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CO_2 emissions mitigation potential of buyer consolidation and rail-based intermodal transport in the China-Europe container supply chains

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ABSTACT

Freight transport is an increasingly important contributor to global warming. With the projected development of international trade, finding the most energy efficient ways of service intercontinental trades is a key challenge. China-Europe containerized trades are among the most important in this setting. The typical structure of the supply chains associated with this trade is that containers are stuffed in China and then cargos are subsequently cross-docked at major European logistics hubs or distribution centers in the destination countries for further road transport to the final retailing points. This solution may not be optimal from an environmental perspective. To pursue an increasingly sustainable supply chain solution, early movers in the market have adopted an alternative solution that is characterized by upstream buyer consolidation and downstream rail-based intermodal transport. This paper develops a set of mathematical models for analyzing the environmental saving potential of such alternative solutions, encompassing relevant energy use and energy mix data of all the legs and nodes in the supply chains. The empirical analysis is based on a case obtained from a Swedish retailer with a chain of retailing points in Scandinavia and Poland. From an activity-based approach, our findings suggest that upstream buyer consolidation may facilitate the integration of rail and road transport in the destination country, increase container utilization, replace 20-foot containers by 40-foot containers and eliminate the extra de-/re-consolidation activity in the traditional solution, thereby reducing CO_2 emissions of the supply chain. This, more efficient supply chain solution, may facilitate a modal shift in the downstream part of the supply chains, which may be attractive to logistics providers, retailers and customers in search of ways of curbing CO_2 emissions. The models and analytical framework developed may also be used by practitioners and researchers for analyzing other alternative supply chain designs.

1. Introduction

Based on data of U.S. National Oceanic and Atmospheric Administration (NOAA), the 2017 average global surface temperature across land and ocean areas was 0.84 °C above the 20th century average of 13.9 °C (NOAA, 2018). This small change in temperature seems unlikely to influence our life largely. However, during the past three decades (from 1988 to 2017), approximately 2.7 million square kilometer of Arctic sea ice has vanished (NASA, 2017a), which is an area more than two times larger than the size of Norway, Sweden, Finland and Denmark. In terms of land ice, Greenland has been losing 286 ± 21 Gigatonnes (Gt) of ice mass per year since 2002 (NASA, 2017b). In order to tackle this problem, a 2 °C global temperature target has become a consensus of the international community, especially after it was adopted by the European Union's Council of Ministers in 1996, the L'Aquila (Italy) G8 Summit in 2009, the Copenhagen Climate Change Conference in 2009 and the Cancún Climate Change Conference in 2010 (Gao et al., 2017). In addition, a recent UN structured expert dialogue of more than 70 experts concluded that the conventional 2 °C safe limit seems inadequate. A tougher warming limit of 1.5 °C above pre-industrial levels should be further investigated (UNFCCC, 2015). Based on this, parties to the Paris Agreement agree to pursue efforts to meet this new 1.5 °C target (UN, 2015).

With the development of international trade, freight transport has become an increasingly important polluter and contributor to

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global warming. Most vehicles for freight transport, like trucks, container ships and airplanes rely on fossil energy to operate, which leads to air pollution and global warming. The transport sector produced around 23% of total energy-related CO_2 emissions in 2010 globally, which was equal to approximately 7.0 Gt CO_2e of direct GHG emissions (IPCC, 2015). Facilitating a modal shift from road to rail and/or short-sea shipping has received a lot of attention. Woodburn and Whiteing (2010) suggested shifting cargo from road to rail as one of the most effective strategies for reducing CO_2 emissions from the freight transport sector. The results of Brain Trains project (Merchan Arribas et al., 2018) shows electric trains or diesel trains may reduce environmental impact by 32% and 3% respectively compared with road transport with a 50% of load factor. The electricity supply mix plays an important role in the environmental impact of electric trains. In their research, German electricity is considered, approximately 50% of which is generated from fossil fuels.

New supply chain designs that might facilitate modal shift or enhanced utilization rates of containers might be a significant contributor to emissions mitigation. These new designs have recently been highlighted by, for example, Lin et al., 2016 who identified a set of new alternative solutions characterized by upstream buyer consolidation activity and downstream intermodal logistics. The findings suggest that buyer consolidation might facilitate the integration of shortsea and rail with road transport in the destination country. Buyer consolidation is an activity provided by logistics service providers (LSP) at a container freight station (CFS) in origin country in order to consolidate cargo belonging to one buyer from multiple suppliers. This service actually turns multiple less than full container load (LCL) shipments into full container load (FCL) shipments in order to reduce downstream activities, e.g. de-/re-consolidation. De-/re-consolidation activities at the LSP's warehouse in the destination country are inevitable if one shipper transports cargo as LCL shipments because each container after commercial consolidation contains cargo belonging to multiple consignees.

Further, Lin et al., 2017 finds that such new alternative supply chain solutions may have cost advantages versus the business-as-usual (BAU) solution, where containers are stuffed at the location of manufacturing in the origin country and subsequently cross-docked at major European logistics hubs or DCs in the destination countries for further road transport to the final retailing points. However, to the author's knowledge, few articles can be found in the literature, which quantitatively reveal the environmental impact of buyer consolidation on a supply chain. Therefore, the study presented herein aims to contribute to the literature in this field by answering the following research question:

- To what extent does upstream buyer consolidation influence supply chain emissions?

This paper is structured as follows: Section 2 provides a review of related research, data sources and standards in the field of supply chain CO_2 emissions calculation, which provides the theoretical basis and data sources for this research. Section 3 presents the supply chain configuration of the case company. The analytical methodology is described in Section 4. In Section 5, two hypothetical solutions are developed for a comparative analysis. Based on the supply chain solutions in Section 3 and 5 and models established in Section 4, carbon emissions of the focal solution and the traditional supply chain designs are calculated in Section 6 with detailed analysis. Finally, conclusions are presented in Section 7, along with an assessment of research limitations and suggestions for further research.

2. Supply chain CO_2 emissions and data sources for the research

Liao et al. (2010) and Rodrigues et al. (2015) calculate whether port selection can contribute to mitigation in freight transport related CO_2 emissions. They adopt an activity-based method to calculate CO_2 emissions in the destination country of an international supply chain and set up hypothetical scenarios for a comparative analysis. In addition, there are also many online calculators providing emission data of road and sea cargo transport, some of which developed by LSPs and shipping lines, like DHL and Maersk. The EcoTransit World tool is a much applied online emission calculation tools with a well-documented and transparent academic background (Heidelberg et al., 2016). EcoTransIT provides a comprehensive report for each calculation, illustrating the energy consumption and GHG emissions in each leg from origin to destination based on inputted supply chain data. This calculator is based on the European standard EN 16258, and provides both tank-to-wheel (TTW) and well-to-wheel (WTW) emissions of 6 types of gases. However, a drawback of this calculator is that emissions at nodes, like ports and warehouses, are not considered. In addition, there are research projects quantifying energy use and GHG emissions of entire supply chains from manufacturers' gates to end consumers. Browne et al. (2008) compared energy consumption of several supply chains delivering imported and domestic produced cargos and identified that maritime shipping and end consumers' shopping trips contribute the most energy consumption. Rizet et al. (2010) estimated GHG efficiency of several fresh food supply chains with different types of retail systems. Two years later, they (Rizet et al., 2012) found that distance, load factors, retailer type and customer density are the most influencing factors on carbon efficiency. However, as far as the author can tell, few studies have quantified the influence of buyer consolidation on CO_2 emissions of an entire international supply chain. Therefore, this article tries to contribute to the literature of this field.

2.1. Road transport

In order to deliver cargo from one location to another, there are typically empty trips before and/or after a freight transport service. Emissions of these empty trips related to a vehicle operation should be included into the total emissions of this logistic service. EN 16258 (EU, 2012), a methodology for calculating and reporting freight transport related energy consumption and carbon emissions, provides a guide to calculate emissions of empty trips, which is used as a guildline of this research. In addition, this standard also provides TTW (tank-to-wheels) and WTW (well-to-wheels) emission factors for a group of commonly used fuels. The GHG emissions considered in this standard are the same set of emissions considered in the Kyoto Protocol, including carbon dioxide (CO_2), methane (CH4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). However, the data at hand on China side does not allow for covering all greenhouse gas emissions. In order to keep consistency, emission factors provided in EN 16258: 2012 are not used in this current research.

2.2. International deep-sea shipping

The carbon emission model for container ships in this research is adopted from NTM which is originally developed by IMO. NTM (The Network for Transport Measures) is a non-profit organization in Sweden. It collects energy consumption data of different types of vehicles and carbon emission calculation methods relating to freight transport in Sweden and international sea shipping. All data is free to access in their website and continuously updated.

However, with the implementation of slow steaming and super slow steaming policy after 2008, the emission model illustrated in NTM's website is likely to overestimate energy consumption of sea shipping. Nevertheless, a roughly estimation can be made based on the third IMO GHG study (IMO, 2015): In terms of container ships with a capacity between 8,000 TEU and 11,999 TEU, fuel consumption is reduced by 71% due to slow steaming policy, considering that the capacity of container ships operating on the route of Far East - North Europe is 11750 TEU in average based on an OECD research (Merk et al., 2015).

2.3. Cargo-handling at warehouses

In terms of warehouse activities, DAI (2011) investigated energy consumption of passenger and freight stations in different climate zones in China. A similar, but much more thorough, survey for all types of commercial buildings is conducted in the United States regularly by the Energy Information Administration (EIA, 2012). The latest survey was conducted in 2012. Therefore, energy consumption data provided by DAI (2011) is adopted in this research as inputs for warehouse emission calculation in China. Due to the lack of energy consumption data for warehouses in Sweden, data provided by EIA (2012) for warehouses located in a cold zone is used in this research. Based on yr (2018), Gothenburg and Skara (the location of deconsolidation centers), with approximately 6898 and 7648 heating degree days (65 °F basis) respectively, belongs to the cold zone according to the standard offered by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE, 2018).

2.4. Container-handling at ports

Seaports facilitate over 80% of international trade flows (UNCTAD, 2017), which also result in significant emissions. Although the energy consumption and the corresponding cost increase dramatically due to the increased cargo flow, container terminal operators adopt few energy-saving techniques (Wilmsmeier and Spengler, 2016). In order to gain insights of container handling processes and the environmental impact of these processes, Geerlings and Van Duin (2011) presented a method to analyse port related CO_2 emissions based on the Port of Rotterdam. Considering that emissions of same type of cranes and terminal tractors are similar in different seaports, the author adopts data in (Geerlings and Van Duin, 2011) as inputs for emission calculation of container handling activities at seaports.

2.5. Emission factors

Due to the reason discussed in Section 2.1, the emission factors provided in EN 16258 are not used in this research. Therefore, the author calculates emission factors for fossil fuels and electricity generation by himself. *2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume* 2 Energy (IPCC, 2006) not only provides emission factors of commonly used fuels – like EN 16258 does, but also explains the methodology of calculating such emission factors, which is used in this research as guidelines for calculating emission factors. Undoubtedly, trucks and trailers typically use diesel as energy. However, in terms of the energy used by ships, investigations are called for. IMO (2015) identified heavy fuel oil (HFO) occupies 85% of market share worldwide in 2012, due to its lower price (Acomi and Acomi, 2014). Except for direct emissions, indirect emissions of electricity also need to be considered. European Environment Agency (EEA) provided an overview of electricity production, consumption and emission factor calculation method (EEA, 2016). The input data (energy production data) required for emission factor calculation can be obtained from Eurostat (2018). In terms of the China side, the newest emission factor was provided by National Development and Reform Commission (NDRC) based on energy used by power generation in 2012 (NDRC, 2014). Electric power losses is inevitable during the processes of transmission and distribution. The percentage of this loss is variable among countries (THEWORLDBANK, 2014).

The case will be further described in Section 3. Interviews were conducted according to a semi-structured interview guide based on literature review and the main research question. After each interview, the interviewer took the responsibility of transcribing transcripts. For the reason of commercial confidentiality, the names of the respondents and focal companies have been anonymized in this article.

3. Case description

The focal company of this current study is a Swedish retailer with 90 stores in Sweden, Norway and Poland, importing mainly do-it-yourself (DIY) equipment from China. Most of the Chinese suppliers are located along the coast. The ones selected for this study are located in the Shanghai area. The majority of shipments that are consolidated in China are smaller than 1 TEU. The average distance from suppliers to the nearby consolidation center is around 100 km.

Truck is the only mode for intra-China transportation in this case because of short travel distances. However, different types of trucks are used based on the size of each shipment. Shipments are typically delivered to the consolidation center as less than truckload (LTL) shipments when their sizes are smaller than 17.5 cbm. Small trucks are used to collect cargo at the manufacturers, bringing them to a freight station where the cargo is crossdocked onto larger trucks for line haul transport to a hub close to the consolidation center. More detailed information relating to this LTL trucking service is illustrated in Table 1. By contrast, due to the cost of crossdocking, shipments larger than and equal to 17.5 cbm are typically delivered as full truckload (FTL) shipments for a trucking service around 100 km.

This focal company uses 26 consolidation centers in China. Unloading of trucks, buyer consolidation and loading of containers are the main activities conducted in these consolidation centers. After consolidation, 80% of cargo is delivered in 40-foot containers. All consolidated consignments are delivered to the ports of loading (POL) by trailers. Quay cranes, rail-mounted stacking cranes and terminal tractors are used in the Port of Shanghai for container handling.

After the international deep-sea leg, consignments arrive at the Port of Gothenburg in Sweden. This focal company and its LSP use a rail-based intermodal solution to transport cargos from the port of Gothenburg to the central warehouse in Skara. More specifically, containers are transported from the Port of Gothenburg to an intermodal terminal in Falköping by rail (120 km in this leg. Only rail crane is used here.) and thereafter delivered to the 150000 m^2 central DC of the focal company in Skara by trucks (27 km in this leg). Based on the current regulation in Sweden, 25.25 m vehicles are used. This type of trucks can transport one 20-foot container and one 40-foot container simultaneously. All cargos from China along with other cargos from other regions are distributed from this DC to all stores located in Norway, Sweden and Poland. This supply chain is briefly illustrated in Fig. 1 .[1]

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[1] A detailed description: see Lin et al., 2016.

Table 1
Logistics solution for LTL shipments in leg 1.

	Distance	Types of trucks	Average shipment volume	Percentage of empty trips
Pre-haulage	10 km	10 cbm	6 cbm	45%
		15 cbm	11 cbm	
		20 cbm	16 cbm	
Line haul	80 km	60 cbm	54 cbm	0%
Post-haulage	10 km	15 cbm	12 cbm	35%
		20 cbm	17 cbm	
		30 cbm	24 cbm	

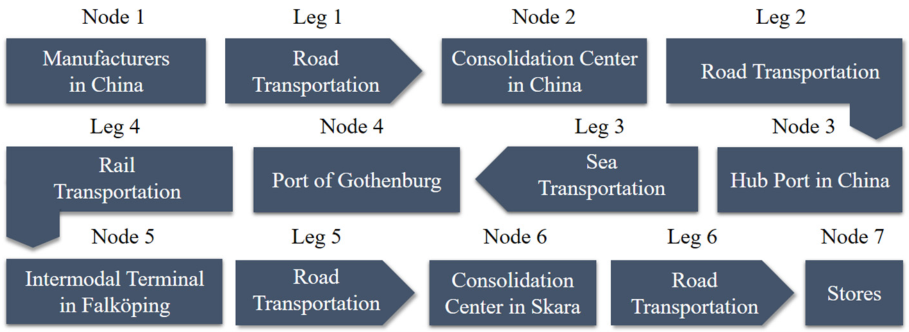

Fig. 1. Supply chain solution of the focal company.

4. Methodology

The new alternative solution characterized by upstream buyer consolidation and downstream intermodal rail-road transport (IRT) system may have a cost advantage versus a business-as-usual (BAU) solution (Lin 2016). This paper aims to illustrate whether the new alternative supply chain solution also outperforms the BAU solutions in terms of carbon emissions.

The choice of research methods should depend on the research question proposed in Section 1. Yin (2014) stated that the more questions seek to explain present circumstances, the more case study research will be relevant. In addition, case study is also relevant to research questions that require an extensive and in-depth description of a phenomenon. Therefore, case study is chosen as the research method of this research project.

It is worth noting that when the author approach candidates for interviews, they are allowed to decide entirely for themselves whether or not they want to participate in an interview, which may lead to self-selection bias. In most cases, self-selection will lead to biased data, because the respondents who are willing to participate will not well represent the entire target population (Lavrakas, 2008). However, the purpose of this project is not to test the possibility of successful implementation in terms of the new solutions. The purpose is to identify the successful examples in the market in order to evaluate the potential benefits brought from the new solution. That is to say, self-selection may not influence the findings of this project.

4.1. Three steps of CO_2 emission comparison

This section provides the methodology for this research: a comparative analysis. Step 1 refers to Section 5 and Section 6 deals with Step 2 and 3.

Step 1: set up two hypothetical scenarios. In order to illustrate the carbon mitigation potential of buyer consolidation and rail-based intermodal transport, the author sets up two hypothetical scenarios for comparison in this research: Hypothetical Solution 1 (HS - LCL) is developed based on the typical BAU solution when a shipment size is smaller than the breakeven shipment volume (BSV). While Hypothetical Solution 2 (HS - FCL) is designed according to the typical BAU solution for shipments larger than BSV. BSV in this case is 17.5 cubic meters. Notably, BSV is not a constant. It changes from case to case and especially sensitive to the sea freight rate.

Step 2: Calculate CO_2 emissions of the factual solution and hypothetical solutions. CO_2 emissions of each solution are calculated based on emission models developed in Section 4.3 and default data illustrated in Section 4.4.

Step 3: Compare CO_2 emissions of different solutions and present findings. CO_2 emissions of each leg and node is compared between the new solution and hypothetical solutions and the reasons why there are differences between these solutions will be discussed in detail.

4.2. Scope of the research

Ideally, such a study should consider all greenhouse gas emissions. However, the data at hand does not allow for covering all greenhouse gas emissions, neither the application of a well-to-wheel principle. These calculations therefore only cover CO_2 emissions from a tank-to-wheel perspective. Besides, in order to simplify this analysis, a typical shipment via the port of Shanghai is selected in this study as an example to demonstrate the carbon mitigation potential of upstream buyer consolidation and the downstream rail-based intermodal solution. The hypothetical solutions are assumed to be no different to the factual solution regarding the use of truck types and handling equipment.

4.3. Emission calculation models

A supply chain emission estimation framework is proposed in this section. The overall model and the models for road transport, sea transport, rail transport, warehouse operations and terminal operations are provided.

4.3.1. Supply chain emissions

Total CO_2 emissions per TEU of cargo (TCE) of a supply chain is the sum of CO_2 emissions per TEU from all m legs and n nodes, i = 1, …, m; j = 1, …, n. For consolidated shipments, carbon emissions per TEU of cargo in one leg (CL_i) is the weighted average of emissions of delivering one 20-foot container ($CL_{i-20foot}$) and one 40-foot container ($CL_{i-40foot}$) according to the percentage of cargo transported in 40-foot containers (ρ_{40foot}). Carbon emissions for handling one TEU of cargo at a node (CN_j) can be calculated in a similar way based on formula (3). In terms of FCL shipments in 20-foot containers, one container may carry any type of cargo larger than 17.5 cbm. Lower container utilization in FCL solution means lower cargo weight per container and lower $CL_{i-20foot}$ and $CN_{j-20foot}$. In order to make findings comparable between solutions, $CL_{i-20foot}$ and $CN_{j-20foot}$ can be converted to CL_i and CN_j according to formula (4) and (5). $Capacity_{40foot-max}$ denotes the maximum capacity of one 40-foot container, assumed equal to 60 cbm in this research. The denominator, $Capacity_{20foot-real}$, denotes the real cargo volume inside a container for each shipment. CO_2 emissions from a group of trucks during the first leg derived from formula (12) can also be converted to CO_2 emissions per TEU of cargo (CL_i) based on formula (4). In addition, $CL_{i-20foot}$ and $CL_{i-40foot}$ can be calculated based on formula (6). $CN_{j-20foot}$ and $CN_{j-40foot}$ can be derived based on formula (7). Carbon emissions per container in a leg ($CL_{i-container}$) is the product of the energy consumption in leg i per container ($EL_{i-container}$) and the corresponding emission factor (F_k). There are typically more than one type of equipment in a node (warehouse, port or inland terminal) consuming different types of energy and emitting CO_2 directly or indirectly. Energy type k consumed for one container of cargo at a node j denotes as $EN_{j-k-container}$, k = 1, …, o. Therefore, the total emissions per container of cargo at a node j ($CN_{j-container}$) is the sum of the product of $EN_{j-k-container}$ and the corresponding emission factor (F_k).

$$TCE = \sum_{i=1}^{m} CL_i + \sum_{j=1}^{n} CN_j \tag{1}$$

Where:

$$CL_i = CL_{i-20foot} \times \left(1 - \rho_{40foot}\right) + CL_{i-40foot} \Big/ 2 \times \rho_{40foot} \tag{2}$$

$$CN_j = CN_{j-20foot} \times \left(1 - \rho_{40foot}\right) + CN_{j-40foot} \Big/ 2 \times \rho_{40foot} \tag{3}$$

$$CL_i = \frac{1}{2} \times CL_{i-20foot} \times \frac{Capacity_{40foot-max}}{Capacity_{20foot-real}} \tag{4}$$

$$CN_j = \frac{1}{2} \times CN_{j-20foot} \times \frac{Capacity_{40foot-max}}{Capacity_{20foot-real}} \tag{5}$$

$$CL_{i-container} = EL_{i-container} \times F_k \tag{6}$$

$$CN_{j-container} = \sum_{k=1}^{o} EN_{j-k-container} \times F_k \tag{7}$$

4.3.2. Energy consumption by trucks

Energy consumption by a truck during a leg (EL_{Road}) is the energy consumption of a round trip: the sum of energy consumed by this truck to deliver cargo (EL_{Road-A}) and the energy used during empty trips. (EL_{Road-B}). The latter includes the energy consumed on the way to collect cargo before cargo transportation and the energy used on the way back, which can be estimated according to truck's energy consumption per km during empty trips ($eL_{Road-empty}$) and total travel distance of related empty trips in km ($D_{truck-empty}$). When delivering cargo, truck's capacity is typically not 100% used. The real energy consumption of a truck (EL_{Road-A} in Formula 9) is determined by the truck's energy consumption per km in full load ($eL_{Road-full}$), truck's energy consumption per km during empty trips ($eL_{Road-empty}$), the actual capacity utilization in terms of weight (LCU_{truck}) and travel distance (D_{truck}). This formula is adopted from NTM (2015b). The actual capacity utilization is the quotient of the gross cargo physical weight ($Weight_{gross}$) and the max weight capacity ($capacity_{weight}$). When cargo is delivered by box trucks, $Weight_{gross}$ equals to total cargo weight ($Weight_{cargo}$). If cargo is delivered by trailers, $Weight_{gross}$ is the sum of total cargo weight ($Weight_{cargo}$), tare weight of (a) container(s) ($Weight_{container}$) and (a) chassis ($Weight_{chassis}$).

$$EL_{Road} = EL_{Road-A} + EL_{Road-B} \tag{8}$$

Where:

$$EL_{Road-A} = \left(eL_{Road-empty} + \left(eL_{Road-full} - eL_{Road-empty}\right) \times LCU_{truck}\right) \times D_{truck} \tag{9}$$

$$EL_{Road-B} = eL_{Road-empty} \times D_{truck-empty} \tag{10}$$

$$LCU_{truck} = Weight_{gross} / capacity_{weight} \tag{11}$$

If more than one type of trucks are used to deliver cargo in a leg, as the situation of LTL shipments described in Table 1, total energy consumed per TEU in this leg (EL_{Road}) can be estimated based on formula (12). $EL_{Road-prehaul}$ denotes energy consumption by trucks before the line haul transport, which equals to the sum of energy consumption of 10 cbm trucks, 15 cbm trucks and 20 cbm trucks because all trucks are assumed to be used at same probability. $EL_{Road-posthaul}$ can be calculated based on the same way. The energy consumed by each truck can be derived based on formula (8), (9), (10) and (11). $N_{trip-pre}$ denotes the number of trips travelled by each smaller trucks to deliver enough cargo, in order to stuff one line haul truck. $N_{trip-post}$ denotes the number of trips travelled by each smaller trucks to distribute all cargo transported by one line haul truck. $N_{trip-pre}$ and $N_{trip-post}$ can be calculated based on the average shipment volume (ASV) of smaller trucks and the line-haul truck.

$$EL_{Road} = EL_{Road-prehaul} \times N_{trip-pre} + EL_{Road-linehaul} + EL_{Road-posthaul} \times N_{trip-post} \tag{12}$$

Where:

$$EL_{Road-prehaul} = EL_{Road-prehaul-10} + EL_{Road-prehaul-15} + EL_{Road-prehaul-20} \tag{13}$$

$$EL_{Road-posthaul} = EL_{Road-posthaul-15} + EL_{Road-posthaul-20} + EL_{Road-posthaul-30} \tag{14}$$

$$N_{trip-pre} = ASV_{truck-60} / (ASV_{truck-10} + ASV_{truck-15} + ASV_{truck-20}) \tag{15}$$

$$N_{trip-post} = ASV_{truck-60} / (ASV_{truck-15} + ASV_{truck-20} + ASV_{truck-30}) \tag{16}$$

4.3.3. Energy consumption by container ships

The energy consumption model of container ships in this research is adapted from NTM emission calculation models (NTM, 2015a). Energy consumption per container during the sea leg ($EL_{sea-container}$) can be calculated based on the energy consumption factor (eL_{sea} in kg fuel/tonne-km), the total weight of a container including $Weight_{cargo}$ and $Weight_{container}$, travel distance during the sea leg from the Port of Shanghai to the Port of Gothenburg ($D_{container\ ship}$) and the percentage of energy reduction due to slow steaming (ρ_{slow}). In addition, $eL_{sea-dwt}$ denotes the energy consumption of a container ship in kg fuel per dead weight tonnage (dwt) kilometer, which is a function with dwt as the parameter. Constants a and c are derived from a regression analysis based on real energy consumption data of ships conducted by IMO and vary based on different ship types. F_{HFO} denotes emission factor of HFO. $PDR_{container\ ship}$ denotes payload dwt ratio, which is also changes based on ship types. $LCU_{container\ ship}$ represents load capacity utilization of a container ship. IMO also provides default data for these variables.

$$EL_{sea-container} = eL_{sea} \times (Weight_{cargo} + Weight_{container}) \times D_{container\ ship} \times (1 - \rho_{slow}) \tag{17}$$

Where:

$$eL_{sea} = eL_{sea-dwt} \Big/ \left(PDR_{container\ ship} \times LCU_{container\ ship}\right) \tag{18}$$

$$eL_{sea-dwt} = F_{HFO} \times a \times dwt^{-c} \tag{19}$$

4.3.4. Energy consumption by trains

The energy consumption per container during the rail leg ($EL_{Rail-container}$) can be calculated by the energy consumption factor of Swedish electric trains (el_{Rail}), the distance of this leg (D_{Rail}), the average weight of containers ($Weight_{gross}$) and electric power loss during transmission and distribution ($Loss_e$). el_{Rail} can be obtained from Flodén (2007), which gives electricity consumption in kWh by Swedish electric trains per kilometer per tonne.

$$EL_{Rail-container} = el_{Rail} \times D_{Rail} \times Weight_{gross} / (1 - Loss_e) \tag{20}$$

4.3.5. Energy consumption at warehouses

The energy consumption in a warehouse for handling one container typically comprises natural gas consumption ($EN_{Warehouse-gas-container}$) and electricity consumption ($EN_{Warehouse-electricity-container}$). Natural gas consumption in a warehouse per square meter per day is $eN_{Warehouse-gas}$. Electricity consumption in a warehouse per square meter per day is denoted as $eN_{Warehouse-electricity}$. The average stay of a container of cargo from shipping in to shipping out from a warehouse is $AStay_{container}$ days. The average space needed for a container of cargo is $ASpace_{container}$ square meters, which can be estimated by the quotient of the average space actually occupied by a container of cargo ($aspace_{container}$) and space utilization of a warehouse ($U_{warehouse}$). The total gas consumption for a container of cargo in a warehouse ($EN_{Warehouse-gas-container}$) can be estimated by the product of $eN_{Warehouse-gas}$, $AStay_{container}$ and $ASpace_{container}$. The total electricity consumption for a container of cargo in a warehouse ($EN_{Warehouse-electricity-container}$) can be calculated by the same logic. In addition, this research also considers electric power transmission and distribution loss ($Loss_e$).

$$EN_{Warehouse-gas-container} = eN_{Warehouse-gas} \times AStay_{container} \times ASpace_{container} \tag{21}$$

$$EN_{Warehouse-electricity-container} = \left(eN_{Warehouse-electricity} \times AStay_{container} \times ASpace_{container}\right) / (1 - Loss_e) \tag{22}$$

Where:

$$ASpace_{container} = aspace_{container} / U_{warehouse} \tag{23}$$

If raw data of $eN_{Warehouse-gas}$ and $eN_{Warehouse-electricity}$ is given in m^3/tonne-day and kWh/tonne-day, $EN_{Warehouse-gas-container}$ and $EN_{Warehouse-electricity-container}$ can be estimated in a similar way based on formula (24) and (25).

$$EN_{Warehouse-gas-container} = eN_{Warehouse-gas} \times AStay_{container} \times Weight_{cargo} \tag{24}$$

$$EN_{Warehouse-electricity-container} = \left(eN_{Warehouse-electricity} \times AStay_{container} \times Weight_{cargo}\right) / (1 - Loss_e) \tag{25}$$

4.3.6. Energy consumption at seaports and inland terminals

Electricity consumption per lift by equipment l (e.g. rail-mounted stacking cranes or quay cranes) in a port or an inland terminal is $eN_{port/terminal-electricity-lift-l}$, l = 1, …, p. One container is typically handled several times by one equipment (N_{lift-l} times) within a terminal. Diesel consumption per kilometer by equipment l (mainly terminal tractors) in a port or an inland terminal is $eN_{port/terminal-diesel-km-l}$, l = p+1, …, q. The total travel distance by equipment l for moving one container is D_l. Therefore, the electricity ($eN_{port/terminal-electricity-container}$) and diesel ($eN_{port/terminal-diesel-container}$) consumption per container in a port or an inland terminal can be estimated according to formula (29) and (30). In addition, some containers are moved directly from ships to trucks/trains or from trucks to ships for onward transport, while other containers are temporarily stored in a stacking yard. The proportion of containers belonging to the former group is denoted as ρ_{direct}. Therefore, the average electricity ($EN_{port/terminal-electricity-container}$) and diesel ($EN_{port/terminal-diesel-container}$) consumption per container in a port or an inland terminal can be estimated based on formula (26) and (27). Furthermore, the overhead electricity consumption per TEU of cargo can be estimated based on formula (28). $EN_{port/terminal-electricity-container}$e is average electricity consumption in diesel equivalent per container. The proportion of energy consumption for buildings and lightings in a port or an inland terminal is denoted as $\rho_{overhead}$. Energy consumption factors of cranes and

tractors are adopted from Geerlings and Van Duin (2011).
Where:

$$EN_{port/terminal-electricity-container} = eN_{port/terminal-electricity-container-direct} \times \rho_{direct} + eN_{port/terminal-electricity-container-viastack} \times (1 - \rho_{direct}) \quad (26)$$

$$EN_{port/terminal-diesel-container} = eN_{port/terminal-diesel-container-direct} \times \rho_{direct} + eN_{port/terminal-diesel-container-viastack} \times (1 - \rho_{direct}) \quad (27)$$

$$EN_{port/terminal-overhead-TEU} = \left(\left(EN_{port/terminal-electricity-TEU}\mathrm{e} + EN_{port/terminal-diesel-TEU} \right) \Big/ (1 - \rho_{overhead}) \right) \times \rho_{overhead} \quad (28)$$

$$eN_{port/terminal-electricity-container} = \times \left(\sum_{l=1}^{p} eN_{port/terminal-electricity-lift-l} \times N_{lift-l} \right) \Big/ (1 - Loss_e) \quad (29)$$

$$eN_{port/terminal-diesel-container} = \sum_{l=p+1}^{q} eN_{port/terminal-diesel-km-l} \times D_l \quad (30)$$

4.4. Input data

In order to estimate the total CO_2 emissions of a typical shipment for the supply chain of the focal company and the other two hypothetical solutions, the values of all aforementioned variables are needed.

Energy consumption data of trucks are derived from China's Ministry of Transport (MOT, 2017). In order to obtain typical energy consumption data for each type of trucks, 20 different trucks for each type of vehicle are randomly selected. The mathematical mean of each attribute is illustrated in the Table 2 below.

As discussed in Section 4.2, this research only consider TTW CO_2 emissions. However, TTW CO_2 emission factors are difficult to be found in previous researches and standards. That is to say, tank-to-wheels CO_2 emission factors need to be calculated dedicatedly for this research. based on formula provided by IPCC (2006), F_{diesel} is 2.64 kg CO_2/liter. $F_{natrual\ gas}$ is 55.5 kg CO_2/GJ when heat value of one cubic feet of natural gas equals to 1.024 Kbtu. Container ships are assumed to use heavy fuel oil (HFO). F_{HFO} equals to 3.1 kg CO_2/kg fuel.

Indirect emissions of electricity are also considered, based on the emission calculation method provided by European Environment Agency (EEA, 2016) and energy production data provided by (Eurostat, 2018), $F_{electricity}$ in Sweden is 10.47 g CO_2/kWh. In terms of China, the newest emission factors are provided by the National Development and Reform Commission (NDRC) based on energy used for power generation in 2012 (NDRC, 2014). $F_{electricity}$ in Southern China is 703.5 g CO_2/kWh.

5. The description of the two hypothetical solutions for comparison

Based on the methodology presented in Section 4.1, this research starts with setting up two hypothetical solutions for comparison.

5.1. Hypothetical solution one (HS - LCL)

Under the first hypothetical solution, suppliers deliver cargos to a bonded warehouse in Shanghai on road for the commercial consolidation service. The logistics solution in this leg is very similar to the one described in Table 1. The only difference is that, due to location of the bounded area in Shanghai, the distance of post-haulage (8 km) is 2 km shorter than the same leg in the focal case. This bonded warehouse is typically operated by a 3 PL service provider who consolidates these shipments coming from the suppliers of the focal company along with shipments from other shippers. After consolidation, all cargos are transported in 40-foot containers because the author assumes a large-scale consolidator always has enough cargo to stuff 40-foot containers every time, unless heavy weight cargo restricts volume due to weight restrictions. However, the scenario of heavy cargo is not considered in the hypothetical cases to make the factual case and hypothetical cases comparable. Therefore, 40-foot container trailers are used to deliver all LCL shipments to the Port of Shanghai (36 km on road in this leg) and thereafter to the Port of Gothenburg by sea. After consolidated shipments arrive at the Port of Gothenburg, containers are stripped and sorted based on ownership of each consignee in a DC operated by the same LSP nearby. This LSP has a DC only 10 km away from the Port of Gothenburg, which is selected

Table 2
Energy consumption data of trucks.

Truck	Capacity		Fuel consumption		
	$capacity_{weight}$	Unit	$eL_{Road-full}$	$eL_{Road-empty}$	unit
10 cbm	1.9	tonne	12.3	7.4	L/100 km
15 cbm	2.7	tonne	13.7	7.9	L/100 km
20 cbm	3.5	tonne	16.2	8.8	L/100 km
30 cbm	6.8	tonne	22.5	11.1	L/100 km
60 cbm	15.7	tonne	31.8	17.6	L/100 km
Trailer in both countries	29.5	tonne	41.0	16.0	L/100 km

For reference, details of the input data and applied sources are presented in Table 3, Table 4, Table 5 and Table 6.

Table 3
Energy consumption data of container ships.

No.	Variables	Value	Unit	Reference
1	$D_{container\ ship}$	20305.8	km	(ECOTRANSIT, 2016)
2	$PDR_{container\ ship}$	0.8	n/a	NTM (2015e)
3	$LCU_{container\ ship}$	0.7	n/a	NTM (2015d)
4	a	0.05595	n/a	Adapted from (NTM, 2015c)
5	dwt	160000	tonne	Adapted from (MaritimeConnector, 2018)
6	c	0.201	n/a	NTM (2015c)
7	ρ_{slow}	71%	n/a	IMO (2015)

Table 4
Energy consumption data of warehouse activities.

No.	Variables	Value	Unit	Reference
1	$eN_{Warehouse-gas}$ in Sweden	27.1	cubic feet/square foot	EIA (2012)
2	$AStay_{container}$ in China	7	days	Case specific data
3	$AStay_{container}$ in Sweden	2	days	Case specific data
4	$eN_{Warehouse-electricity}$ in China	422.3	kWh/tonne-year	Adapted from Dai (2011)
5	$eN_{Warehouse-electricity}$ in Sweden	61.4	kWh/m^2-year	Adapted from EIA (2012)
6	$aspace_{container}$ for 40-foot container in Sweden	28.3	m^2	Case specific data
7	$U_{warehouse}$ for both countries	70%	n/a	Case specific data

Table 5
Energy consumption data of seaport and inland terminal activities.

No.	Variables	Value	Unit	Reference
1	ρ_{direct}	33%	n/a	Rodrigues et al. (2015)
2	$\rho_{overhead}$	6%	n/a	Wilmsmeier and Spengler (2016)
3	$eN_{port/terminal-electricity-lift-l}$ of quay cranes (QC)	6	kWh/lift	Geerlings and Van Duin (2011)
4	$eN_{port/terminal-electricity-lift-l}$ of rail cranes (RC)	5	kWh/lift	Geerlings and Van Duin (2011)
5	$eN_{port/terminal-electricity-lift-l}$ of rail-mounted stacking cranes (RSC)	7.25	kWh/lift	Geerlings and Van Duin (2011)
6	N_{lift-l} of QC at both ports for both scenarios of direct transport and via stacking area	1	time	Rodrigues et al. (2015)
7	N_{lift-l} of RC at POD both scenarios	1	time	Rodrigues et al. (2015)
8	N_{lift-l} of RSC at POL for scenarios of direct transport	1	time	Rodrigues et al. (2015)
9	N_{lift-l} of RSC at POL for scenarios of via stacking area	7	time	Rodrigues et al. (2015)
10	N_{lift-l} of RSC at POD for scenarios of direct transport	3	time	Rodrigues et al. (2015)
11	N_{lift-l} of RSC at POD for scenarios of via stacking area	6	time	Rodrigues et al. (2015)
12	N_{lift-l} of RC at inland terminal	1	time	Case specific data
13	$eN_{port/terminal-diesel-km-l}$ of terminal tractors (TT)	4	Liter/km	Geerlings and Van Duin (2011)
14	D_l of TT at POL from gate to stacking area	1.2	km	Estimated based on Google Map
15	D_l of TT at POL from stacking area to berth	0.5	km	Estimated based on Google Map
16	D_l of TT at POL from gate directly to berth	1.4	km	Estimated based on Google Map
17	D_l of TT at POD from berth to stacking area	0.3	km	Estimated based on Google Map
18	D_l of TT at POD from stacking area to train	3	km	Estimated based on Google Map
19	D_l of TT at POD from berth directly to train	3.2	km	Estimated based on Google Map

Table 6
Other default data.

No.	Variables	Value	Unit	Reference
1	$Weight_{cargo}$ per cbm	138	kg	Case specific data
2	$Weight_{container}$ for 20-foot container	2300	kg	DSV (2017)
3	$Weight_{container}$ for 40-foot container	3750	kg	DSV (2017)
4	$Weight_{chassis}$ for both 20 and 40 foot	2954	kg	MSC (2018)
5	eL_{Train}	0.0205	kWh/tonne-km	(Flodén, 2007)
6	$Loss_e$ in China	5.47%	n/a	(TheWorldBank, 2014)
7	$Loss_e$ in Sweden	4.78%	n/a	(TheWorldBank, 2014)

in this hypothetical solution. After de-/re-consolidation activities at the destination country, reconsolidated cargo will be delivered to the focal company's DC in Skara for final distribution (124 km in this leg). Only the focal company's cargo is transported in this leg after reconsolidation. Therefore, the number and type of containers should be same as those in the focal solution in the same leg (Leg 5), namely 80% of cargo is transported in 40-foot containers, others in 20-foot containers. See Fig. 2. Trucking is the best solution in this leg. This is because after sorting and stuffing containers based on each consignee, containers have to be transported to a rail terminal if rail-based intermodal solution is chosen in this leg. However, the extra pre-haulage and the container handling activity in the terminal will dramatically weaken the cost competitiveness of such an intermodal solution.

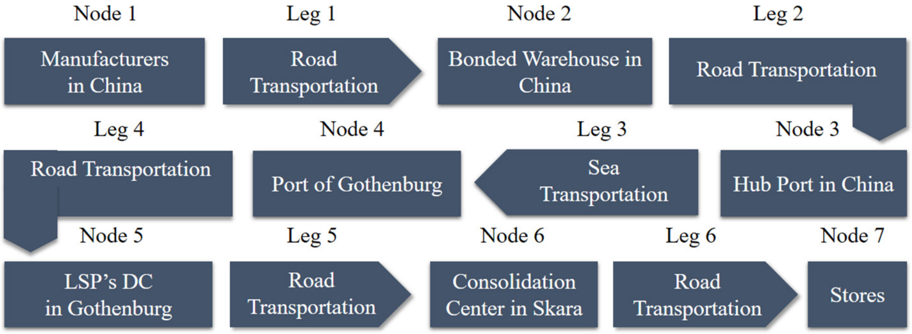

Fig. 2. The hypothetical solution one for LCL shipments.

5.2. *Hypothetical solution two (HS - FCL)*

Under the second hypothetical solution, suppliers deliver cargo in 20-foot containers directly to the Port of Shanghai by trailers from the places of manufacturing. The percentage of empty trips in this leg is around 20% on average. These containers will thereafter be transported to the Port of Gothenburg via the international deep-sea shipping. After containers arrive at the POD, the focal company can also transport its containers by rail-based intermodal transport system to its consolidation center in Skara for the final distribution. See the Fig. 3. The solution adopted in HS - FCL is very similar to the focal solution during the leg from POL to node 6 (consolidation center in Skara). The only difference is that 20-foot containers are exclusively used in this hypothetical solution.

6. Modal application and analysis

This section applies the carbon emission estimation models developed in Section 4 to the case study. The purpose is to identify the (dis)advantages of the new solution against the traditional solutions in terms of CO_2 emission mitigation.

6.1. *Emission mitigation potential of the new alternative solution compared with HS - LCL*

Based on the aforementioned CO_2 emission models, the differentials of CO_2 emissions in each leg and node per TEU between the focal supply chain solution and HS - LCL are illustrated in Table 7 and Fig. 4. It is worth noting that 80% of the cargo is transported in 40-foot containers in the focal solution, which means 29.8 cbm of cargo per TEU on average. By contrast, only 40-foot containers are used in HS - LCL except for leg 5, meaning 30 cbm of cargo per TEU. Therefore, all emission results of HS - LCL except for leg 5 are multiplied by $\frac{29.8}{30}$ for adjustment.

Table 7
Emissions in each leg and node of the focal solution and HS - LCL, kg CO_2/TEU.

	Focal Solution	HS - LCL	Differentials
Leg 1	49.17	47.58	−1.59
Node 2	24.77	24.77	0
Leg 2	25.97	21.13	−4.84
Node 3	32.06	27.03	−5.03
Subtotal – China	131.98	120.51	−11.47
Leg 3 – Sea leg	1000.26	984.20	−16.06
Node 4	21.10	17.48	−3.62
Leg 4	0.16	5.87	5.71
Node 5	0.04	2.00	1.96
Leg 5	14.23	52.83	38.60
Subtotal - Sweden	35.53	78.18	42.65
total	1167.76	1182.89	15.13

A 2 km travelling difference in leg 1 between these two solutions leads to a small difference in emissions. When cargo arrives at Node 2, the result shows that buyer consolidation and commercial consolidation activities generate the same amount of CO_2 emissions under the two solutions because identical cargo is handled and same types of equipment are used. In addition, 20% of the cargo is transported in 20-foot containers under the focal solution after Node 2, meaning that more containers are transported. This means some extra (tare) weight needs to be transported from Node 2 to Node 5, which leads to extra emissions in the focal solution.

After consolidation, cargo is delivered to the Port of Shanghai. Again, 2 km difference in this leg between the solutions leads to a marginal advantage of HS - LCL. CO_2 emissions from transporting 40-foot containers are assumed to be the same between the solutions during the leg from node 3 to node 4. The difference in container types discussed above is the only reason resulting the difference in emissions. The major differences between the focal solution and HS - LCL lie in the leg from the Port of Gothenburg to

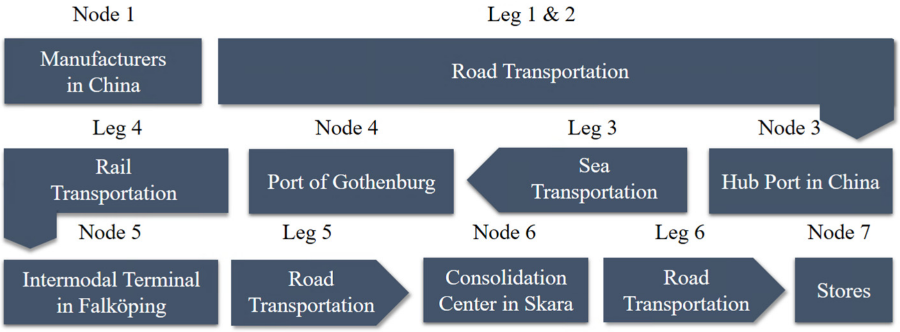

Fig. 3. The hypothetical solution two for FCL shipments.

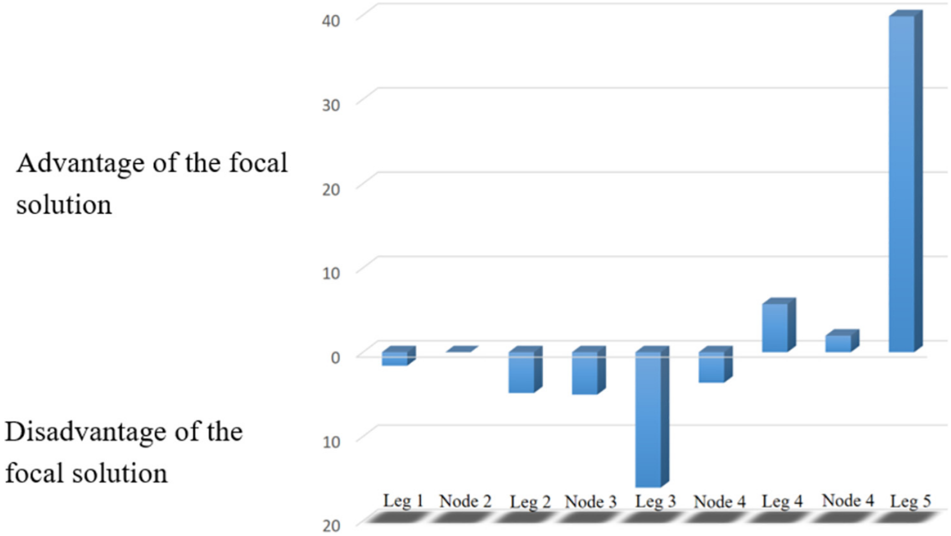

Fig. 4. CO_2 emissions comparison between the focal solution and HS - LCL.

the DC in Skara (Leg 4, Node 5 and Leg 5). More specifically, in the current solution, the focal company uses an intermodal rail-based solution between the port of Gothenburg and their central warehouse in Skara, which is a more cost-saving and environmentally friendly solution. While, in the hypothetical solution, the LSP has to transport containers on road. Different modes lead to large differentials on the destination side.

The calculation result shows that total direct and indirect CO_2 emissions in the Chinese part per TEU of cargo are 131.98 kg and 120.51 kg under the current supply chain solution of the focal company and the HS - LCL respectively. The focal solution generates 11.47 kg CO_2/TEU (9.5%) more than the HS - LCL does. This is because of longer travel distance and the use of 20-foot containers in the focal solution.

Compared with the relatively smaller difference in terms of carbon emissions in the Chinese side of the chain, the major benefits of buyer consolidation and intermodal transport solution occur downstream in the destination country (Sweden in this case). The result shows the total direct and indirect CO_2 emissions in Sweden side per TEU are 35.53 kg and 78.18 kg under the current supply chain solution of the focal company and HS - LCL respectively. This carbon mitigation is mainly due to the rail-based intermodal solution and the eliminated warehouse activities in Gothenburg. More specifically, consolidated shipments after buyer consolidation in China makes the train service in the destination country possible. By contrast, trucking suits cargos shipped as LCL shipments in HS - LCL. In addition, due to the upstream buyer consolidation service in China, the focal company does not need to have their cargos sorted and consolidated in Gothenburg, which makes it possible to save 100% of the emissions at the DC in Gothenburg. In total, 42.65 kg CO_2 emissions per TEU (54.6%) on destination side is reduced due to the buyer consolidation activity at origin.

It is also worth noting that the carbon emissions in Sweden are significantly lower than those in China. This phenomenon can be explained by the following: Firstly, economies of scale in transportation does not exist until the buyer consolidation is conducted in China. Suppliers have to transport LTL cargo to the consolidation center, which leads to high carbon emissions per unit of cargo in China side. The economies of scale due to the consolidation activity reduces the carbon emissions in the following part of this supply chain. Secondly, coal is the primary energy source in China. Thermal power accounts for 72.2% of total electricity generation in 2016 in China (NBS, 2017), which means that indirect carbon emissions per kWh of electricity in China is 67 times higher than that in Sweden.

Overall, the total CO_2 emission mitigation due to upstream buyer consolidation and downstream intermodal rail-based transport solution is estimated at 15.13 kg CO_2 per TEU for shipments smaller than 17.5 cubic meters in this case. However, considering that the total CO_2 emissions of HS - LCL is estimated as around 1182.89 kg CO_2/TEU from the point of manufacture in China to the DC in Skara, the new alternative solution may reduce total CO_2 emissions by a modest 1.3% of the total emissions. Because the sea leg from the Port of Shanghai to the Port of Gothenburg is 20305.8 km based on EcoTransIT online calculator, more than 80% of emissions are generated at sea in both scenarios. More importantly, emissions in China are almost kept at the level of the BAU solution (9.5% increase), but significantly reduced (54.6%) in Sweden.

6.2. Emission mitigation potential of the new alternative solution compared with HS - FCL

When the shipment volume is larger than BSV, cargo owners typically transport cargo by a FCL service under the business-as-

Table 8
Emissions in each leg and node of the focal solution and HS - FCL, kg CO_2/TEU.

	Focal Solution shipment volume (cbm)		HS - FCL shipment volume (cbm)		Differentials shipment volume (cbm)	
	17.5	29	17.5	29	17.5	29
Leg 1	65.95	51.11				
Node 2	24.77	24.77	155.11	98.34	38.42	−3.51
Leg 2	25.97	25.97				
Node 3	32.06	32.06	85.50	52.77	53.44	20.71
subtotal - China	148.75	133.91	240.61	151.11	91.86	17.2
Leg 3 – Sea leg	1000.26	1000.26	1783.64	1080.17	783.38	79.91
Node 4	21.10	21.10	59.75	36.08	38.65	14.98
Leg 4	0.16	0.16	0.29	0.18	0.13	0.01
Node 5	0.04	0.04	0.10	0.06	0.06	0.03
Leg 5	14.23	14.23	20.86	13.57	6.64	−0.65
Subtotal - Sweden	35.53	35.53	81	49.89	45.47	14.36
Total	1184.54	1169.7	2105.25	1281.17	920.71	111.47

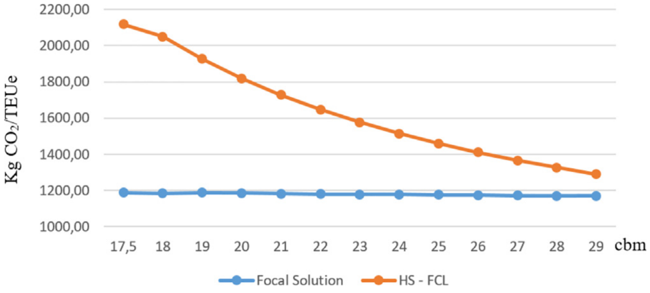

Fig. 5. CO_2 emissions comparison between the focal solution and HS - FCL.

usual solution in order to avoid extra de-/re-consolidation costs in the destination country. In this case, when the shipment volume is larger than 17.5 cubic meters, cargo is transported as FCL shipment in 20-foot containers under HS - FCL. Based on the aforementioned reason, all findings of HS - FCL are multiplied by $\frac{29.8}{30}$ for adjustment. The differentials of CO_2 emissions in each leg and node per TEU between the focal supply chain solution and HS - FCL are illustrated in the Table 8 and Fig. 5.

As can be seen from Table 8, under the focal solution from Node 2 onwards, CO_2 emissions do not change with the increase of shipment volume. This is because buyer consolidation activity increases container utilization. All legs and nodes after consolidation benefit from this service and gain economies of scale. That is to say, CO_2 emissions in each leg and node after buyer consolidation are not influenced by the original shipment volume when cargo departs from the location of manufacturing. The slight decrease in total emissions of the focal solution with the increase of shipment volume is because of LTL transportation during Leg 1. Increased shipment volume per truck means less CO_2 emissions per cbm of cargo. However, as can been see from Fig. 5, the CO_2 emissions per TEUe increase slightly when cargo volume reaches 19 cbm. This is because larger vehicle is used when cargo volume bigger than 18.5 cbm. Because capacity utilization of trucks hardly reaches 100% in practice, practitioners typically transport shipments from 17.5 to 18.5 cbm by 20 cbm trucks and transport shipments larger than 18.5 cbm by 30 cbm trucks. By contrast, CO_2 emissions per TEU of HS - FCL decreases significantly with the increase in shipment size. This is because, without buyer consolidation, smaller container utilization when shipment volume is low means that more containers should be transported in each leg and node in HS - FCL, which makes CO_2 emissions per TEU a sensitive function of shipment volume.

The differences on CO_2 emissions between these two solutions start with the first leg. Compared with container trucks in HS - FCL, smaller trucks adopted in the focal solution increases efficiency. Therefore, the focal solution emits less CO_2 during the first two legs. However, buyer consolidation is an extra activity in the focal solution, which means extra emissions. Even so, the reduced CO_2 emissions due to reduced container handling activities at the Port of Shanghai compensates extra emissions at Node 2 and enables the new solution to have a positive overall environmental impact on the Chinese side. The reason why the new solution yields lower CO_2 emissions can be summarized as increased container utilization and reduced gross weight due to buyer consolidation. Cargo weight is same between the solutions. However, the new solution transport less 20-foot containers than the HS - FCL does, thereby reducing tare weight of containers.

To sum up, the CO_2 emission mitigation potential is estimated in the range from 111.47 kg to 920.71 kg CO_2 per TEU including both direct and indirect emissions, based on the size of each shipment when shipment volume larger than 17.5 cubic meters. In addition, the total CO_2 emissions of HS - FCL is estimated in the range from 1281.17 kg to 2105.25 kg CO_2 per TEU during the leg from the points of manufacture in China to the gate of the DC in Skara. Therefore, the new alternative solution may reduce the CO_2 emissions by from 11.4% to 38.2% in China, by from 28.8% to 56.1% in Sweden and by 8.7%–43.7% in total in terms of shipments bigger than 17.5 cbm based on the case of the focal company.

From the analysis above, a more general conclusion can be inferred: the new alternative solution characterized by upstream buyer consolidation and downstream rail-based intermodal transport may be the most favorable for situations with shipments less than a full container load. This is because compared with commercial consolidation service, buyer consolidation in the origin country enables intermodal transport in the destination country and eliminates extra consolidation activities for each consignee in a warehouse close to POD. Furthermore, compared with the traditional solution of shipping nearly FCL shipments as FCL shipments, buyer consolidation increases container utilization and decreases the total number of transported containers. Reduced activities mean reduced carbon emissions.

In addition, facilitating the integration of road and rail/shortsea transport at destination is one of the main advantages of the new solution. However, if such intermodal transport services are not available downstream or cargo owners decide to use road only transport to gain better performance on lead-time and punctuality, the performance of the solutions characterized by buyer consolidation may be weakened. Under such a situation, based on the focal case, the new solution may increase CO_2 emissions by 11.47 kg per TEU (10%) in China and 16.06 kg per TEU (2%) on the sea and decrease CO_2 emissions by 3.82 kg per TEU (5%) in Sweden. The reason for the increasing CO_2 emissions in the focal solution is that 20% of cargo is transported in 20-foot containers, which generates more traffic flows. The eliminated downstream warehousing activity in the LSP's warehouse makes the new solution reduce some emissions on the Sweden side. In total, the new solution generate 23.71 kg CO_2 per TEU (2%) more compared with the traditional LCL solution does.

When it comes to the shipment volume larger than BSV, if there is no intermodal transport service downstream, based on the focal case, the new solution my reduce CO_2 emissions by from 17.2 kg (11.4%) to 91.9 kg (38.2%) per TEU in China, from 79.9 kg (7.4%) to 783.4 kg (43.9%) per TEU on the sea and from 24.56 kg (24.8%) to 81.97 kg (52.4%) per TEU in Sweden. In total, the new solution reduces CO_2 emissions by from 121.66 (9.1%) to 957.19 kg (43.9%) per TEU. The CO_2 mitigation potential is not changed largely under this situation because the lack of IRT influence both the new and the traditional solutions.

6.3. *Sensitivity analysis*

When considering CO_2 emissions of a supply chain, the traditional factors, like sea freight rate, terminal cost and labor cost differences between origin and destination, do not influence the supply chain performance to a large extent. In this research, the author analyzes the impact of the use of 40-foot containers and/or 20 foot containers after buyer consolidation on supply chain environmental performance. Higher percentage of cargo delivered in 40-foot containers after buyer consolidation activity means better utilization of the new solution. In this section, two sensitivity analyses are conducted in order to illustrate the impact of changes in this percentage on the comparative (dis)advantage of the new solution against the two traditional ones.

In terms of shipment volume smaller than BSV, as can be seen from Table 9, CO_2 emissions of HS − LCL keep constant in this analysis because there is no buyer consolidation service in this

Table 9
Sensitivity analysis, Focal solution vs. HS − LCL, Factor: Percentage of cargo delivered in 40-foot containers, in kg CO_2/TEU.

Percentage of cargo delivered in 40-foot containers after buyer-consolidation	CO_2 emissions of the focal solution	CO_2 emissions of HS - LCL
0%	1251.43	1182.89
10%	1243.85	1182.89
20%	1232.77	1182.89
30%	1221.64	1182.89
40%	1210.46	1182.89
50%	1199.21	1182.89
60%	1187.88	1182.89
65%	1182.18	1182.89
70%	1177.20	1182.89
80%	1167.76	1182.89
90%	1158.05	1182.89
100%	1148.14	1182.89

traditional solution. By contrast, CO_2 emissions per TEU of the new solution decreases with the increasing percentage of cargo delivered in 40-foot containers. In addition, based on this case, at least 65% of cargo delivered in 40-foot containers makes the new solution outperform HS − LCL in terms of environmental impact.

In terms of shipment volume larger than BSV, as can be seen from Table 10, CO_2 emissions of the traditional solution also do not influenced by the variable. While, CO_2 emissions of the new solution decreases with the increase of shipment volume and the percentage of cargo delivered in 40-foot containers. In addition, the new solution always performs better than HS − FCL does. This is because HS − FCL uses 20-foot containers only, which is not efficient and leads to more traffic in the whole supply chain. In addition, delivering shipments of somewhat lower volume than the capacity of a container as FCL shipments reduces container utilization in HS − FCL.

7. Conclusions and implications

7.1. Concluding remarks and implications

This paper develops a group of models for analyzing environmental saving potentials of a new alternative solution. In this paper, the models are applied to a case obtained from a Swedish retailer with a chain of retailing points in Scandinavia and Poland. The findings are that the alternative solution may reduce carbon emissions due to the following two aspects. Firstly, in terms of the small-sized shipments, compared with the traditional commercial consolidation service (LCL/LCL service), the buyer consolidation service (LCL/FCL service) can convert LCL shipments to FCL shipments, thereby avoiding de-/re-consolidation and sorting activities in the destination country. These two activities must be conducted in the traditional solution because every container contains cargos belonging to more than one consignees after commercial consolidation. In addition, the FCL shipments transported by intermodal containers could more easily be transported by a rail-based intermodal solution after arriving at the port of the destination country. Reduced warehouse activities and the possibility of using intermodal solutions in the downstream of the supply chain may lead to reduced lower carbon emissions.

Secondly, shipments of somewhat lower volume than the capacity of a container may often be transported as FCL shipments under the traditional solution to avoid extra activities of re-/deconsolidation and sorting at the destination. However, this traditional solution may lead to lower container utilization and higher traffic. By contrast, without the need of deconsolidation and sorting at the destination, our study illustrates that upstream buyer consolidation may be efficient and environmental friendly even if almost full 20-foot container shipments are converted into 40-foot container FCL shipments in China under certain assumptions. That is to say, buyer consolidation in China may facilitate harvesting economies of scale from most of the legs and nodes of this China-Europe supply chain from the point of buyer consolidation in China to the buyer's DC in Europe. Reduced container volumes may in turn lead to reduced traffic on congested networks in China and Europe and better shipping space utilization on the deep sea legs. This may mean decreased total carbon emissions of the supply chain.

In addition, facilitating the integration of road and rail/shortsea transport at destination is one of the main advantages of the new solution. However, such intermodal transport service may be not always available downstream. The author also quantitatively analyzes the impact of absence of such service on the environmental performance of the new solution.

This research also conducted two sensitivity analyses and illustrate that the use of 40-foot containers plays an important role in CO_2 emissions mitigation. Scattered suppliers restrict the application of the new solution. If all cargo from multiple suppliers in a region is not enough to stuff a 40-foot container, the benefit of the new solution is limited or even negative in some cases. Currently, the focal company imports 10000 TEU annually from China. In order to increase the percentage of cargo delivered by 40-foot containers, they reduce the number of suppliers and POLs used in the origin country. Due to the more congregated suppliers, 87% of buyer consolidated cargo is delivered in 40-foot containers after consolidation, which means better environmental performance of the new solution in the focal company.

The originalities of the current research are as follows: First, to the best of the authors' knowledge, this research is the first one to

Table 10
Sensitivity analysis, Focal solution vs. HS − FCL, Factor: Percentage of cargo delivered in 40-foot containers and shipment volume, in kg CO_2/TEU.

	Percentage of cargo delivered in 40-foot containers after buyer-consolidation	Shipment Volume (cbm)						
		17.5	19	21	23	25	27	29
The focal solution	0%	1268	1270	1265	1262	1258	1256	1253
	10%	1260	1263	1258	1254	1251	1248	1246
	20%	1249	1252	1247	1243	1240	1237	1235
	30%	1238	1241	1236	1232	1229	1226	1224
	40%	1227	1229	1225	1221	1218	1215	1212
	50%	1216	1218	1214	1210	1206	1204	1201
	60%	1205	1207	1202	1198	1195	1192	1190
	70%	1194	1196	1192	1188	1184	1182	1179
	80%	1185	1187	1182	1178	1175	1172	1170
	90%	1175	1177	1173	1169	1165	1162	1160
	100%	1165	1167	1163	1159	1155	1153	1150
HS - FCL	0−100%	2105	1913	1716	1567	1450	1357	1281

identify the environmental impact of buyer consolidation on an intercontinental supply chain. Second, this research provides a CO_2 estimation framework and applies it to a case study. The framework considering both direct and indirect emissions and covering road, sea and rail transport can be applied to any types of supply chain solutions.

7.2. Limitations and scope for further research

Although the case selected for this study is believed to be representative of many relevant China-Europe supply chains, the conclusions could not be easily generalized to all such supply chains. However, the methodology, including mathematical models, developed in this paper can be applied to other supply chain configurations and other geographical cases. This study illustrates that the concept of upstream buyer consolidation has a potential to reduce CO_2 emissions. However, market penetration of this kind of solution will be highly dependent on acceptable lead-time implications. Therefore, a more comprehensive model including cost, environmental and lead-time constitutes an important area for further research.

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