	621 410,000	0,000	53 310,000	874 850,000	253 440,000
W 03/2020	536 920,000	0,000	84 490,000	790 360,000	0,000
W 04/2020	495 970,000	0,000	40 950,000	749 410,000	0,000
W 05/2020	804 540,000	337 920,000	29 350,000	720 060,000	0,000
W 06/2020	738 240,000	0,000	66 300,000	653 760,000	0,000
W 07/2020	703 860,000	0,000	34 380,000	619 380,000	0,000
W 08/2020	643 650,000	0,000	60 210,000	812 610,000	253 440,000
W 09/2020	758 250,000	168 960,000	54 360,000	758 250,000	0,000
W 10/2020	701 660,000	0,000	56 590,000	701 660,000	0,000
Total	**Average: 733 445,769**	**2 531 760,000**	**2 503 780,000**	**Average: 677 751,923**	**2 196 480,000**

C-7. Material Y Transportation Well-to-Wheel GHG Emissions Results from EcoTransIT World for TCO Computation

Avg Comparison Order Size (tonnes)	0.195

ORIGIN DESTINATION MODE OF TRANSPORT	Shanghai to Geneva by Plane	Shanghai to Geneva by Ship	Aubonne to Vevey by Refrigerated Truck	Aubonne to Vevey by Truck
GHG Plane (tCO2e)	1.4310	-	-	-
GHG Ship (tCO2e)	-	0.0199	-	-
GHG Truck (tCO2e)	0.0005	0.0055	0.0009	0.0007
GHG TOTAL (tCO2e)	1.4314	0.0254	0.0009	0.0007

Carbon Price	Order Cost Change			
$5.00	$7.16	$0.13	$0.00	$0.00
$25.00	$35.79	$0.64	$0.02	$0.02
$100.00	$143.14	$2.54	$0.07	$0.09