Optimising end-to-end maritime supply chains: a carbon footprint perspective

Patrick Rigot-Muller
Marine Science and Technology, Newcastle University, Newcastle, UK
Chandra Lalwani
Hull Business School, Hull University, Hull, UK
John Mangan
Marine Science and Technology, Newcastle University, Newcastle, UK
Orla Gregory
School of Management, Dublin Institute of Technology, Dublin, Ireland, and
David Gibbs
Logistics Institute, Hull University, Hull, UK

Abstract

Purpose – The purpose of this paper is to illustrate an optimisation method, and resulting insights, for minimising total logistics-related carbon emissions for end-to-end supply chains.

Design/methodology/approach – The research is based on two real-life UK industrial cases. For the first case, several alternative realistic routes towards the UK are analysed and the optimal route minimising total carbon emissions is identified and tested in real conditions. For the second case, emissions towards several destinations are calculated and two alternative routes to southern Europe are compared, using several transport modes (road, Ro-Ro, rail and maritime). An adapted Value Stream Mapping (VSM) approach is used to map carbon footprint and calculate emissions; in addition Automatic Identification Systems (AIS) data provided information for vessel specification allowing the use of more accurate emission factors for each shipping leg.

Findings – The analysis of the first case demonstrates that end-to-end logistics-related carbon emissions can be reduced by 16-21 per cent through direct delivery to the UK as opposed to transhipment via a Continental European port. The analysis of the second case shows that deliveries to southern Europe have the highest potential for reduction through deliveries by sea. Both cases show that for distant overseas destinations, the maritime leg represents the major contributor to CO_2 emissions in the end-to-end supply chain. It is notable that one of the main apportionment approaches (that of Defra in the UK) generate higher carbon footprints for routes using Ro-Pax vessels, making those not optimal. The feasibility of the optimal route was demonstrated with real-life data.

Originality/value – This research used real-life data from two UK companies and highlighted where carbon emissions are generated in the inbound and outbound transport chain, and how these can be reduced.

Keywords Carbon footprint, Maritime supply chain, Value stream mapping

Paper type Research paper

This is the first of four articles based on papers presented at the 17th International Symposium on Logistics (www.isl21.net) held in July 2012 in Cape Town, South Africa. The conference saw over 75 papers presented, a shortlist of 17 papers was drawn up and the authors invited to submit extended versions for peer review in this journal. Of the four papers accepted, all build around the conference theme of "New Horizons for Logistics and Supply Chain Management". This paper has been guest edited by Dr Andrew Potter and Dr Seamus O'Rielly.

1. Introduction

The purpose of this research is to develop optimisation methods for minimising total logistics-related carbon emissions for end-to-end supply chain distribution systems. Appropriate tools for calculating the carbon emissions for the maritime leg of global supply chains are discussed. The research is based on real-life global supply chain data from two different cases. One case focuses on end-to-end analysis, with mainly inbound flows and local UK distribution, and the other case focuses on outbound distribution flows from the UK to Europe and some worldwide destinations. The analysis of the first case demonstrates that end-to-end logistics-related carbon emissions can be reduced by 16-21 per cent through direct delivery to the UK as opposed to transhipment via a Continental European port. An adaptation of the Value Stream Mapping (VSM) approach was employed and proved to be a flexible tool that can be adapted to measure and analyse CO_2 emissions with different calculation methods. The analysis of the second case shows that deliveries to southern Europe have the highest potential for reduction of emissions through deliveries by sea. Both cases show that for distant overseas destinations, the maritime leg represents the major contributor to CO_2 emissions in the end-to-end supply chain. The applications of the different calculation methods, which depend on the data available, are presented followed by the discussion of the results.

2. Literature review

With the increased focus on anthropogenic CO_2 emissions and climate change, companies are showing an increased interest in managing the climate change risk impact of their activity. The growing number of participating members in the activities of the Carbon Disclosure Project (2012) illustrates this evolution. The measurement of carbon footprint within end-to-end supply chains is of increasing interest to many stakeholders. Standard methodologies are only just beginning to emerge (GHG Protocol, 2011) and more recently, in the European context, EN 16258:2012 (British Standards Institute (BSI), 2012). While the focus of this paper is on the carbon footprint, this is only one particular aspect of the wider and emergent subject area of "green logistics" which encompasses not just carbon footprinting, but cognate topics such as alternative fuels, reverse logistics, supply chain optimisation and design for supply chain efficiency, corporate social responsibility, etc. (see e.g. McKinnon *et al.*, 2010; Carbone and Moatti, 2011). In the academic field, many studies have been conducted with the aim of developing appropriate methods for calculating carbon emissions in the context of specific industrial applications. Piecyk and McKinnon (2010), for example, endeavoured to forecast the carbon footprint of road freight transport in 2020. Edwards *et al.* (2009) studied the carbon footprint of the "last mile delivery", and compared emissions between standard and on-line shopping. To assess carbon emissions from road transport they used an approach based on emission factors in $g\,CO_2$/tonne km, using data provided by the National Atmospheric Emissions Inventory agency of the UK's Department of Environment, Food and Rural Affairs (Defra), by the UK Road Haulage Association and by the UK Freight Transport Association. Edwards *et al.* (2009) highlighted the importance of the number of items purchased, showing that for large numbers of items purchased, "standard" traditional shopping is more carbon effective, and for smaller numbers of items on-line shopping and delivery are more effective. This approach (the delivery size), expressed in their study in number of items purchased, will be considered in our paper as the "truck load" expressed in average tonnages and in percentage. Miyoshi and Mason (2009) analysed

emissions from airfreight transport, calculating emission factors in $gCO_2/$ passenger km using fuel consumption models and showed that results could change significantly depending on the route selected, and differences in airlines' strategies such as aircraft types used, load factors and aircraft configurations. We can see similar issues in the maritime sector, where emission factors of maritime supply chains are particularly difficult to measure due to a variety of reasons, including different emission factors and allocation possibilities depending on the vessel type and size, the routes and distances, the number of days at sea and days at port, the fuel choice, the average speed and the average load, as shown, for example, in Leonardi and Browne (2010) and in Rizet et al. (2008). Leonardi and Browne (2010) also highlighted some limitations, such as the uncertainties about the container load and the lack of analysis with regard to the introduction of new technologies on board vessels. Rizet et al. (2012) also show, for consumer products, that the maritime transport and the consumer leg represented relatively high emissions in the overall supply chain.

A major report from the International Maritime Organisation (IMO, 2009) provided an important data set on emissions factors (vessels emissions in $kgCO_2/tonne$ km) by ship type and size. These results were adapted by Defra (2011) as a reference for the UK. In parallel, the industry-led Clean Cargo Working Group approach (www.bsr.org/en/our-work/working-groups/clean-cargo) also produced emissions factors by trade routes for container vessels (measured in CO_2/TEU) based on real fuel consumption. Also, an independent approach led by the Carbon War Room (a group of entrepreneurs, led by Sir Richard Branson, who seek to "accelerate profitable, entrepreneurial solutions that reduce carbon emissions at the gigaton level"), aims to provide an individual vessel rating, using a methodology that consists in extrapolating the Energy Efficiency Design Index formula for existing vessels (International Maritime Organisation, 2012). In this study, we have analysed a large number of possible alternative routes, thus we will use an approach based on Defra's emission factors in $gCO_2/tonne$ km, without calculating intermediate steps such as the energy consumption. We will compare the results obtained using this approach with the recent recommendations established by the European Committee for Standardisation under the European Standard EN16258 (BSI, 2012).

With regard to supply chain mapping, modelling and optimisation covering the "end-to-end" supply chain, a number of studies have been carried out recently. Sundarakani et al. (2010) propose an approach based on the Lagrangian and Eulerian box model, which aims to cover carbon footprints embedded in products, and they also highlight a lack of detailed industry data available. Ramudhin et al. (2008) provide an optimisation method based on linear programming and that takes into consideration carbon trade under a cap-and-trade situation. The application of linear programming methods makes sense when an extremely large number of options are possible, which is not the case in this research. The number of possible, realistic logistics routes is limited and no carbon trading policies are applicable to our cases. Also, VSM, which is a lean mapping tool originally created to reduce waste and increase productivity from industrial processes (Rother and Shook, 2009), has also been applied in a sustainability context. Lean thinking researchers and practitioners have already defined concepts such as "Sustainable VSM" (Simon and Mason, 2003; Norton, 2007), "Carbon Stream Map" (Windsor, 2010) or the "Voice of Environment VSM" (Olson, 2009). In this paper we propose to investigate the application of VSM to optimise end-to-end maritime supply chains, with specific attention to the construction and formalisation of the VSM databoxes, as we will see in Section 4.

3. Description of the problem

This research is based on two real-life industrial cases, with activity data from 2011 to 2012. The first case concerns inbound flows to the UK, and the second case concerns outbound flows from the UK.

The first case concerns a UK-based distributor of plastic products. Most products for this case company are sourced from the suppliers DCs, located either in the UK or in the EU, but the original production facilities are based in Asia and the Middle East. Once sourced, products are stored in a central warehouse in the UK's East Midlands and then shipped to more than 600 delivery points in the UK.

The scope of our analysis is the end-to-end supply chain for the major product sold by the distributor, a high-density resin. This product is manufactured in the production facility in Saudi Arabia and delivered to the final customers in the UK in containers, on pallets and in bulk form. The optimisation levers considered are the study of alternative delivery routes (including direct delivery to the UK) and the UK warehouse location, based on an analysis of the customers' centre of gravity. The company had not carried out supply chain carbon mapping before this research and therefore there were no available supply chain environmental data. All logistics operations (warehousing, upstream and downstream transport) are carried out by logistics service providers. Upstream transport is provided either by transport providers (for local sourcing by road) or by freight forwarders (for distant sourcing by maritime transport). The warehousing operations and the final delivery to the customers are provided by the distributor's main logistics service provider based in the East Midlands, who runs the UK warehouse.

The second case focuses on developing a carbon footprint metric for a manufacturer of industrial paints with a production plant in the north of England. The case company has worldwide delivery range, but most flows are concentrated in continental Europe. An interesting aspect of this case is the variety of transport modes used in the supply chain including road transport, containerships, Ro-Ro vessels and rail transport. Some destinations are delivered by two different routes (with two transport modes) which allowed carbon footprint comparisons to be made by mode.

In this research, the emission measure covers only the transport and warehousing operations. This means that indirect emissions such as the distributor's central offices, employee business travel, etc. are not included. We have used whenever required emission factors from Defra (2011) which provides the national standards for the UK. We will be using in this paper the expression "carbon footprint" as a generic synonym for emissions of carbon dioxide or greenhouse gases expressed in CO_2 equivalents (Wiedmann and Minx, 2008).

Tables I and II show the routes analysed for cases 1 and 2, respectively. Table I illustrates the different selected end-to-end routes from the plant in Saudi Arabia. This table specifies the transport mode for the product collection, the main maritime route, the transhipment port (if applicable), the supplier warehouse in Antwerp (if a warehousing operation is applicable in the specified route), the Ro-Ro route towards the UK (if applicable), the distributor warehouse in East Midlands (if a warehousing operation is applicable in the specified route) and the transport mode for the final delivery. Table II illustrates the selected delivery routes from the northern UK production facility to different destinations. Its structure is similar to Table I, excepted that the flows are outwards oriented and that some changes were made in the table columns representing the main stages, adapted to the flows structure of the second case.

Final delivery location	Unit type	Collection	Maritime (main)	Transhipment	Supplier WH	UK Ro-Ro	Distributor WH	Final delivery
					Route specification			
UK-wide	Container/pallet	Road	Jeddah-Antwerp	None	Antwerp	Zeebrugge – Purfleet	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Immingham	Zeebrugge	None	None	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Liverpool	Le Havre	None	None	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Antwerp	None	None	Zeebrugge – Hull	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Rotterdam	None	None	Hoek – Harwich	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Antwerp	None	None	Osten – Ramsgate	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Antwerp	None	None	Dunkerque – Dover	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Antwerp	None	None	Calais – Dover	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Antwerp	None	None	Zeebrugge – Purfleet	East Midlands	Road
UK-wide	Container/pallet	Road	Jeddah-Felixstowe	None	None	None	East Midlands	Road
UK Newport	Container/bulk	Road	Jeddah-Antwerp	None	Antwerp	Zeebrugge – Purfleet	None	Road
UK Newport	Container/bulk	Road	Jeddah-Southampton	None	None	None	None	Road

Table I.
Illustration of inbound routes (case study1)

Final delivery Location	Unit type	Collection mode	UK Rail	Route specification Maritime	Transhipment	Final delivery
Holland	Sea Container	Road	None	Teesport – Rotterdam	None	Road
Sweden	Box/tanker	Road	None	Immingham – Gothenburg	None	Road
Turkey (by sea)	Sea container	Road	None	Felixstowe – Gebze	Antwerp	Road
Turkey (by road)	Trailer	Road	None	Dover – Calais	None	Road
Spain	Trailer	Road	None	Dover – Calais	None	Road
Italy	Trailer	Road	None	Dover – Calais	None	Road
UK (domestic)	Trailer	Road	None	None	None	Road
Greece (by sea)	Sea container	Road	None	Teesport – Piraeus	Antwerp	Road
Greece (rail + sea)	Sea container	Road	Selby – Felixstowe	Felixstowe – Piraeus	None	Road
China	Sea container	Road	none	Teesport – Shanghai	Zeebrugge	Road
Korea	Sea container	Road	none	Teesport – Busan	Zeebrugge	Road
USA	Sea container	Road	Selby – Felixstowe	Felixstowe – Houston	None	Road
Singapore	Sea container	Road	none	Teesport – Singapore	Zeebrugge	Road
Australia	Sea container	Road	Wakefield – Southampton	Southampton – Brisbane	None	Road
India	Sea container	Road	Leeds – Southampton	Southampton – Chennai	None	Road
Brazil	Sea container	Road	Selby – Tilbury	Tilbury – Rio de Janeiro	None	Road
Dammam	Sea container	Road	Leeds – Southampton	Southampton – Dammam	None	Road

Table II.
Illustration of outbound routes (case study 2)

4. Methodology and analysis

The first main step for this research was to map the end-to-end supply chains. Considering the extent of the scope for analysis, particular attention is given to the geographical location addresses, the transport mode and the average shipment weight. More specifically, we developed a "current state" VSM (Rother and Shook, 2009) for case study 1, for which the databoxes will be explained in the following sub-sections. Even though in most cases emissions were assessed using emission factors using the methodology as provided by Defra (2011), when the supplier was able to provide its own emission factors by measuring its own transport fuel consumption or energy consumption in the warehouses, those ones have replaced the Defra standard values. The approach we used consisted of defining a set of product and packaging data (pallet weight, pallet per container, pallets per lorry trailer) which can be applied to the whole supply chain map, even though for different supply chain stages specific approaches for carbon footprint calculation could be used.

4.1 Product and packaging data

Product and packaging data contain mainly product weight, size and packaging specifications. In case 1, products are transported in containers and most of them are palletised. Each 40-foot container is able to transport 18 pallets weighing on average 1,375 tonnes, representing 24.75 tonnes in each loaded container. This information is useful in that it allows conversion of weight data into logistics units (trucks, containers) and vice-versa, and then uses the appropriate emission factors, which can be based on both weight and transport unit. In case 2, the situation was more diverse, due to the analysis of several routes (with different transport means) and many products (with different densities). As a consequence we tried to avoid using a single average truck load. We collected the detailed weight for every shipment (either in containers or in trucks) and thus the exact information in terms of number of shipments and truck load could be used for each shipment. Figure 1 illustrates the average shipment weight for each route (all departing from the same production facility in the north of England).

4.2 Road transport

For the case of full truck load (FTL) traffic, carbon emissions were calculated using Defra's emission factors in a vehicle km basis. This was preferred to the tonne km basis since tonne km assumes percentage weight laden and average payload of 61 per cent and 11.49 tonnes, respectively, which did not match to our cases studies data, where the
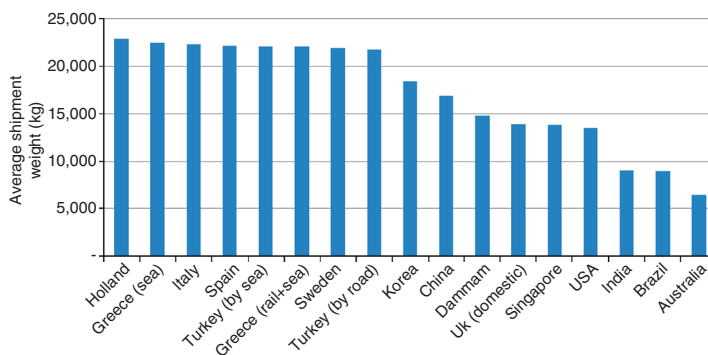

Figure 1.
Average shipment weight
in kg, for each route
(case study 2)

average weight laden is close to 100 per cent for all upstream flows of case 1 (24.75 tonnes) and also for most of the traffic in case 2.

In case 1, we used the FTL value, which can be justified by the fact that every inbound transport voyage, either in Saudi Arabia, in Europe or in the UK is realised in a full truck with one single product, so the average weight and thus emissions are rather similar and simple to calculate, since we can assume that each voyage is similar in terms of average load and number of products. In case 2, even though most traffic was in FTL, we used an extrapolation of Defra's values, using a linear regression approach. The emission factor for each load factor was weighted according to the truck load factor, as shown in Figure 2. In the x-axis we represent the truck load, and in the y-axis the percentage of the FTL emission factor that we apply for this specific load. For instance, an empty truck will generate 60 per cent of the emissions of a fully loaded truck.

For final deliveries in case 1, from the UK distributor to the final customer, the exact measure is more complex, since deliveries are realised in less than truck load (LTL) mode to multiple customers, and with delivery routes that can change depending on the daily demand pattern. The difficulty here lies in defining the appropriate allocation rule considering the available data as collected by the transport provider. The data provided covers one year of activity and does not track the routes used by the transport providers for each of the delivery points. It does not cover either the truck load, or the share of this truck load used by our distributor (in case of multi-pick collection). Considering these data availability constraints, we have assessed the emissions from final deliveries using two approaches: the first one was to use the emission factors provided by Defra in a vehicle km basis, and assuming a truck percentage weight laden of 61 per cent, the average UK truck load according to Defra (2011). Even though it does not represent the exact situation of each delivery, the use of an average here can be justified by the fact that the LTL deliveries are typically for multi-references and multi-drop deliveries.
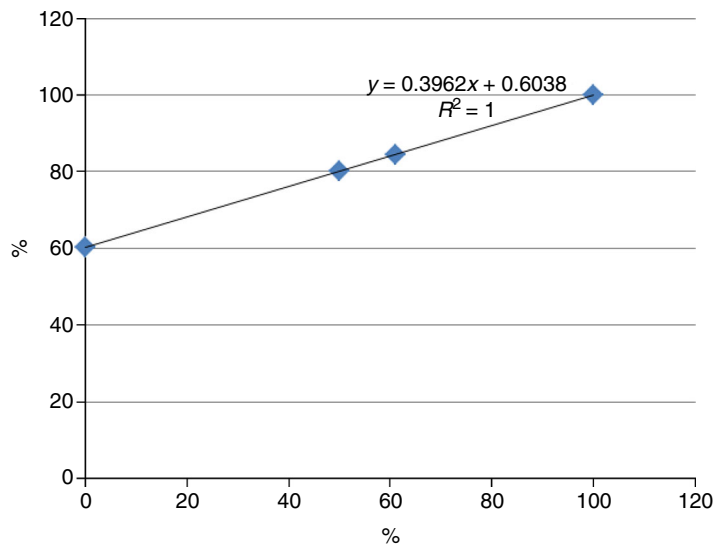

Figure 2.
Extrapolation of Defra's emission factor (y-axis) vs truck load (x-axis), expressed as a percentage of the full truck load

The application of this rule provided a result of 19.07 kg CO_2e/pallet for the final delivery. The approach is summarised in Table III.

Where:

- Distance average: is the weighted average distance between the warehouse and the final customers (weighted by the tonnes delivered).
- Truck load (kg): is the average truck load assuming 11 pallets carried.
- Truck load (per cent): the resulting value of truck load (kg) expressed in per cent of the truck capacity (assumed here at 25 tonne). This result (61 per cent) is used as it represents the average UK truck load.
- kg CO_2e/km: emission factor applied in kg CO_2e/vehicle km.
- kg CO_2e/pallet: CO_2e emissions per pallet.

The second approach, used for case 1 only, consisted in asking the transport provider for the emissions based on their actual fuel consumption. Theoretically, this approach is more accurate since we measure the actual fuel consumption from this transport provider, but on the other hand the transport provider was not able to provide a better customer allocation method than a share based on the total tonnages delivered (which does not include the distance factor). For this reason, the Defra method was used and the transport provider result was used to corroborate the result. The transport provider average emissions were 16.93 CO_2e/pallet, which represent a difference of 11 per cent when compared with the first approach. For FTL transport (upstream transport, in our case), the same data is applied, but using the appropriate emission factor for 100 per cent truck load and using the exact distance between the origin and the destination points (which are known points, such as ports, factories or warehouses).

4.3 Maritime emissions

Emissions factors from maritime traffic were also collected using Defra methodology, which are based on previous results obtained from the IMO's Greenhouse Gases Study published in 2009 (IMO, 2009), excepted for Ro-Pax vessels. Defra added the CO_2e emission factors from CH_4 and N_2O to the IMO results. These emissions are expressed in kg CO_2e/tonne km. Just as for road traffic, emission factors from maritime traffic depend heavily on the vessel used for the journey, and the IMO has segmented emission factors based on the ship type and ship size. For accurate end-to-end supply chain "carbon mapping", it is then imperative to collect such information about the vessels that are transporting the goods. When the company has an appropriate traceability by way of Bills of Lading (B/L) – which includes the vessels name – it is possible to track the exact vessel specifications. When such information is not available, the information can be collected at the shipping company level. For the case study 1, for the service between Jeddah and the UK, a 5,700 TEU container vessel was used as a reference. Due to the lack of B/L data, the use of information provided by

Distance (km), average	177
Truck load (kg)	15,125
Truck load (%)	61
kg CO_2e/km	1.18643
kg CO_2e/pallet	19.07

Table III.
Sample databox to calculate road traffic emissions

Automatic Identification Systems (Marine Traffic, 2012) was very useful to validate if vessels associated to shipping services were actually being used. Maritime distances were calculated on a port to port basis and were adjusted when the ports of call were not in the direct trajectory. Tonnages were directly provided by the distributor. Table IV illustrates the databox used for maritime emissions.

Where:

- distance: is the maritime distance between the port of loading and port of unloading;
- container load: is the average load of a 40 foot container;
- $kg\,CO_2e$/tonne km: emission factor as provided by Defra (here, for a 5,000-7,999 TEU containership); and
- $kg\,CO_2e$/tonne km: resulting CO_2e emission per pallet for the voyage (considering the number of pallets per container provided in the product and packaging section).

Port emissions. At present, there is a lack of any carbon emissions factors from port operations provided by Defra. But some UK ports have recently started to measure their carbon footprint operations (Mangan *et al.*, 2011), and some information is thus available. However, the information is released as an aggregate value for all port operations, regardless of the type of cargo loaded and unloaded. This can be a problem since some cargo such as dry and liquid bulks tend to be much heavier than unitised cargo, causing then distortions if we apply a direct allocation based on the weight only. To avoid this problem, two-specific UK ports that actually measure their carbon emissions were used as reference ports: Felixstowe for containers and Dover for Ro-Ro. The main reason that led to this choice is that these ports are specialised ports, with most traffic being containerships and Ro-Ro vessels, respectively (Department for Transport, 2010). We assumed then that the port activity profile was the best driver to assess emissions in the absence of detailed emissions by ship type. However, due to their small impact in the overall supply chain, as was pointed by Mangan *et al.* (2011), we decided not to include port operations in the VSM illustration (Figure 3).

4.4 Warehouse emissions
Defra does not provide average emission factors for warehousing operations. It was then necessary to define an appropriate framework and identify the possible data sources for case 1 (case study 2 does not have warehousing operations in its scope). The information provided by the 3PL in charge of the warehousing operations in East Midlands was directly used. It was easy for the 3PL to calculate its overall electricity consumption and allocate to the distributor an appropriate share, based on the volume of products distributed belonging to each of its own customers. The resulting warehouse emissions, using the 3PL provided data, are detailed in the databox (Table V).
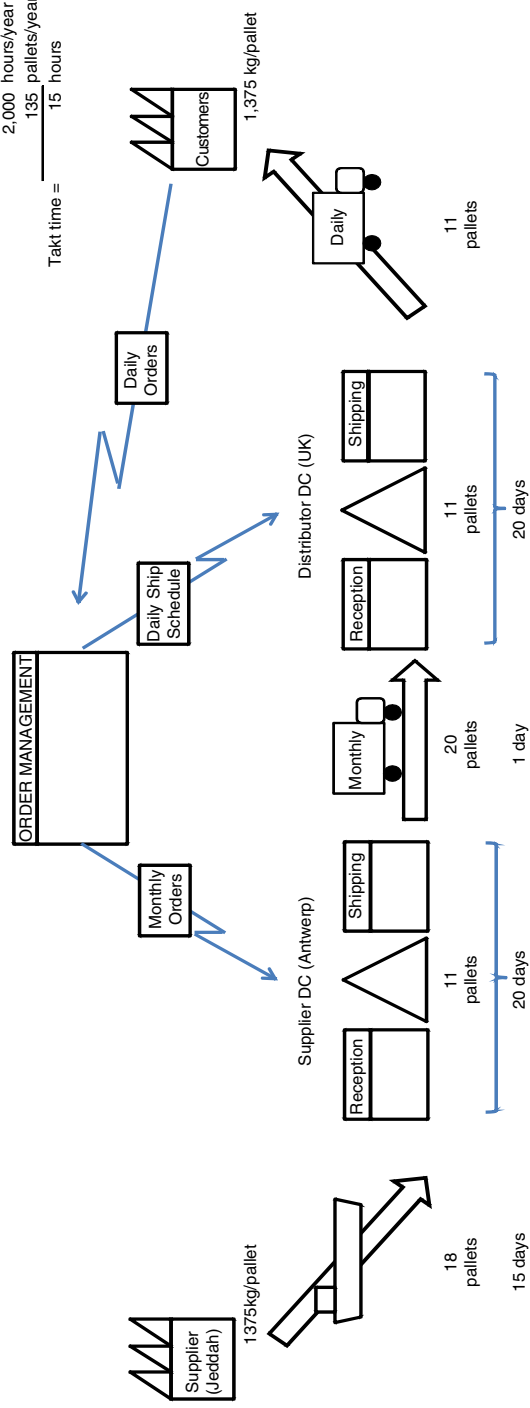
Where:

- pallets delivered: is the annual number of pallets delivered for the distributor;

Table IV. Sample databox to calculate maritime emissions	

Distance (km)	7,346
Container load (kg)	24,750
$kg\,CO_2e$/t km	0.01957
$kg\,CO_2e$/pallet	197.68

Takt time = $\dfrac{2{,}000 \text{ hours/year}}{135 \text{ pallets/year}} = 15 \text{ hours}$

Customers

1,375 kg/pallet

Daily

11 pallets

Distance (km), average	177
Truck Load (kg)	15,125
Truck Load (%)	61%
kgCO$_2$e/km	1.18643
kg CO$_2$e per pallet	19.07

Daily Orders

ORDER MANAGEMENT

Daily Ship Schedule

Distributor DC (UK)

Shipping

Reception

11 pallets

20 days

Days of Stock	21
Pallets delivered	12,828
KWh/year (electricity)	22,800
kgCO$_2$/KWh (Electricity UK)	0.525
kgCO$_2$/year	11,961
kgCO$_2$/pallet	0.93

Monthly

20 pallets

1 day

Distance (km)	97
Truck Load (kg)	27,500
Truck Load (%)	98%
kgCO$_2$e/km	1.40325
kg CO$_2$e per pallet	6.78

Monthly Orders

Supplier DC (Antwerp)

Shipping

Reception

11 pallets

20 days

Days of Stock	21
Pallets delivered	1,069
KWh/year (electricity)	22,800
kgCO$_2$/KWh (Electricity UK)	0.282
kgCO$_2$/year	6,430
kgCO$_2$/pallet	0.50

Supplier (Jeddah)

1375kg/pallet

18 pallets

15 days

Distance (km)	7,346
Container Load (kg)	24,750
kgCO$_2$e/T.km	0.01957
kg CO$_2$e per pallet	197.68

Figure 3.
Current state Value
Stream Mapping
(illustration)

• kWh/year (electricity): the annual electricity consumed by the 3PL allocated to the distributor (including logistics operations, such as the forklifts);

• $kg\,CO_2/kWh$ (electricity UK): average emission factor applied for the electricity generation in the UK; and

• $kg\,CO_2/pallet$: resulting CO_2 emissions associated to each pallet delivered.

For the warehousing operations situated outside of the UK – in Antwerp, Belgium – due to lack of information from the 3PL, the same energy consumption as applies in the UK was used for operations, but using the electricity emission factor (in $kg\,CO_2/kWh$) from Belgium.

An alternative way to assess warehouse emissions was using results with square metres as a basis. We investigated a method based on an emission factor of $17.3\,kg\,CO_2/m^2/year$, provided by Cox and Graham (2010) for a typical large warehouse. The result is presented in Table VI.

Where:

• Days of stock: is average days of stock for this specific reference.

• m^2 WH/pallet: the average ratio of warehouse surface and pallet capacity.

• $kg\,Co_2/m^2/year$: average annual CO_2 emission factor for the warehouse per m^2.

• $kg\,CO_2/pallet$: resulting CO_2 emissions associated to each pallet delivered. The resulting emission is calculated by multiplying the three previous values and dividing by 365 (e.g. a pallet with 365 days of stock would provide here a result of $17.3\,kg\,CO_2$).

4.5 The transport routes and their carbon footprint
The list of possible transport routes was identified based on available options, and they were classified in three groups:

• "Ro-Ro routes": end-to-end routes from Saudi Arabia, with a warehousing operation in the supplier's facility in Antwerp (20 days of stock), then a transfer to the UK warehouse using one of the available Ro-Ro services;

• "direct Lo-Lo routes": end-to-end routes with direct delivery to the UK with a transhipment operation in Continental Europe; and

• "direct routes": end-to-end routes with a direct delivery to a UK port.

Days of stock	21
Pallets delivered	12,828
kWh/year (electricity)	22,800
$kg\,CO_2/kWh$ (electricity UK)	0.525
$kg\,CO_2/year$	11,961
$kg\,CO_2/pallet$	0.93

Table V.
Sample databox used to calculate warehouse emissions

Days of stock	21
M^2 Wh/pallet	1.0
$kg\,CO_2/m^2/year$	17.30
$kg\,CO_2e/pallet$	1.00

Table VI.
Alternative possible databox to calculate warehouse emissions

For each route 13 generic steps were defined, and the total carbon footprint associated to a container delivery was then calculated for each route by adding the emissions generated at each point of the supply chain.

5. Results and analysis
5.1 Case 1: end-to-end inbound flows to the UK
The analysis of case 1 data shows that VSM is a flexible tool that could be adapted to measure and analyse CO_2 emissions with different calculation methods. The databox is an efficient tool to calculate carbon emissions using our approach based on emission factors. Figure 3 provides an illustration of the VSM for carbon footprint calculation, focused on the main operations.

The end-to-end supply chain mapping shows that some Ro-Ro routes, such as "Hoek – Harwich", "Ostend – Ramsgate", "Dunkerque – Dover" and "Calais – Dover" did not create any reason for deeper analysis compared to the current Ro-Ro route "Zeebrugge – Purfleet", because they generated higher distances of travel if we consider the specific origin (Antwerp) and destinations (East Midlands and Wales) in this case study. This latter route was then selected as the only option among all the possible "Ro-Ro" routes. The calculation of the carbon footprint for the end-to-end supply chain shows that the maritime leg was the main source of CO_2 emissions, as we can see in Figures 4 and 5 (the numbering of routes on the x-axis of both charts refers to the range of routes analysed). It also shows that the direct routes via Felixstowe (for the East Midlands warehouse) and Southampton (for the customer in Wales) were the best options to minimise carbon emissions to deliver the plastic products from Saudi Arabia to the customers in the UK. For the case company, among the existing routes from Continental Europe to the UK, Zeebrugge-Purfleet by Ro-Ro has the lowest carbon footprint, followed by container feedering through the Zeebrugge-Immingham service. It was also found that current allocation choices used by Defra, based on tonnages of freight and passengers, generate higher carbon footprints for routes using Ro-Pax vessels and thus in fact penalise those routes. Indeed, unlike other emissions factors provided by the IMO (2009), emission factors from Ro-Pax are provided by a different study, realised by Best Foot Forward for the Passenger Shipping Association (Defra, 2011). In that study, the average freight unit is
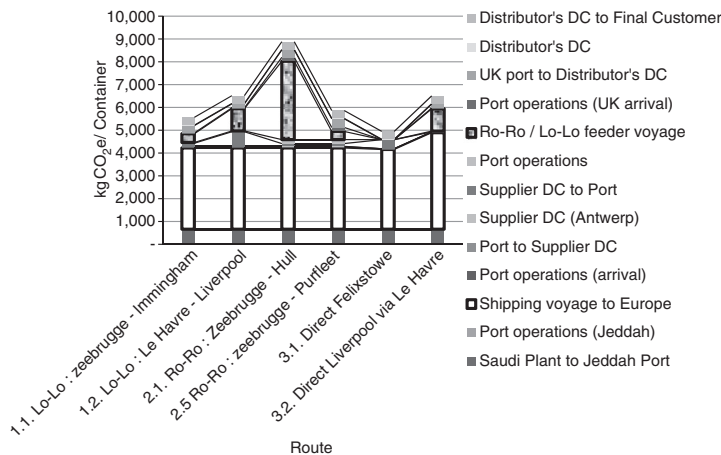

Figure 4.
End-to-end CO_2 emissions
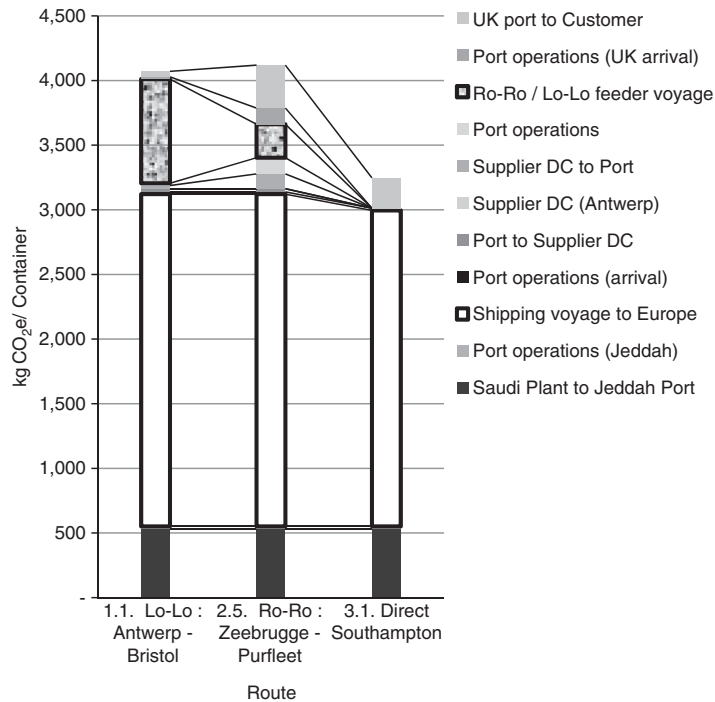for different routes of
palletised products

Figure 5.
End-to-end CO_2 emissions
for different routes
of bulk products

estimated at 22.173 tonnes whereas the average coupled passenger + car unit is estimated at 1,350 tonnes, implying a significant CO_2 allocation towards the freight activity in comparison to the passenger activity. In other words, we can conclude that even though most of the underperformance of Ro-Pax vessels is due to operational and design factors related to the passenger traffic (comfort, speed, etc.), most of their CO_2 emissions are apportioned to the freight activity. As a consequence, "Ro-Pax freight" emissions factors are much higher than Ro-Ro freight emissions.

Comparing the current route (Zeebrugge – Purfleet) with the best route (direct to Felixstowe/Southampton), it can be seen in Table VII that through direct routes to the UK ports, these emissions could be reduced by 16-21 per cent, depending on the products and routes.

The analysis of the centre of gravity showed that the current location of the distribution centre was already near to the optimal even considering the impact that the direct deliveries could have in the total flow within the warehouse. This analysis was carried out using a tonne miles minimisation and is detailed in Table VIII, where we can see that the difference is only −0.32 per cent.

The methodology used in this research enables the distribution company to exchange information about emissions with the partners in the supply chain including logistics service providers. From a management perspective for the case company, direct sailing to the UK ports will have an impact on inventory management practices with reference to a need to recalculate the safety stocks for the new delivery times for the customers. On the other hand it should have a limited impact on order sizes, since this is unlikely to change with the suggested route of direct sailing to the UK.

Stage (palletized products)	Ro-Ro route	Direct route	Stage (bulk products)	Ro-Ro route	Direct route
Saudi Plant to Jeddah Port	35	35	Saudi plant to Jeddah port	534	534
Port operations (Jeddah)	2	2	Port operations (Jeddah)	17	17
Shipping voyage to Europe	198	194	Shipping voyage to Europe	2,570	2,444
Port operations (arrival)	2	2	Port operations (arrival)	17	17
Port to supplier DC	2	–	Port to supplier DC	25	–
Supplier DC (Antwerp)	1	–	Supplier DC (Antwerp)	-	–
Supplier DC to Port	7	22	Supplier DC to port	115	–
Port operations	10	–	Port operations	125	–
Ro-Ro/Lo-Lo feeder voyage	20	–	Ro-Ro / Lo-Lo feeder voyage	259	–
Port operations (UK arrival)	10	–	Port operations (UK arrival)	15	–
UK port to distributor's DC	21	–	UK port to customer	332	235
Distributor's DC	1	1	Distributor's DC	–	–
Distributor's DC to final customer	19	19			
Total emissions (kg CO$_2$e/pallet)	326	275	Total emissions (kgCO$_2$e/container)	4,119	3,248
		–16%			–21%

Table VII.
Detailed emissions, illustrations for bulk and palletized products, with the Ro-Ro route (Zeebrugge-Purfleet) and direct routes

Table VIII.
Total 2010 tonne miles from the current 3PL location and from the new centre of gravity if direct deliveries were applied to all candidate orders

Sales	16,657	Tonnes
Transport work (from new centre of gravity)	1,896,902	Tonnes.miles
Transport work (from current 3PL location)	1,903,004	Tonnes.miles
Difference (%)	−0.32	

Note: Year: 2010, sales data excluding candidate orders for direct deliveries

To work out the industry impact, the four-step practical approach to achieve "Competitive Advantage on a Warming Planet" proposed by Lash and Wellington (2007) can be employed:

- step 1: quantify your "carbon footprint";
- step 2: assess your carbon-related risks and opportunities;
- step 3: adapt your business; and
- step 4: do it better than rivals.

Case company 1 has applied Steps 1-3 based on the analysis of this research and found it extremely useful mainly in anticipation of regulatory, supply chain and reputation risks. Cost-effectiveness of direct routes was an important driver that allowed the achievement of Step 3. Without the cost factor the company would have remained in Steps 1-2. We cannot say that the change was driven exclusively by environmental factors but more likely by a combination of economic, regulatory, reputational and environmental factors. No comparison with rivals supply chains has been carried out by them yet.

5.2 Case 2: outbound distribution flows from the UK
The analysis in case 2 shows that the total emission factor of routes from the UK to southern European destinations such as Turkey, Spain and Italy could be significantly

higher than the ones to distant overseas countries, as can be seen in Figure 6. This is due to the use of road transport as the main transport mode for the near destinations and maritime transport for the distant destinations, as illustrated in Table II.

It is important to note that those southern European destinations are among the ones with the best load factor, suggesting that under identical product density and package specifications, the difference between their per unit carried emissions and those for distant destinations could actually be even higher.

Two of the destinations in this case analysis are delivered via two different routes: Turkey and Greece. The analysis of the flows for Turkey supports the idea that delivering southern European destinations (here, Spain and Italy) via maritime means is a major lever of emissions reduction. The analysis of flows for Greece showed that transport by maritime means, from a local port (here, Teesport) with transhipment in Antwerp was slightly more efficient than transport by rail to Felixstowe for a direct maritime service to Greece.

The company in case 2 achieved Step 1 of the Lash and Wellington (2007) approach during this case study. They were surprised by the outcome ("local" destinations are the most carbon-intensive destinations) and became aware of the main sources of emissions in their supply chain. Further steps for the company should identify solutions to reduce emissions from those routes and implement changes.

6. Discussion and conclusions

The research presented in this paper has attempted to map the end-to-end carbon footprint for given supply chains by two case companies in two different industrial sectors. The results from both cases demonstrated that in the case of distant overseas countries as origins or destinations, the maritime leg remains the main part of the end-to-end supply chain's carbon emissions, corroborating Rizet *et al.* (2012) results applied for consumer products. Even though maritime transport is more efficient than other modes of transport for emissions, it is still the important focus for efforts concerning the reduction of emissions as nearly 90 per cent of international trade uses maritime transport.

The results from case 2 for southern European destinations suggest that local sourcing does not always have a lower emissions benefit when different transport modes are used.
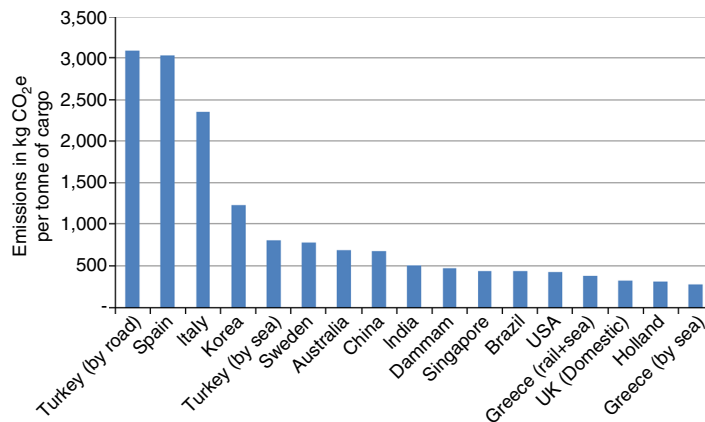

Figure 6.
Total emissions in kg CO_2/ tonne of cargo for each route analysed for case 2

In both cases analysed in this paper, it appeared that the data availability, reliability and the allocation rule play crucial roles in the modelling process, and results must be considered with regard to the restrictions and approximations used. For working out the emission factors, we have mainly used Defra's data, but if we look at all the data sets employed, they can be classified with the following levels of detail:

- level 1: international averages or national averages extended to other countries (used e.g. for international shipping and foreign road transport);

- level 2: national averages applied to the corresponding country (used e.g. for UK road transport and Ro-Ro shipping);

- level 3: company benchmarks from equivalent business (used for the port activity, or – as a possible alternative – for warehousing);

- level 4: company averages (used in case 1 to corroborate final distribution values); and

- level 5: company averages for this specific business (used for warehousing in the UK, and the homogeneity of warehousing activity made it possible for the 3PL to calculate it).

However, caution needs to be exercised where different secondary data sets are applied. Different sources of secondary data may be based on different assumptions, thus a decision maker needs to be aware and make an informed judgement as to their comparability.

This work was realised before the publication of the EN 16258 standard (BSI, 2012), hence a few differences or specificities can be observed between our approach and this new standard. First, this work focuses on the standard short declaration (BSI, 2012, item 10.2): "well-to-wheels GHG emissions" calculation, with no information in the databoxes about "tank-to-wheel GHG emission", or energy consumption. Also, emissions are calculated directly from Defra emission factors, without the assessment of fuel consumption as an intermediate step. However, Defra values are "default values" and, as such, provide final results compatible with the EU standard. An interesting difference, however, concerns the ship work unit for maritime freight: Defra suggests tonne km and the EN16258 example (annex F) proposes TEU km. This difference is important since the measure in TEU km provides identical emissions independently of the container load ("rewarding" containers with a better fill rate), whereas measure in tonne km provides identical emissions independently of the number of containers used ("rewarding" the reduction of cargo only). Further developments of maritime standards should investigate better allocation systems, combining probably a mix of unit and weight factors.

In our opinion, in complex supply chains, such as used in the case studies presented in this paper, the availability of more accurate data (exact emissions or fuel/energy consumptions for each logistics operation) is difficult. The use of averages and standard emission factors are part of the optimisation process and such constraints have an impact on the range of optimisation study conclusions. Also, this approach is perhaps the only way to use methods such as VSM with calculation rules that are simple, and thus, more likely to be applied by logistics service providers. GHG Protocol (2011) points out in its guidelines the importance of formalising the business goals of each study before starting any modelling process. We think that this guideline is key in helping to build models with enough accuracy in the areas where optimisation levers

are applicable, and with simpler rules in areas that would not have an impact in the final results and conclusions. The approach recommended in this paper provides a simple and effective way of estimating carbon emissions and can help companies to make steps in the right direction for achieving CO_2 emission reductions.

Acknowledgements

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Corresponding author
Professor John Mangan can be contacted at: john.mangan@ncl.ac.uk