UK SUPPLY CHAIN CARBON MITIGATION STRATEGIES USING ALTERNATIVE PORTS AND MULTIMODAL FREIGHT TRANSPORT OPERATIONS

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ABSTRACT

In the last few decades, the building evidence that CO_2e emissions lead to climate change has pointed to a need to reduce CO_2e emissions. This research uses five scenarios in the context of UK import trade to assess total CO_2e emissions and costs of import re-routing containers. The overall objective is to assess possible carbon mitigation strategies for UK supply chains by using a combination of alternative ports and revised multimodal strategies. The model adopted includes three elements: port expansion, container handling and freight transport. The alternative scenarios explore different settings modal shift and short sea shipping.

Keywords: International freight transport, port choice, CO_2e reduction and supply chain decision-making.

1. Introduction

Examination of international freight transport chains and supply chains has recently been highlighted by, for example, Sanchez Rodrigues *et al* (2014) who investigated possible options for the use of alternative ports as a way of contributing to supply chain carbon mitigation strategies. This was in contrast to the greater proportion of research into supply chain structures which largely relate to the coordination of the chains and the distribution of economic value among supply chain partners (see, for example, Leslie and Riemer, 1999; Oro and Pritchard, 2011; Alvarez-SanJaime *et al*., 2013). Further, Alvarez-SanJaime *et al*. (2013) suggest that vertical integration is crucially important to bring about high level of performance in the maritime segment of freight transport chains. However, the literature tends to exclude port selection as a key component of performance improvement in maritime supply chains, since research into how commodity chains and networks work has concentrated mainly on the management of relationships within supply chains.

Ports are important nodes in global distribution networks and as such they can significantly influence the performance of global supply chains. Even though, in the literature, there is a considerable degree of emphasis on the topic of port selection, the large majority of the research focuses on economic aspects of port choice, such as market forces and port efficiency (Suykens and Van de Voorde, 1998; Tongzon, 2001; Malchow and Kanafani, 2004; Gonzalez and Trujillo, 2008; Tongzon, 2009; Steven and Corsi, 2012). Steven and Corsi (2012) analyzed port selection in the context of the United States while Leachman (2008) and Tongzon (2009) focus on the management of inland distribution as a port choice factor. The remit of these studies did not extend to CO_2e reduction or to how future changes in the carbon intensity of road freight transport could influence port selection decisions. Further, global supply chain and shipping line decision-making has not incorporated CO_2e emissions as a factor in the port choice process, although Emission Control Areas (ECA) have led to some organisational and tactical modifications by shipping lines to their operations in order to be aligned with the current legislation (Fathom Shipping, 2013).

A key aspect of improving the environmental performance of global maritime-based supply chains is the reduction of their overall carbon intensity. This can be achieved in several ways: reducing the fuel consumption of vehicles *per se*, which occurs as a consequence of port selection and which alters if an alternative port is selected, shrinking the carbon content of the fuels themselves, or by transferring freight from road to less carbon-intensive freight transport modes such as water-borne transport and rail. Related to this, in the context of international freight movements, is the 'sea-maximising-land minimising' principle whereby ports which are located close to the market regions to which the cargo is destined are selected, thereby minimising road miles. Recently, research into the mitigation of the carbon footprint of freight transport has concentrated on the reduction of carbon emissions in separate modes of transport. For example, Qi and Song (2012), Cheng *et al* (2013) and Chen *et al* (2014) have focused on a number of initiatives which can be adopted to reduce the carbon footprint of the maritime leg of freight transport chains. However, the literature on port selection in maritime supply chains does not incorporate CO_2e emissions as a factor in port choice. Furthermore, when evaluating the alternative solutions for shifting cargo from road to less carbon intensive modes, it is important to include opportunities for CO_2e reduction within road transport operations. Therefore, there is a need for more disaggregated analysis to be undertaken in order to estimate the impact of port selection under a range of scenarios which include the carbon intensity of road freight transport as a key variable.

This paper therefore extends the work of Sanchez Rodrigues *et al* (2014) in considering whether the use of alternative port gateways can contribute significantly to an overall reduction in freight transport-related CO_2e emissions in international supply chains. The approach taken in this study mirrors that of Liao *et al* (2010) and Sanchez Rodrigues *et al* (2014); an activity-based CO_2e emission model is used to estimate the cost and CO_2e impact of five Scenarios which are described in the paper as the "current situation" and four "proposed Scenarios". The model includes a carbon reduction parameter to account for likely future reduction in the carbon intensity of road freight transport. The paper includes several new contributions to the literature: firstly the model developed by Sanchez Rodrigues et al. (2014) has been substantially expanded here by considering different scenarios aimed at minimising overall road distance travelled (the land transport matrix is resolved using Excel Solver). We also introduce a road-based carbon reduction parameter as part of the modelling and analysis of the carbon mitigation strategies. In addition, we consider implications of modeling the London Gateway port on the network operations to reflect current ambitious plans of the British Government to expand the London Gateway port. We also include cost and CO_2e related to port expansion and we estimate the total CO_2e emissions generated from changes in the level of congestion as a consequence of transferring containers from less carbon intensive modes and / or route combinations. Finally the model developed in the current paper assesses the tradeoffs between CO_2e reduction in road freight transport and modal shift from road to water and/rail. The impact of the modelling exercise on ports' capacities is also discussed where each scenario determines a transport framework and the port capacities required to satisfy all demand.

In terms of the modelling approach adopted in this study, a range of variables which can impact on the overall cost and CO_2e emissions are considered. These factors include terminal building costs, transport operating costs, intermodal freight transfer cost, and CO_2e emissions derived from the use of alternative modes and routes. The Scenarios modelled in the paper include a baseline scenario and a series of scenarios which capture the outcomes when alternative routes are used.

The model is constructed at a strategic level rather than at an operational or tactical level, since the purpose of the modelling approach is to formulate a broad picture of the cost and CO_2e impacts of re-routing containers. Nevertheless, the model integrates some tactical aspects which are linked to changes in traffic volume generated by the shift of containers among the Scenarios.

The aim of the modelling process is to achieve an understanding of how UK import containers may potentially be re-routed such that either costs or CO_2e emissions, or both, could be reduced. The variables used in model can be broken down into several parameters which could impact on the overall cost and CO_2e emissions of re-routed containers. These parameters which are incorporated into the model are: port expansion cost, transport cost per TEU, port/intermodal terminal handling charges per TEU, and CO_2e emissions per TEU-km. In order to account for the expected changes in the CO_2e levels in the modelled scenarios, variable carbon conversion factors, which are dependent on the average speed of vehicles in all the port origin-destination routes, have been incorporated. The speeds of vehicles on all the port origin-destination routes used in the five scenarios are estimated from average number of vehicles per day statistics on all the relevant routes used in the study, gathered from the Department for Transport (DfT, 2013).

2. Road freight transport-based decarbonisation initiatives

There is a growing body of research into carbon mitigation in supply chains and freight transport operations. In this paper, we outline recent developments in the area of CO_2e mitigation in the supply chain and freight transport literature with a focus on through transport and gateway port selection. There are a range of decarbonisation initiatives for freight transport and the literature focuses on a number of CO_2e reduction elements, namely shifting to less carbon intensive transport modes, more efficient consolidation of goods, running a more carbon efficient fleet and reducing the carbon content of the fuel used. The classification of these initiatives varies from author to author. For instance, in the areas of carbon footprint reduction and Green Supply Chain Management (GSCM), Rao (2003) and Sarkis (1999) focused on how a range of initiatives can make outbound logistics greener. Murphy and Poist (2003) meanwhile suggested that the logistics activities which have the worst environmental effects are: salvage and scrap disposal, packaging, transport, return goods handling, purchasing, international logistics and customer service.

Elsewhere Srivastara (2007) classified GSCM into three main areas: green design, green operations and green manufacturing.

Several studies have investigated practices aimed at 'greening' supply chains (e.g. Beamon, 1999; Murphy and Poist, 2003; Srivastava, 2007; Sheu and Talley, 2011) as well as how organizations can reduce their overall supply chain carbon footprint. Nevertheless, most of this "framework" research has concentrated on individual supply chain elements, such as carbon reduction in freight transport (Tacken *et al*., 2014), carbon efficiency in warehousing (Marchant, 2010) or the carbon dimension of product design (Sarkis, 2003). McKinnon and Piecyk (2012) provide an insight into how to develop a decarbonisation strategy for logistics. Earlier, McKinnon (2007; 2010) developed an analytical framework which focuses on guiding the decarbonisation of the road freight transport sector and networks. The framework encompasses seven parameters: modal split, average handling factor (or the average number of nodes in supply chains), average length of haul, average load on laden trips, average empty running per trip, energy efficiency and emissions per unit of energy used. Tacken *et al.* (2014) connected these parameters with four key areas where road freight transport operations could focus in order to reduce emissions. The four areas suggested are: modal split, logistics efficiency, vehicle fuel efficiency and carbon intensity of fuel used. In light of the Tacken *et al*. (2014) study, the objectives of this paper are, firstly, to examine the impact of container routeing alternatives on the CO_2e footprint derived from the total TEU-kilometers performed and, secondly, to assess how port selection affects this footprint.

Carbon reduction initiatives have often been highlighted and widely explored. They are often linked to efficiency measurement and improvement, for example better routeing and scheduling of vehicles were first identified by Wu and Dunn (1995) and extended by, for example, Wee *et al*. (2005) and McKinnon (2007, 2008). Also, inter-company collaboration has been advocated by several authors (e.g. Mason *et al*. 2007) as a way of reducing the carbon footprint of road freight transport networks. Furthermore, other measures are focused on vehicle efficiency, e.g. increased vehicle dimensions (Wee *et al.*, 2005), driver training/driving incentives (McKinnon, 2010) and improved aerodynamic profiling of trailers and reduced vehicle weight (Shell Deutschland Oil GmbH, 2010). Moreover, some authors have focused their discussions on specialised technical measures (Shell Deutschland Oil GmbH, 2010) to increase the carbon efficiency of transport modes (Wee *et al*., 2005), modal shift (Woodburn and Whiteing, 2010) or the optimisation of routeing (Eglese and Black, 2010).

3. Modal Shift

The concept of modal shift is not new. A wide range of initiatives, with substantial financial support, have been developed at local, regional, national or trans-national levels over a period of several decades (Woodburn *et al.*, 2007; Jonkeren *et a*l, 2011; Lattila *et al*., 2013; Chen *et al*., 2014; EC, 2014). These initiatives are focused mainly on reducing the amount of transport carried out by carbon-intensive modes, especially road, and on substituting the movements with transport by less carbon-intensive methods, typically inland waterway, coastal shipping or rail. The shifting of freight (or passengers) away from one mode and on to another is not simple. A large number of factors influence modal choice in the first instance. The early work of McKinnon (1989) classified these factors into 'service related', 'consignor related' and 'traffic related' allowing some visibility of the commercial elements which affect modal choice. The work, however, is focused on ‘head-to-head’ choices e.g., road versus rail or rail versus inland waterway, it does not take a multimodal approach, nor does the work attempt to weight the factors according to commercial circumstances or according to their effects on the carbon footprints of particular solutions.

Nonetheless, McKinnon’s factors, e.g. traffic conditions, transport distances, vehicle capacity, fuel costs, service reliability and time sensitivity, remain extremely important in freight routeing, modal choice and, by implication, modal shift. Specific operational considerations e.g. train scheduling / frequency of departure, vessel schedules, berthing constraints and road vehicle driver’s hours limits are also important. Notwithstanding these operational limitations, the capacity of the major gateway ports permits them to serve all major inland towns, although not always via the most direct route which is sometimes compromised by, for example, the rail corridor loading gauge (discussed in detail in Section 5 below). The container flows between the gateway ports and inland centres which are used here are therefore necessarily simplified, but they remain realistic.

Road haulage is consistently the dominant method for most inland container movements implying that the carbon efficiency of road haulage itself is central to the overall carbon footprint for container transport. In this regard, several studies have considered the use of alternative fuels as a valid carbon reduction measure in road freight transport (for example, Eglese and Black, 2010; Wee *et al.*, 2005; Wu and Dunn 1995). However, Tacken *et al*. (2014) found that alternative fuels such as bio-fuels are not as carbon efficient as initially thought. In relation to this study, a parameter for carbon reduction is included in the modelling to include likely levels of future road-based carbon intensity as a key factor in the process of port selection within supply chains. This is because the more the carbon intensity of road freight transport is reduced; the less radical a shift from road to greener transport modes would be required.

In addition, some research has focused on the role of rail and water freight transport as alternative, solutions which are less carbon intensive than road freight transport. For example, Woodburn *et al.* (2007) identified four types of measure which could be adopted to incentivise modal shift in the UK and European Union countries. Also, Lattila *et al*. (2013) demonstrated the positive effects of the increasing use of rail-road inland terminals in the overall carbon footprint of logistics chains. Chen *et al*. (2014), on the other hand, focuses on the role of costal shipping service as a low carbon alternative to road freight movements. Also, on the marine side, a parallel thread of research is beginning to suggest that marine propulsion itself could be very different in the future with various energy management systems, hybrid engines and new fuels currently being developed. (Gunton, 2014)

4. UK Ports and Inland Container Transport

While there is a large body of literature on the need for carbon mitigation in freight transport, there has been little consideration of how this might impact on the choice of route, mode or method in specific cases. Of particular importance is the selection process regarding alternative ports of call, where the choice may play a significant role in reducing the overall carbon emissions of a given supply chain. This issue has been considered by Sanchez Rodrigues et al (2014) who provide some insights into the changes that could be implemented. A key aspect of the mitigation process would be the choice of port of entry, and changes in the level of demand which could affect the demand for port services. The next section therefore presents a review of the literature on port selection and its relationship to inland container transport.

Port capacity expansion decisions for a given region are important in terms of economic development. However, as Sanchez Rodrigues (2014) highlights, the literature on port selection generally focuses on economic and commercial aspects rather than on the role of ports in contributing to carbon emission reduction in supply chains. Port selection is a complex problem often studied from an economic perspective (Slack, 1985; Lirn *et al.*, 2004; Leachman, 2008; Tongzon, 2009; Steven and Corsi, 2012) and decisions by shipping lines can have an impact creating either congestion or overcapacity (Tongzon, 2002; Tongzon and Sawant, 2007; Fan *et al*., 2012). This is especially likely when major lines switch ports causing very large numbers of containers to be funneled into a particular port or terminal and large volumes to be lost elsewhere. Port selection approaches from the perspective of logistics chains and inter-modal transport operations is therefore an important aspect which needs to be considered in the overall approach (Robinson, 2002; Malchow and Kanafani, 2004). A study by Chen *et al*. (2014) demonstrates how coastal shipping services can reduce the overall emissions of logistics chains; but the study does not explicitly connect port selection with coastal shipping as an alternative to traditional road freight transport services. A major issue for the UK ports industry in the late 1990s and early part of the 2000s was the forecast growth in volumes and the associated problem of a lack of capacity at the major UK container ports. Additional capacity was a recognized need and several major developments were proposed to deal with the shortfall (DfT, 2009; MDS Transmodal, 2006a). Only a small number of ports (Liverpool, Felixstowe, Thamesport, Tilbury and Southampton) handled most of the existing volumes and the extra capacity was needed largely in the south and east; this can be seen essentially as a problem of over-concentration (Dawe, 2001; Pettit and Beresford, 2009).

One of the main issues identifiable from the existing research is that, while carbon efficiency is an important variable which should be taken into account by the shipping lines in the port selection process, to date the criteria relating to port selection have primarily focused on the economic impact of inland transport minimization rather than on the problems of CO_2e emissions generated due to economics-driven port selection. In the recent past, however, the increasing importance of carbon mitigation at a global level has led to increased pressure on transport modes with disproportionately high CO_2e emissions; the development of carbon reduction measures such as modal shift from road to less carbon intensive modes, and other road-based carbon mitigation initiatives have thus emerged. As this paper seeks to demonstrate, CO_2e emissions generated from road freight transport can be reduced by having a more sensitive port selection process and by increasing the carbon efficiency of road freight transport in the aggregate.

With more carefully defined logistics strategies, knowledge of the origins and destinations of containers has become a very important aspect of optimising port choice and total freight transport cost solutions. Thus it seems pertinent to assess the environmental as well as economic impacts of the potential joint transport-based carbon mitigation solutions which can include port selection, mode choice and improvements in the carbon intensity of road freight transport. In respect of the movement of containers, destinations are linked closely to the principal concentrations of industry and population, such as the Scottish lowlands, Northwest and central Northern England, Tyne/Tees, Humber, Midlands; parts of South Wales and Western England, and much of the

Southeast (Pettit and Beresford 2007; MDS Transmodal 2006a). The latter study made predictions regarding the growth of container volumes over the next twenty years and, while this cannot be verified, the predictions, do give some indication of how containerised volumes are likely to be distributed. Previous studies have not included origin to destination movements based on the minimisation of inland transport-related freight-based CO_2e emissions through decarbonisation strategies such as modal shift and other relevant road-based carbon mitigation measures. This paper addresses this issue.

5. Methodology

With reference to the approaches taken by Liao *et al*., (2010) and Sanchez Rodrigues *et al*., (2014), this paper develops a series of new Scenarios designed to model the increased or decreased use of port alternatives. The overall aim of the current paper is to simulate possible CO_2e mitigation strategies along supply chains in the UK. TIn the methodology, transport movements are analysed on a more disaggregated basis than similar investigations carried out elsewhere. Furthermore this study, for the first time, incorporates a new carbon reduction parameter to assess road CO_2e solutions as an alternative to carbon reduction for the UK freight transport sector. New UK port developments such as London Gateway are taken into account in the modelling of the impact of CO_2e emissions for container routing.

In order to understand the impacts of port choice on logistics solutions and the potential impact that new solutions may have on the level of CO_2e emissions, three UK port clusters are considered for the analysis. One cluster is located in the 'southern gateway' (Felixstowe, London Gateway and Southampton), another two clusters are in the southwest (Bristol) and in the 'northern gateway' (Hull, Immingham and Liverpool). Felixstowe port is an established deep sea port serving the whole of the UK, London Gateway is projected to grow considerably in the next few years and Southampton complements these two ports in terms of capacity and location. Bristol, Hull, Immingham and Liverpool operate at the northern and western limits of possible deep sea vessel calls with various physical or geographical constraints, such as tidal range and depth alongside effectively capping their capacity and / or growth potential. Bristol was chosen as a potentially viable south-western gateway as it has obtained approval for a new deep-sea container terminal in March 2010 (Port of Bristol, 2013). The six demand regions outlined in the studies by Pettit and Beresford (2007) and Sanchez Rodrigues (2014) were used to support the main assumptions which form the platform for this paper.

Data related to seven ports used in all modelling scenarios are shown in the Table 1. Those ports are Bristol, Dover, Felixstowe, Hull (with Grimsby and Immingham), Liverpool, London (including Medway and Tilbury) and Southampton (with Portsmouth). As can be seen from the table, some ports are grouped together due to their close geographical proximity as in the case of the port of Hull that was clustered with Grimsby and Immingham. All ports selected for this study jointly handle around 70% of the total UK containerised imports. These ports are incorporated in the study since they are major container handling ports as well having significant growth potential. Table 1 also presents the baseline data, comprising cargo volumes in thousands of TEUs (including both Lift-On Lift-Off (Lo-Lo) and Roll-On Roll-Off (Ro-Ro) units through relevant ports, as published by the Department for Transport (DfT, 2013). The number of TEUs was calculated by using a conversion factor of 1.7 to convert units published, to the number of TEUs.

Table 2 presents the forecast demand data for 2015 estimated from the MDS Transmodal report (2006a) as the basis for TEUs per destination region. For the Midlands, East England and South East regions, the MDS Transmodal projections for 2010 were recalibrated, using population statistics from the Office for National Statistics (2011), to account for the fact that eastern England and the south east statistically absorb the majority of Midlands' TEUs. For each region a central reference city was used for the calculation of the TEU-miles from ports of origin to destinations. The reference cities are used because they have concentrated populations in the regions being considered.

PORT	Imports (000' TEUs)
Bristol	37.4
Dover	1,645.6
Felixstowe	1,861.5
Hull (including Grimsby and Immingham)	1,009.8
Liverpool	569.5
London (including Medway and Tilbury)	950.3
Southampton (including Portsmouth)	894.2
Total import containers for the selected ports:	**6,968.3**
Total UK imports	**9,914.4**

(Source: adapted from Department for Transport (DfT, 2013))

Table 1. Selected port data for UK import containers (000s TEUs).

Destination Region	Reference City	000' TEUs	Destination Region	Reference City	000' TEUs
Scotland	Glasgow	120.46	North West	Liverpool	441.79
	Edinburgh	120.46		Manchester	441.79
North East	Newcastle	156.66	Wales	Swansea**	56.40
York & Humber	Leeds	250.66	South West	Exeter	131.60
	Sheffield	250.66	East England	Northampton	907.07
Midlands	Derby*	1,558.67	South East	London	2,532.11

(Source: Author's estimates based on population consumption estimates)

*- Derby is use as a representative of a Midlands location although in practice it is in Central-Northern England
** - Swansea is taken a mid-point for South Wales

Table 2. TEUs allocation by destination region.

The datasets were used to calculate the TEU-kilometres for five Scenarios. For the purposes of this paper, operational considerations, which are very complex, have been simplified. In the modelling approach taken in the five Scenarios, flows of non-standard containers, e.g. 48', 45' or High Cube (W10/W12 gauge), were not estimated separately, since such boxes are still in the minority at most ports. It is also the case that the work required to lift them at the ports and to transport them by road is similar to that required for standard 40' boxes; over-sized boxes are thus considered as 40' containers. The principal constraints with these non-standard (over length or High Cube) boxes apply to rail transport with restrictions on routeing resulting from loading gauge constraints. The restrictions are complicated by the selective use of specialist low-liner wagons which can accommodate High Cube containers, but with a purchase cost penalty. Over-length containers are also sometimes restricted in terms of how they are mixed with 20' or 30' boxes, again implying a small cost penalty.

Operationally, the response is often to concentrate flows along gauge-cleared corridors (Woodburn, 2008, Network Rail, 2007, Network Rail, 2013). However, most trainloads conform to W9 gauge standards, allowing unrestricted access to the rail network from all the major ports (Network Rail, 2007). Nevertheless, the use of standard 40' containers (or 2 TEUs) is therefore a reasonable proxy for the overall flows which are the main focus of this paper. The seven unit-load ports considered here, which are accessible to the rail freight network, are assumed to be operating at current capacity. In order to build the five Scenarios, origin data in TEUs is allocated to the destination cities considering minimisation of distance travelled by road as the primary goal.

The five Scenarios are:

- *Base Scenario A*: the baseline Scenario minimizes total road distance travelled and assumes that the capacity of the seven ports remains constant.
- *Scenario B* is modelled by assuming that the expansion of Bristol, Hull (plus Grimsby and Immingham), Liverpool and London will minimize total TEU- road distance travelled because ships will call at the port which is closest to the final inland destinations of the containers. The main aim of this Scenario is to reduce CO_2e and inland transport costs by minimizing freight transport movements at a macro level; this will also tend to reduce traffic congestion. This Scenario has been considered due to the UK Northern Gateway project, which aims at increasing the container handling volume of the UK Northern ports (Port of Hull, 2013; Port of Liverpool, 2013; Northern Gateways, 2014).
- *Scenario C* is estimated by assuming that Southampton can be expanded and that Derby, (representing central northern England), Manchester, Glasgow and Edinburgh can be fed by rail from the port of Southampton. This Scenario could be driven by strategic changes linked to the UK ports of call on the part of the Liner shipping companies. Further investment in the UK rail network would be required. This Scenario has been driven by the investment commitment to the expansion of the port of Southampton by Dubai Ports World (Dubai Ports World, 2013; Port of Southampton, 2013).

- *Scenario D* assumes that some expansion of the port of Felixstowe is feasible and that Derby, Manchester, Glasgow and Edinburgh can be fed by rail container services instead of transporting containers by road. This scenario is driven by the increasingly large vessels that have restricted alternatives in terms of their ports of call. Felixstowe and London Gateway, the UKs only ports that accept vessels of the Maersk E Class or equivalent, allow the construction of this Scenario (Port of Felixstowe, 2013; Collingridge, 2014).
- *Scenario E* assumes extensive expansion of London Gateway (including Medway and Tilbury) is feasible and that Derby, Manchester, Glasgow and Edinburgh can be fed by rail instead of transporting containers by road. The ambitious expansion of southeast England's container handling capacity by the construction of London Gateway currently being brought on-stream in phases from 2014 to 2016 justifies the inclusion of this port (Collingridge, 2014).

Each scenario is formulated as a transport problem that determines the number of TEUs that can be transported to the destination points in order to satisfy all customer demand, subject to capacity constraints, while minimizing overall road distances travelled. The adoption of a road transport-based model is driven by the core research purpose of the study. This is to evaluate the impact of reducing total road transport miles to inland container destinations in order to reduce overall carbon emissions. The selection of a road transport-based model is underpinned by the fact that road freight transport is considerably more carbon intensive and costly compared to rail and sea transport modes (DEFRA, 2013). Therefore, it is hypothesized in the paper that the minimization of road miles can lead to the minimization of transport cost and CO_2e emissions. Nevertheless, the paper also evaluates the impact of the scenarios on the cost and CO_2e emissions of the container handling process at ports as well as port expansion. In our paper we focus on the strategic and macro nature of decisions rather than operational and micro decisions. A transport distance problem formulation is adopted because loaded containers do not typically hold inventory at UK ports, rather they are transported directly to their destination, spending only a short time at the ports, for example up to 5 days without additional charge (Fung et al, 2003; GHK, 2008; Port of Felixstowe, 2012). Nevertheless, there is the potential to extend the research presented in this paper to specific commodities and clusters of end transport users (e.g. manufacturers and retailers from a given sector) using primary data. Such models would incorporate actual container handling charges and decisions regarding the transportation mode, which in practice varies from port to port and from service to service.

Import TEU containers are received at m different port locations, $i=1,\ldots,m$. The supply (throughput) of TEUs at each port i is s_i. The demand for the TEUs is spread out at n different reference cities, $j=1,\ldots,n$. The demand at the jth demand location is b_j. The shipping distance from port i to city j for transporting one TEU from port i to city j is d_{ij}. The total supply of TEUs is assumed to be equal to the total demand for each scenario. The problem is to transport TEUs from specific port locations to a reference city at minimum road distance travelled where x_{ij} is defined to be the number of units shipped from port i to reference city j.

$$\min \sum_{i=1}^{m} \sum_{j=1}^{n} d_{ij} x_{ij} \qquad (1)$$

subject to

$$\sum_{j=1}^{n} x_{ij} = s_i \quad for\ all\ i = 1, \ldots, m. \quad (2)$$

$$\sum_{i=1}^{m} x_{ij} = b_j \quad for\ all\ j = 1, \ldots, n. \quad (3)$$

$$x_{ij} \geq 0, \qquad for\ all\ i = 1, \ldots, m.;\ j = 1, \ldots, n. \quad (4)$$

Constraint (2) ensures that the capacity constraints for TEUs are not violated and constraint (3) ensures that the demand at each city is satisfied. Constraint (4) enforces the non-negativity restriction on the decision variable used in the model.

Figure 1 provides an overview of the input and output variables used in the model. The input variables include: locations and container volume data for all routes analysed in the five scenarios; fixed costs and CO_2e parameters related to the operation, and expansion of ports; port container handling costs; freight transport costs; fixed carbon conversion factors for rail and sea; and variable carbon conversion factors (depending on the average speed for the main road used in the five scenarios). The output variables used in the model are: cost and CO_2e emissions generated in the scenarios due to port expansion and the transfer of containers from routes in the baseline scenario to alternative routes. The model minimises road-based TEU-kms in the five scenarios, since the rail and sea freight transport modes are assumed to be more carbon efficient than road. A road-based carbon reduction parameter is incorporated in the model to test the sensitivity that the model has to future improvements in the carbon efficiency of road freight transport. Excel Solver is used to find an optimal solution for each scenario.

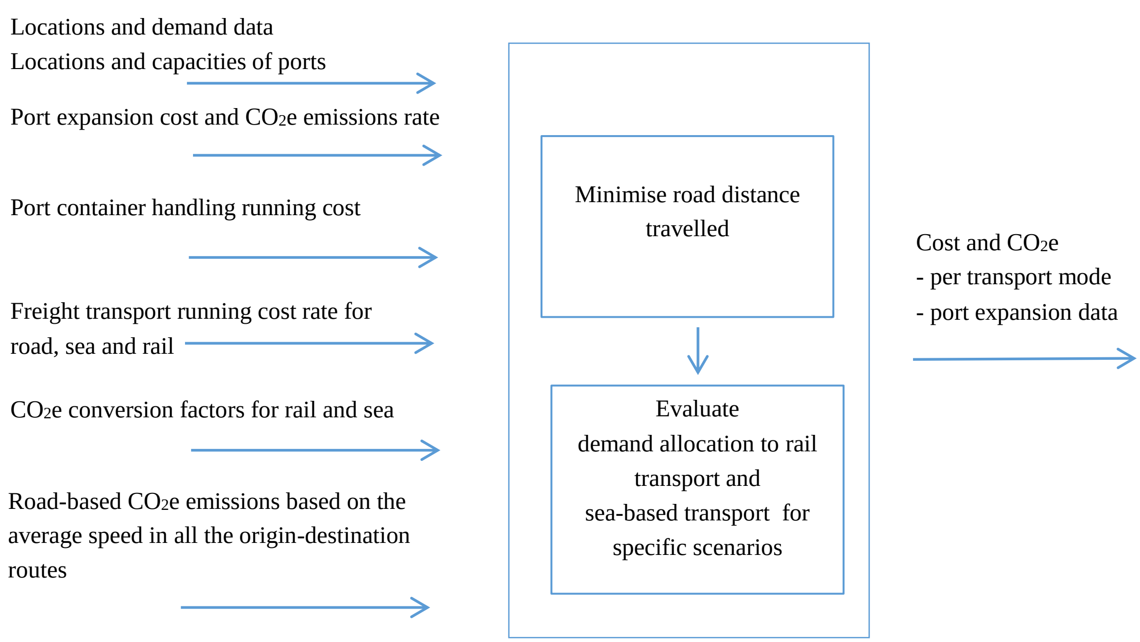

Figure 1. Overview of the model.

The first stage of the modelling process determines the transport plan for a road-based scenario as discussed in the Scenario A. In scenarios B, C, D and E, we relax all port capacity constraints and force some of the demand locations to be served by a specific rail path. This allows the establishment of the transport plan and determines capacities needed for each port under consideration. Table 7 illustrates all changes in port capacities as a result of the optimization. After determining an optimum road-based transport plan we derive CO_2e and cost values for rail and shipping, as discussed below. Data related to differences in distances between ports and the destinations are calculated using an on-line distance calculator (Daft Logic, 2011) and we allocate differences in those maritime distances when a serving port changes from the one that is in Scenario A to a new supply location in Scenarios B, C, D and E. The Isles of Scilly is used as a reference point to calculate the differences in equivalent road miles generated for the sea leg between Scenarios B-E and the actual Scenario A. Table 3 shows the differences in equivalent road miles. It was assumed that the majority of containers which arrive at Bristol, Felixstowe, Liverpool, London Gateway and Southampton are transported through the western approaches past the Isles of Scilly (see for example MDS Transmodal, 2006b; Lloyd's, 2013).

In scenarios C - E selected demand locations are served by rail. Derby, Manchester and Glasgow were specified as rail hubs for these rail routes. The locations of these hubs were chosen based on their density of population, freight generation / consumption and geography. Rail route distances from the ports of Southampton, Felixstowe and London Gateway to each rail hub were calculated. No additional road kilometers were added to the rail kilometers in those scenarios because the freight that could be moved by road is transferred by rail from Southampton, Felixstowe and London Gateway by rail.

5.1. Transport related factors: calculation of CO_2e emissions and costs

Table 4 details the parameters used for the calculation of CO_2e emissions, following the standard approach taken by the Department for the Environment, Food and Rural Affairs (DEFRA, 2013). Costs per TEU-km for each of the transport modes, as suggested by the Department for Transport (DfT, 2012), are also shown. In the case of rail and sea modes, the factors used in the modelling exercise are based on average loading factors of the vehicles for the respective modes of transport. These loading factors are widely accepted as being representative for the majority of freight hauls in the UK. However, in the case of the CO_2e parameters for road, the conversion factors used are variable and dependent on the estimated average speed, especially on the principal road used, for the route being modelled. The reason for using a variable carbon conversion factor for road freight transport is that road freight vehicle journeys are impacted by traffic congestion problems, which is not the case for rail and sea transport modes. Appendix A shows the steps taken to estimate the range of CO_2e emission conversion factors for all the major roads in the five scenarios. These steps are:

- Step 1 – Identifying the predominant major road for each of the routes from Google Maps
- Step 2 – Calculating the average number of vehicles using the road from traffic volume statistics from the UK Department for Transport (DfT, 2014)
- Step 3 – Estimating the average speed of vehicles in each of the predominant major roads identified in Step 1 (DfT, 2007)
- Step 4 – Calculating the CO_2e emissions conversion factors for all predominant major roads identified in Step 1 (DfT, 2010)

Newly assigned Port – Original Port	**Miles**	**Newly assigned Port – Original Port**	**Miles**
Southampton-Hull	-370	Felixstowe-Hull	-220
Southampton-Liverpool	-150	Felixstowe-Liverpool	30
Southampton-Felixstowe	-180	Felixstowe -Southampton	180
Southampton-London	-175	Felixstowe-Dover	30
Hull-Southampton	370	Felixstowe -London	-10
Hull-Felixstowe	220	London-Dover	80
Bristol-Liverpool	-130	London-Southampton	175
Bristol – Southampton	30	London – Felixstowe	10
Bristol-Felixstowe	-150	London-Liverpool	40
Liverpool-Bristol	130	London-Hull	-160
Liverpool-Hull	-210		

Table 3. Difference in 'road miles'.

A baseline scenario (Scenario A) was established using the above approach. The average numbers of vehicles for Scenarios B to E are estimated by accounting for the changes in the volume of freight among the scenarios. Hence, on routes where the total number of vehicles decreases, the decreases are subtracted from the average number of vehicles estimated for baseline scenario. In the case of routes with an increase in the total number of vehicles, the increases are added to the average number of vehicles calculated from the UK traffic volume statistics.

In the modelling exercise, a road-based CO_2e reduction parameter was included to assess the sensitivity of the output variables (namely overall CO_2e emissions and total freight transport cost) to such changes. The five Scenarios have been modelled with six values for this parameter: 0%, 10%, 20%, 30%, 40% and 50%. According to Piecyk and McKinnon (2010), in the absence of any new policy initiatives (i.e. business-as-usual scenario) GHG emissions from road freight transport in the UK should decline from around 10% from the 2007 baseline. In the optimistic scenario, a reduction of up to 56% can be expected, as suggested by Piecyk and McKinnon (2010). The paper uses six parameters for road-based CO_2e reduction initiatives and it incorporates pessimistic values of road-based CO_2e reduction rates to allow for the impacts of the recent economic downturn and acknowledge that the resources available to logistics operators to improve their carbon efficiency may still be sparse.

Transport Mode	CO2e Parameter (Kg per TEU-km)	Cost parameter (£ per TEU-km)
Road	Variable*	0.99
Maritime	0.17655	0.62
Rail	0.33693	0.31

** Dependent on route and traffic conditions* - *see Appendix A*

Table 4. CO_2e and cost parameters by activity used in the study.

Diesel (standard biodiesel blend for the UK) is the only road fuel included in the model, as this is virtually the only fuel used in long-haul transport by articulated 44 tonne gvw trucks (McKinnon, 2007). A small proportion of trucks in the UK fleet are electric; however these are predominantly small rigid vehicles used in urban distribution. There is almost no evidence that would suggest improvements in technology significant enough to make electric trucks a viable option for long-haul distribution in the foreseeable future, although there are currently some trials underway to test other fuel options (McKinnon and Piecyk, 2009b). Thus, due to the uncertainty over which other fuel options are likely to be viable within the timeframe referred to in the study; only diesel-powered trucks are included in the modelling.

5.2. Port/Rail operations: calculation of CO_2e emissions and costs.

An additional element in the overall pattern of container movement is the lifting and transport of containers within the seaport, specifically at the container terminal. Terminal operations are widely recognised as complex and varied as they depend upon factors such as: the routeing of the containers through the terminal (e.g. whether or not the containers are held temporarily in a stack), whether the containers move out of the terminal by rail or road, whether the containers are immediately transported out of the terminal or not, and finally what type of equipment is used to move the containers within the terminal. Many of these factors are also linked in a complex way to the size, shape, and configuration of the terminal, the size of ships served, terminal operator policy and other influences.

Nonetheless, these movements can be resolved into standard emission factors by generalising the configuration of the terminal and of the container movements within it. Geerlings and van Duin (2011) suggest a method for assessing carbon emissions for container terminals, using the Port of Rotterdam as a case for analysis. In their study they detail emissions for the various types of equipment and for the different routes containers follow through a prescribed terminal. This enables a range of values to be calculated running from the most complex routeing (Ship to Road via Stack using several different types of equipment) to the simplest (Ship direct to truck for immediate distribution). Nieuwenhuis *et al* (2012) also offer some insights into emissions generated by terminal operations in a multimodal freight transport environment, although their analysis applies to the large scale shipment of cars, rather than containers. Geerlings and van Duin’s (2011) estimates for emissions range between 0.39 kg CO_2e per container for Reach Stackers to 4.37 kg CO_2e per container for Multi Trailer Systems. The estimate of carbon emissions for car movements on a terminal (Nieuwenhuis *et al,* 2012) are 0.164 kg CO_2e per kilometer. In both cases the overall emissions of CO_2e account for around 2% of total emissions for the transport chain. In contrast, Walnum (2011) suggests that trans-oceanic tanker lifecycle emissions of CO_2e can be split as follows: Ship operation – 83%; port operation – 15%; ship production – 2%; ship maintenance – 0.01 % and construction of port facilities 0.01%.

Notwithstanding the fact that this macro-analysis applies to liquid bulk transport, the proportions suggest that the ship operation is heavily dominant, although the port operation is also significant in terms of its environmental footprint. It appears that the trades (container, liquid bulk, potentially Ro-Ro and others) largely determine the overall carbon footprint with some being determined quite heavily by either the port / transfer operation, while others appear to be determined almost entirely by the transport (especially the shipping) operation. For the purposes of this study, specific assumptions were made concerning the proportion of containers moving through a terminal. These assumptions were, firstly, that any one move in the terminal generates 1.85 kg CO_2e per TEU. This figure is derived from averaging the statistics listed by Geerlings and van Duin (2011) in respect of CO_2e generated by different types of terminal handling equipment. Secondly, the proportions of containers following particular pathways through the terminal were specified as: 67% moved from the ship to the stack prior to leaving the port; and 33% moved directly trucks for immediate onward transport. To account for the fact that most containers are handled and moved several times within a terminal, multiplication factors for the number of times a container is moved were set at 2 moves for direct transfer from ship to road, 5 moves for transfer from ship to rail and 8 moves for ship to road or rail via a stacking yard. These multiplication factors were verified by comparing the lifting / movement activities modelled here with those proposed by Geerlings and van Duin (2011).

In respect of costs for the movement of containers within a terminal there is again variation in the total charge levied by ports depending on a range of factors including volume and commercial judgement. However, although container handling rates do vary considerably, the lifting and transfer of containers from ship to road transport at a port typically costs around £100 per TEU, while the transfer of containers onto rail is on average £150 (European Commission, 2009).

5.3. Port expansion: calculation of CO_2e emissions and costs.

The cost factor related to construction activity necessary to expand a port was also considered in this study. Some academic papers show that port infrastructure contributions to port lifecycle emissions are relatively small (Simonsen, 2011). Using the Port of Liverpool as an exemplar, estimates of the total cost of expansion and CO_2e emissions per TEU were derived. A projected total construction cost of £300 million and an increase in containers handled from 700,000 per annum to 3.7 million in 2030 (BBC, 2014; The Merseyside Partnership, 2014) provide a basis for calculating these estimates. Maas (2011) provided Life Cycle Analysis comparisons for different quay wall designs (concrete, steel, wood and composites) with particular reference to CO_2e emissions. Maas (2011) suggests that the construction of a concrete quay wall will generate around 50,000 kg of CO_2e per metre of wall. Tables 5 and 6 capture the pertinent data. The literature related to CO_2e emissions for port expansion is still scarce, therefore future research needs to be undertaken to examine the impact of construction at different ports as a result of port development.

Quay extension descriptors	Units	Total
Total cost of the expansion	£	300,000,000
Length of Liverpool quay extension	meters	854
1m of quay wall, mainly concrete	kg CO2e	50,000
Carbon equivalent footprint for Liverpool container terminal quay extension	kg CO2e	42,700,000

Sources: BBC, 2014; The Merseyside Partnership, 2014; Maas, 2011; Hill et. al., 2012.

Table 5. Data related to Liverpool quay extension.

Port operating period	Number of TEUs	CO2e (kg, per TEU)	Cost (per TEU)
17 years TEU throughput at Liverpool (2014-2030)	44,399,973	0.9617	£6.76
35 years TEU throughput at Liverpool (2014-2050)	110,999,973	0.3846	£2.70
50 years TEU throughput at Liverpool (2014-2065)	166,499,973	0.2564	£1.80

Table 6. Data used in the study based on Liverpool quay extension.

6. Findings from the modeling of the five scenarios

As discussed in Section 5 (Methodology), five Scenarios were analyzed and the freight transport costs and CO_2e calculated for each scenario using the assumptions discussed above.

The output variables used in the five Scenarios are tonnes of CO_2e and total cost of three elements, namely port expansion, container handling and freight transport. The logic applied in the five Scenarios is that minimizing the TEU-km run by road can lead to minimization of the CO_2e emissions within the five Scenarios. Moreover, the CO_2e reduction factor for road freight transport that varied between 0% and 50% has been used to explore the sensitivity of each Scenario to likely CO_2e reductions linked to carbon efficiency improvements in road freight transport. Figure 2 summarises the findings and shows that Scenario C, the expansion of the port of Southampton with a shift of containers from road to rail, has the lowest values for total freight transport cost and CO_2e emissions. Scenario A only has similar levels of CO_2e emissions to Scenario C, if a 50% reduction in the carbon intensity of road freight were possible. Scenarios D and E, that use rail based options from Felixstowe and London Gateway produce similar results, hence they are closely aligned in Figure 2. Scenarios D and E have slightly lower values of tonnes of CO_2e emissions and total cost than Scenario A. However, if the carbon intensity of road freight is reduced by 40%, Scenario A has about the same carbon intensity than Scenario D and E. Furthermore, Scenario B has lower values of tonnes of CO_2e and cost than Scenario A, but the latter is more carbon intensive and has a higher cost than Scenario C.

According to the findings, as can be seen in Table 7, Scenario C seems to be the least carbon intensive and most economical scenario with outputs of 585,000 tonnes of CO_2e emissions and a cost of around £1.5 billion, which represents reductions of CO_2e emissions and cost, relative to Scenario A, of about 48% and 20% respectively. Scenario C assumes that Southampton can be expanded and that Derby, Manchester, Glasgow and Edinburgh can be fed by rail from the port of Southampton. The findings show that, even with a road-based reduction factor of 50%, Scenario A will not reduce to equal the total CO_2e emissions and cost of Scenario C i.e. even in a very optimistic future carbon reduction scenario for road freight transport.

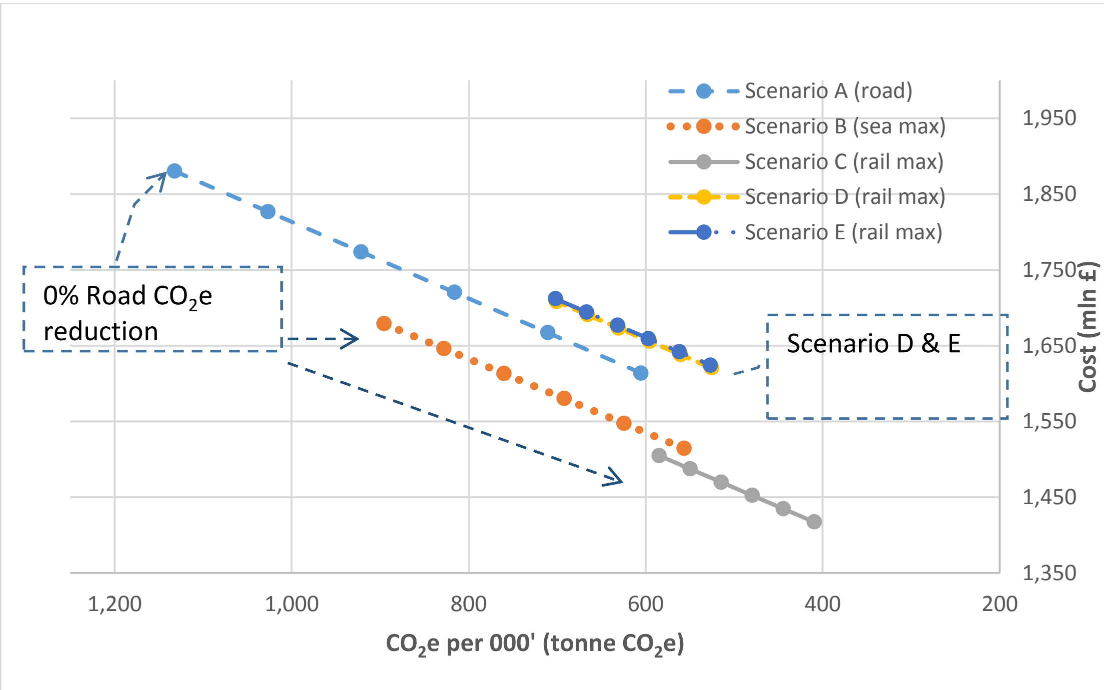

Figure 2. Comparative results of the five scenarios (50 year model).

Similarly, Scenarios D and E assume feasible expansions of the ports of Liverpool, Bristol, Felixstowe and London, and that Derby, Manchester, Glasgow and Edinburgh can be fed by rail from these ports. These scenarios will have better values for CO_2e outputs and total costs compared to a 40% improvement in the road-based scenario. These two Scenarios present considerably lower outputs of cost and CO_2e emissions, respectively about £1.7 billion and just above 700 thousand tonnes of CO_2e emissions; nevertheless, their total cost and CO_2e emissions are not as low as the ones estimated for Scenario C.

On the other hand, Scenario B shows that the total freight transport cost and CO_2e emissions are lower than in Scenario A; however, the reductions in cost and CO_2e emissions are not as substantial as in the cases of Scenario C. Scenario B presents reductions of total freight transport cost and CO_2e emissions relative to Scenario A of about 11% and 21% respectively. Nevertheless, Scenario A could have a lower value of CO_2e emissions if the road-based CO_2e reduction factor is just above 30% compared to Scenario B without any reduction in road-based CO_2e emissions. With this finding, it can be concluded that for a feasible reduction of below 20% of the CO_2e output for road freight transport, it would be more carbon efficient to improve the intensity of road freight transport operations through technological advancement rather than shifting cargo to maritime-based modes.

% Road Reduction	Scenario A				Scenario B				Scenario C			
	Cost (£ million)	% savings	CO_2e, (000' Tonne)	% savings	Cost (£ million)	% savings	CO_2e, (000' Tonne)	% savings	Cost (£ million)	% savings	CO_2e, (000' Tonne)	% savings
0	1,880	-	1,132	-	1,679	-	896	-	1,505	-	585	-
10	1,827	2.83	1,027	9	1,646	1.96	828	7.57	1,488	1.16	550	5.99
20	1,774	5.66	921	19	1,613	3.92	760	15.14	1,470	2.33	515	11.98
30	1,720	8.50	816	28	1,580	5.88	692	22.71	1,453	3.49	480	17.97
40	1,667	11.33	711	37	1,547	7.84	624	30.28	1,435	4.65	445	23.96
50	1,614	14.16	605	47	1,514	9.80	557	37.85	1,417	5.82	410	29.95

% Road Reduction	Scenario D				Scenario E			
	Cost (£ million)	% savings	CO_2e, (000' Tonne)	% savings	Cost (£ million)	% savings	CO_2e, (000' Tonne)	% savings
0	1,708	-	701	-	1,712	-	702	-
10	1,691	1.03	666	5.00	1,694	1.02	667	4.99
20	1,673	2.05	631	10.00	1,677	2.05	632	9.98
30	1,656	3.08	596	15.00	1,659	3.07	597	14.97
40	1,638	4.10	561	20.00	1,642	4.09	562	19.96
50	1,621	5.13	526	25.00	1,624	5.11	527	24.95

Table 7. Total costs and CO_2e emissions for five scenarios (50 year model).

Table 8 shows a more detailed breakdown of the findings related to different transport modes. As the table shows, two main factors determined the results of the five Scenarios: the significantly lower carbon intensity of rail and maritime freight movements and the additional maritime miles required in some Scenarios. In the case of Scenario C, due to the strategic location of Southampton, the reallocation of the supply ports, there will be a saving in maritime miles relative to Scenario A, and at the same time the overall costs and CO_2e are significantly lower than the baseline scenario. The reduction in maritime miles and shifting of containers from road to rail in Scenario C contributes to the significantly lower cost and CO_2e emissions in comparison to Scenario A. On the other hand, additional maritime miles are required in the cases of Scenarios B, D and E. Nevertheless, the positive effect of Scenario B is offset by this factor (since the additional maritime miles required are greater than in the cases of Scenarios D and E) and the high cost of road transport movements. The penalty of additional maritime miles is the main reason why Scenario A, compared to Scenario B, is less carbon intensive if a road-based CO_2e reduction of less than 30% is achieved.

Scenario	% Road Reduction	Cost (£ million)			CO2e, (000' Tonne)		
		Road	**Rail**	**Ship**	**Road**	**Rail**	**Ship**
A Base Scenario, Road Based	0	1,183	-	-	1,054	-	-
	10	1,130	-	-	948	-	-
	20	1,077	-	-	843	-	-
	30	1,024	-	-	738	-	-
	40	970	-	-	632	-	-
	50	917	-	-	632	-	-
B Sea Max	0	731	-	243	678	-	138
	10	698	-	243	610	-	138
	20	665	-	243	543	-	138
	30	633	-	243	475	-	138
	40	600	-	243	407	-	138
	50	567	-	243	339	-	138
C Rail Max (Southampton)	0	389	422	-123	350	229	-70
	10	372	422	-123	315	229	-70
	20	354	422	-123	280	229	-70
	30	337	422	-123	245	229	-70
	40	319	422	-123	210	229	-70
	50	302	422	-123	175	229	-70
D Rail Max (Felixstowe)	0	389	434	71	350	235	40
	10	372	434	71	315	235	40
	20	354	434	71	280	235	40
	30	337	434	71	245	235	40
	40	319	434	71	210	235	40
	50	302	434	71	175	235	40
E Rail Max (London Gateway)	0	389	409	96	350	222	54
	10	372	409	96	315	222	54
	20	354	409	96	280	222	54
	30	337	409	96	245	222	54
	40	319	409	96	210	222	54
	50	302	409	96	175	222	54

Table 8. Transport related costs and CO_2e emissions (road-rail-ship).

Table 9 depicts the findings from the modelling exercise related to the estimated cost and CO_2e emissions generated from container handling in ports and intermodal terminals. As Table 9 shows the cost impacts of container handling are considerably bigger (between 37% and 53% of the total cost) than the CO_2e impacts of this element of the model, which are below 13% in all Scenarios. Scenarios C, D and E have higher levels of container handling-based cost (around £809 million) than Scenarios A and B. This is because the parameter used for incorporating the water-rail container handling factor is 50% higher than the parameter used for the cost of lifting containers off road freight vehicles.

With regard to the values used for CO_2e emissions, Scenarios A and B have higher values than Scenarios C, D and E, since the water-rail container handling CO_2e parameter incorporated in the model is slight lower than the water-road container handling CO_2e parameter. However, the key outcome from the container handling element of the model is that CO_2e emissions generated from container handling represent a small proportion of the total CO_2e emissions which could be generated in the Scenarios modelled in the paper.

Type of handling	Container handling costs (£ million)				
	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Ship to road transport	696.8	696.8	472.7	472.7	472.7
Ship to rail transport	-	-	336.2	336.2	336.2
% of total	37.1	41.5	53.8	47.4	47.3

(a) Costs associated with container handling.

Type of handling	Container handling (000' Tonne of CO2e)				
	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Ship to road transport	78.5	78.5	53.2	53.2	53.2
Ship to rail transport	-	-	21.0	21.0	21.0
% of total	6.9	8.8	12.7	10.6	10.6

(b) CO_2e associated with container handling.

Table 9. Costs and CO_2e emissions related to the container handling.

The required change in the capacity of the ports included in the study is a fundamental aspect which needs careful attention. As Table 10 shows, Scenario B involves significant increases in capacity at Bristol, London, Liverpool and Hull. In particular, the capacity of the port of Bristol requires an increase of 402%. Furthermore, Scenario C requires significant capacity increases of 262% and 403% at the ports of London and Bristol respectively. These capacity changes have significant impacts on the CO_2e emissions of the Scenarios included in the paper if construction-based carbon emissions were estimated. Moreover, reductions in the total numbers of TEUs handled, possibly down to a complete removal of container handling at some ports such as Felixstowe, Southampton and Dover, would be required in Scenarios B, C, D and E, as capacity would not be required at these ports. This is a significant issue which needs to be considered in the expansion plans of the ports of Southampton and London. For Scenarios D and E, while they have similar costs and CO_2e emissions they have very different port expansion or container handling reduction outcomes. For Scenario D, Felixstowe would see only a small increase in capacity of around 20% whereas in Scenario E there would be the total removal of container handling at the port. London Gateway, however, would be expanded in both Scenarios by 262% and 498% respectively. In all 4 scenarios the port of Bristol would be expanded by over 400%.

Port	Scenario				
	A (Base Scenario)	B	C	D	E
Hull	0%	94.7%	-59.7%	-59.7%	-59.7%
Liverpool	0%	141.5%	21.6%	21.6%	21.6%
Bristol	0%	402.7%	402.7%	402.7%	402.7%
Dover	0%	-100%	-100%	-100%	-100%
Southampton	0%	-100%	150.7%	-100%	-100%
Felixstowe	0%	-100%	-100%	20.4%	-100%
London	0%	261.9%	261.9%	261.9%	497.8%

Table 10. Overall capacity change of selected seven ports.

Table 11 shows the cost and CO_2e emissions generated from capacity expansion of ports in the five Scenarios. If the life of the port expanded in the five Scenarios is a assumed to be 50 years, the increases in cost and CO_2e emissions due to port expansion is very marginal, more specifically, below 0.6% of the total cost and 0.2% of total CO_2e emissions generated in Scenarios B, C, D and E. Furthermore, if the life of the expanded ports is assumed to be 17 years, proportion of the cost and CO_2e generated from port expansion activities relative to the total cost and CO_2e emissions of the Scenarios B, C, D and E are just over three times higher than if the life of the ports is assumed to be 50 years. However, the cost and CO_2e emission generated from port expansion are still a very low percentage of the total cost and CO_2e emissions of these four Scenarios, namely below 0.6% and 0.2% respectively.

7. Conclusions

Traditionally, research into carbon footprinting of freight transport has emphasized the importance of the transfer of freight from road to less carbon intensive modes in order to improve the overall environmental performance of freight transport operations (O'Connor, 1987; Robinson 2002). Recent work by Alvarez-SanJaime *et al.* (2013) on the other hand emphasizes the importance of vertically integrated supply chain models which can enhance the performance of maritime freight transport chains. In that context, it is very important to incorporate port selection as one of the key activities of vertical integration of supply chains. However, the large majority of previous research works focuses on economic aspects of port choice, such as market forces and port efficiency (Suykens and Van de Voorde, 1998; Tongzon, 2001; Malchow and Kanafani, 2004; Gonzalez and Trujillo, 2008; Tongzon, 2009; Steven and Corsi, 2012).

Port	Cost (£ million)				CO2e (000' Tonne)			
	Scenario B	Scenario C	Scenario D	Scenario E	Scenario B	Scenario C	Scenario D	Scenario E
Hull	1.723	-	-	-	0.245	-	-	-
Liverpool	1.452	0.222	0.222	0.222	0.207	0.032	0.032	0.032
Bristol	0.271	0.271	0.271	0.271	0.039	0.039	0.039	0.039
Dover	-	-	-	-	-	-	-	-
Southampton	-	2.427	-	-	-	0.345	-	-
Felixstowe	-	-	0.684	-	-	-	0.097	-
London	4.484	4.484	4.484	8.523	0.638	0.638	0.638	1.213
% of total	0.47%	0.49%	0.33%	0.53%	0.13%	0.18%	0.11%	0.18%

Table 11. Cost/ CO_2e of port expansion based on 50 years of port operations for five Scenarios.

More recently, Sanchez Rodrigues *et al*. (2014) demonstrated that rerouting of containers away from traditional large ports in the UK southeast could significantly reduce the overall CO_2e emissions generated by marine-based container transport. This would be achieved by using ports in the north and north-west ports and/or shifting freight from road to rail in container movements between ports and inland origins/destinations. The contribution of our paper addresses the shortcomings of the Sanchez Rodrigues *et al*. (2014) study. Our paper integrates certain important decision-making elements such as future reductions in the rate of CO_2e emissions generated from road freight transport, the cost of container handling at port and rail terminals, and the cost and CO_2e emissions generated from the port expansion activities. Also, the paper account for the impact of changes in the levels of traffic congestion on major roads on CO_2e emissions in the Scenarios modelled. Moreover, previous studies did not link carbon mitigation strategies to the import of containers, nor did they consider the reallocation of import containers between alternative gateway ports. Nevertheless, the results presented in the paper need to be taken with caution since the level of demand could affect the demand for port services.

The paper also contributes to the academic literature by demonstrating how CO_2e reduction can be a significant factor in the selection of ports in maritime-based supply chains. The paper shows that reductions in CO_2e emissions achieved by freight transport operations in maritime-based supply chains can be driven by changes in the structure of freight transport chains as well as potential future road-based CO_2e reduction initiatives driven by technology and process advancements. Moreover, the study demonstrates that cost and CO_2e emissions generated from port expansion is marginal when compared to the total cost and CO_2e emissions generated from the three elements included in the model, namely: port expansion, container handling and freight transport. This is similar to the findings of Simonsen (2010).

Specifically, this paper compares five different Scenarios that link UK import container flows with inland freight transport movement. A methodology based on road distance minimization was applied to the five Scenarios. A CO_2e reduction parameter is used to assess the sensitivity of the five Scenarios to likely reductions in the carbon intensity of road modes. CO_2e emissions generated from road freight transport were estimated based on the levels of freight volume on the major roads for all the routes used in the five Scenarios. Also, the two main output variables were used to compare the five Scenarios for overall CO_2e emissions and total cost. For all values of the road-based CO_2e reduction parameter (0% to 50%), Scenario C is the least carbon intensive and most cost effective. However, the outcome is that additional capacity is required at four ports including a 150% expansion at Southampton and 262% at the London Gateway. In the case of Scenario D, even though the total cost and CO_2e emissions are higher than in the case of Scenario C, there is the requirement for additional capacity at Liverpool, Bristol and London, and a small expansion at Felixstowe.

The results obtained from this study are a starting point for future research in a number of areas:

- Modelling tactical and operational aspects of container transport and port operations where any such study would include fewer ports and specific commodities to provide a more detailed reflection of the situation;
- The model can be extended from an environmental perspective to evaluate further the impacts of the Scenarios on other externalities such as level of traffic congestion and polluting gases generated locally at ports such as sulphate. Also, carbon reduction rates for sea transport and rail modes can be introduced to explore the sensitivity of the findings to future reductions in the carbon emission rates of ships and trains;
- The approach adopted by the study can be replicated in another geographical context at continental or domestic level to explore how geographic partners can impact on the carbon reduction strategies tested in the study;
- It will be necessary to reflect on the preparedness of the five Scenarios to likely climate change event as well as to propose potential contingency measures which the five Scenarios should have.

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APPENDIX A: Calculation of CO_2e emissions for road freight operations based on traffic volumes on UK roads.

Step 1: Identify predominant major road from origin to destination point (estimated from google maps).

	Glasgow	Edinburg	Newcastle	Leeds	Sheffield	Derby	Liverpool	Manchester	Swansea	Exeter	Northampton	London
Hull	M62W	M62W	A1N	M62W	A1N	M1S	M62W	M62W	M5S	M5S	M1N	M1N
Liverpool	M6N	M6N	M62E	M62E	M62E	M6S	A565S	M62E	M6S	M6S	M6S	M6S
Bristol	M5N	M5N	M5N	M5N	M5N	M5N	M5N	M5N	M4W	M5S	M4W	M4W
Dover	M6N	M6N	M1N	M1N	M1N	M1N	M6N	M6N	M4W	M4W	M1N	M20W
Southampton	M6N	M6N	M1N	M1N	M1N	M1N	M6N	M6N	M4W	A30W	M1N	M3N
Felixstowe	M6N	M6N	A1N	A1N	A1N	M1N	M6N	M6N	M4W	M4W	A14W	A12S
London	M6N	M6N	M1N	M1N	M1N	M1N	M6N	M6N	M4W	M4W	M1N	A13W

* Predominant / decisive major road in the route from Port of origin to reference city of destination

Step 2: Calculate average number of vehicles per day (DfT 2014).

	Glasgow	Edinburg	Newcastle	Leeds	Sheffield	Derby	Liverpool	Manchester	Swansea	Exeter	Northampton	London
Hull	44934	44934	30163	44934	30163	53431	44934	44934	41076	41076	54284	54284
Liverpool	45433	45433	42348	42348	42348	45159	12455	42348	45159	45159	45159	45159
Bristol	42619	42619	42619	42619	42619	42619	42619	42619	47390	41076	47390	47390
Dover	45433	45433	54284	54284	54284	54284	45433	45433	47390	47390	54284	35354
Southampton	45433	45433	54284	54284	54284	54284	45433	45433	47390	8236	54284	44274
Felixstowe	45433	45433	30163	30163	30163	54284	45433	45433	47390	47390	24876	19934
London	45433	45433	54284	54284	54284	54284	45433	45433	47390	47390	54284	29515

Step 3: Speed of vehicles (km/hr) (DfT, 2007).

	Glasgow	Edinburg	Newcastle	Leeds	Sheffield	Derby	Liverpool	Manchester	Swansea	Exeter	Northampton	London
Hull	70	70	91	70	91	59	70	70	76	76	57	57
Liverpool	70	70	74	74	74	70	115	74	70	70	70	70
Bristol	73	73	73	73	73	73	73	73	67	76	67	67
Dover	70	70	57	57	57	57	70	70	67	67	57	83
Southampton	70	70	57	57	57	57	70	70	67	116	57	71
Felixstowe	70	70	91	91	91	57	70	70	67	67	112	113
London	70	70	57	57	57	57	70	70	67	67	57	92

Step 4: Estimated vehicle CO_2e emissions (kg/km) for HGV, artic, 40-50 tonnes, diesel, Euro V engine (DfT, 2010).

	Glas	Edin	New	Leeds	Shef	Derby	Liv	Man	Swan	Exeter	North	Lon
Hull	0.84669	0.84669	0.89470	0.84669	0.89470	0.89131	0.84669	0.84669	0.84392	0.84392	0.90509	0.90509
Liverpool	0.84669	0.84669	0.84318	0.84318	0.84318	0.84669	0.89470	0.84318	0.84669	0.84669	0.84669	0.84669
Bristol	0.84344	0.84344	0.84344	0.84344	0.84344	0.84344	0.84344	0.84344	0.85372	0.84392	0.85372	0.85372
Dover	0.84669	0.84669	0.90509	0.90509	0.90509	0.90509	0.84669	0.84669	0.85372	0.85372	0.90509	0.85939
Southampton	0.84669	0.84669	0.90509	0.90509	0.90509	0.90509	0.84669	0.84669	0.85372	0.89470	0.90509	0.84519
Felixstowe	0.84669	0.84669	0.89470	0.89470	0.89470	0.90509	0.84669	0.84669	0.85372	0.85372	0.89470	0.89470
London	0.84669	0.84669	0.90509	0.90509	0.90509	0.90509	0.84669	0.84669	0.85372	0.85372	0.90509	0.89470

Glas – Glasgow; Edin – Edinburgh; New – Newcastle; Sheff – Sheffield; Liv – Liverpool; Man – Manchester; Swan – Swansea; North – Northampton; Lon - London