Sustainability SI: Multimode Multicommodity Network Design Model for Intermodal Freight Transportation with Transfer and Emission Costs

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Abstract Intermodal freight transportation is concerned with shipping of commodities from their origin to destination using combinations of transport modes. Traditional logistics models have concentrated on minimizing transportation costs by appropriately determining the service network and the transportation routing. This paper considers an intermodal transportation problem with an explicit consideration of greenhouse gas emissions and intermodal transfers. A model is described which is in the form of a non-linear integer programming formulation, which is then linearized. A hypothetical but realistic case study of the UK including eleven locations forms the test instances for our investigation, where uni-modal with multi-modal transportation options are compared using a range of fixed costs.

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1 Introduction

The transportation industry is rapidly changing due to technological advances and the constant need to find faster and cheaper ways to transport freight across the globe. Intermodal freight transport is a system for transporting goods, particularly over longer distances and across international borders, which has played a significant role in the freight transportation industry. An intermodal freight transportation system includes ocean and coastal routes, inland waterways, railways, roads, and airways. Intermodal transportation is the shipment of commodities from one point to another using combinations of at least two different transport modes (e.g., truck to train to barge to ocean-going vessel) (Bektaş and Crainic, 2007).

The volume of freight transport has grown rapidly in the last four decades. In 1971, the domestic freight market totalled just 134 billion tonne-kilometres, while by 2010 it has expanded to more than 220 billion tonne-kilometres (Department for Transport, 2012). Increasing freight transportation brings with it concerns about air quality and climate change. Freight transportation is largely driven by fossil fuel combustion, mostly diesel fuel, resulting in emissions of greenhouse gases (GHG), such as Carbon dioxide (CO_2), Nitrogen oxide (NO_X), Sulfur oxide (SO_X), particulate matters and air toxics.

GHG emissions not only are harmful to the health of humans, but also have harmful impacts on environment, including the increased drought, more heavy downpours and flooding, greater sea level rise and harm to water resources, agriculture, wildlife and ecosystems. Global emissions of CO_2 as the primary GHG increased by 3% in 2011, reaching an all-time high of 34 billion tonnes in 2011 (Oliver et al, 2012). In the UK, the total GHG emissions from transport have increased by 13% between 1990 and 2009. The proportion of total UK GHG emissions from transport have increased from 18% in 1990 to 27% in 2009 (Department for Transport, 2011). In 2009, the freight transport within the UK is estimated to account for 21% of domestic transport GHG emissions and 5% of all UK domestic GHG emissions (Department for Transport, 2011).

Traditional logistics models have concentrated on minimizing operational transportation costs. But the consideration of the wider objectives and issues especially related to GHG emissions leads to new models and technologies. In this paper, an intermodal transportation problem is described that includes consideration of GHG emissions, in which CO_2 emissions are explicitly modelled. In our model, the objective is to minimize the total costs in an intermodal system, including the capital costs, operational costs, intermodal transfer cost and the GHG emissions cost, such that a number of commodities are shipped from their origin to destination. The decisions to be made comprise: (i) the selection of routes and transport modes and (ii) the flow distribution through the selected route and mode. The resulting green service network design model is a non-linear mixed integer program. We propose a linearization to transform the model into an integer linear programming formulation which is then solved by off-the-shelf optimization software.

The key contributions of this paper can be summarized as follows: (i) We present a model which, to the best of our knowledge, is the first to explicitly include intermodal transfer cost in its objective when modeling a green intermodal transportation system. (ii) we present the results of a hypothetical but realistic numerical study based on data collected from the UK.

The rest of the paper is organized as follows: In the following section, a brief literature review is presented. Section 3 discusses a way of estimating emissions and presents a non-linear service network design model with intermodal transfer cost, which is then linearized. In Section 4, a hypothetical case study from the UK is provided and results of computational experiment and analyses are presented. The paper concludes in Section 5.

2 A Brief Review of the Literature

An informative overview on intermodal transport is given in Bektaş and Crainic (2007) and Crainic and Kim (2007). A general description of current issues and challenges related to the large-scale implementation of intermodal transportation systems in the United States and Europe is presented by Zografos and Regan (2004). A large body of mathematical solutions, mostly operational research models and methods, have been applied to generate and evaluate the transportation network. Macharis and Bontekoning (2004), and Janic and Bontekoning (2002) present the opportunities for operational research in the intermodal transportation research application field. They have concluded that modeling intermodal freight transport is more complex than modeling uni-modal systems. They also define the problems and review the associated mathematical models that are currently in use in this field. However, their overview covers publications only up to 2002. In recent 10 years, a significant number of papers on this topic have appeared. For example, Meng and Wang (2011) proposed a mathematical formulation to design an intermodal hub-and-spoke network for multi-type container transportation, which is suitable when there are multiple stakeholders such as the network planner, carriers, hub operators, and intermodal operators. Arnold et al (2004) presented a systematic approach to deal with the problem of optimally locating the rail/road terminals for freight transports in relation to the cost criterion. The problem is solved using a heuristic approach involving the solution of a shortest path problem for each commodity. Yamada et al (2009) presented a bi-level programming model for strategic, discrete freight transportation network design, in which the genetic local search mothod is suggested to find near-optimal actions to maximise the freight-related benefit-cost ratio depending on their impact on freight and passenger flows. The model is applied to an actual inter-regional intermodal freight transport network in Philippines. The above three models do not consider the external costs associated with the logistics and transportation network.

According to Crainic and Laporte (1997), decision makers in transportation are faced with planning problems of three different time horizons, namely

strategic, tactical and operational level of planning. Strategic planning (long term) involves the highest level of management. Decisions at this planning level affect the design of the physical infrastructure network, see Steenbrink (1974), Magnanti and Wong (1984), Crainic and Rousseau (1986) and surveys in Campbell et al (2002) and Ebery et al (2000). Tactical planning (medium term) helps improving the performance of the whole intermodal transportation system by ensuring an efficient allocation of existing resources over a medium term horizon, see Crainic and Kim (2007) and Crainic and Laporte (1997). Operational planning (short term) is performed by local management, at which level, day-to-day decisions are made in a highly dynamic environment where the time factor plays an important role, see Crainic and Laporte (1997), Christiansen et al (2007) and Crainic and Kim (2007).

The service network design problem is a key tactical problem in intermodal transport, which is also the case in our paper. Service network design formulations are generally used to determine the routes on which service will be offered, the type of service, as well as the frequency of the schedule of each route Crainic (2000). The performance of the service network design model is evaluated by the tradeoffs between total operating costs and service quality. In solving freight transportation network design problems, much effort has been dedicated to the variant of the problem where there are no limitations on the transportation capacity and significant results have been obtained. Balakrishnan et al (1989) have presented a dual-ascent procedure for large-scale uncapacitated network design that very quickly achieves lower bounds within 1–4% of optimality. Later research has focused on the capacitated service network design problem to capture more realistic settings. Holmberg and Yuan (2000) formulate a general model for capacitated multi-commodity network design and propose its Lagrangian heuristic algorithm. A recent and up-to-date review of service network design problem, we refer the reader to Crainic and Kim (2007) and Crainic and Laporte (1997).

Service network design models are extensively used to solve a wide range of tactical planning and operations problems in transportation, logistic and telecommunications systems. For example, Ben-Ayed et al (1992) describe a formulation of the highway network design problem as a bi-level linear program for optimizing the investment in the inter-regional highway network. They then apply this model to the Tunisian network using actual data. Kuby et al (2001) present a spatial decision support system for network design problems in which different kinds of projects can be built in stages over time and apply this model to the Chinese railway network. They also introduce some easy-to-implement innovations to reduce the size of the problem to be solved by branch-and-bound.

Winebrake et al (2008b) present a geospatial intermodal freight transport model to help analyse the cost, time-of-delivery, energy, and environmental impacts of intermodal freight transport. Three case studies are also applied to exercise the model. However, they use single criterion objective functions (such as minimizing cost, or time or CO_2), which provide the extreme values across the different criteria. We break away from this research by modeling the

emissions and transfers as external costs in our model. Moreover, Winebrake et al (2008b) only consider a single origin-destination commodity. In contrast, we test several commodities in our model for a more systematic analysis.

Bauer et al (2009) are the first to explicitly consider GHG emissions as a primary objective and propose a linear cost, multi-commodity, capacitated network design formulation to minimize the amount of GHG emissions of intermodal transportation activities. They also apply this model in a real-life rail freight service network design and present the tradeoffs between conflicting objectives of minimizing time-related and environmental costs. Our model differs from Bauer et al (2009) in the objective function. We minimize the total transportation costs, including the operating cost, fixed cost, GHG emission cost and intermodal transfer cost.

One other often ignored aspect when modeling intermodal transportation problems is the terminals where classification operations are carried out. As pointed out by Bektaş and Crainic (2007), terminals are "perhaps the most critical components of the entire intermodal transportation chain", and "the efficiency of the latter highly depends on the speed and reliability of the operations performed in the former". This is therefore important to capture terminal operations in a modeling framework. However, it is difficult to explicitly model speed and reliability of terminal operations at a tactical level, as these meaesures require a treatment at an operational level. To overcome the difficulty, in this model we capture this phenomenon by using transfer cost.

3 Problem Description and Mathematical modeling

3.1 Estimating Emissions

There are several approaches for estimating the GHG emissions including an energy-based approach and an activity-based approach. For a review of several vehicle emission models, we refer the reader to Demir et al (2011). Most of the models presented therein are of microscopic nature. For our modeling approach which is at a more strategic/tactical level of planning, we have opted to use an activity-based function by McKinnon and Piecyk (2010) to estimate CO_2 emissions in intermodal transportation. This approach is also commonly used, e.g., Treitl et al (2012) use it to estimate the total transport emissions in a petrochemical distribution network in Europe, and Park et al (2012) use it to calculate CO_2 emissions in a road network for trucks and railway in intermodal freight transportation in Korea.

According to McKinnon and Piecyk (2010), the total cost of CO_2 emissions of a vehicle carrying a load of l (in tonnes) over a distance of d (in km) calculated by equation (1) below,

$$l \times d \times e, \tag{1}$$

where e is the average CO_2 emission factor (g/tonne-km). To convert CO_2 emissions into monetary units, we adopt the figures provided by the World

Bank (The World Bank, 2012), in particular we use \$100 per ton (=£71.6 per tonne).

The rationale for adopting this CO_2 emissions function is in its ease of use. First, it has the advantages of including variables to measure the total freight weight as well as the corresponding distance transported, while avoiding the elements that are hard to measure or calculate, such as different vehicle and fuel types for each mode of transport. Second, it is applicable to different transportation modes. For a given mode of transportation, the total CO_2 emissions are dependent on the shipping distance and the weight of the commodities shipped.

3.2 Problem Description

The problem is defined on a network, represented by a set of nodes N, a set of links A connecting these nodes, a set of transportation modes M and a set of commodities K. The traffic flows between the nodes can be expressed in terms of an origin-destination flow matrix. Each vehicle of a given mode has a load capacity when running on a particular link. The total transportation cost results from a vehicle moving over a link, including variable and fixed costs. The variable cost per weight unit of commodities is the transportation cost, which covers the carrier's fuel costs, crew costs, overhead costs and administration costs. We assume that variable transportation cost is constant over time and that they depend only on the link. The fixed cost consists primarily of operators' wages and handling costs incurred for moving commodities on and off the vehicles. We assume that each vehicle of the same mode of transport incurs the same fixed cost. Intermodal transfer cost arises from transferring freight from one transportation mode to another in an intermodal yard (e.g., port and rail yard). In our modeling, we assume that transfer cost does not depend on the combinations of nodes involved in the transfer. While this might be seen as a strong assumption, there are two reasons why we do so. First, the literature on intermodal transportation modeling states that the internal handling costs are only depend on the load, e.g., Janic (2007) and Winebrake et al (2008b) The only case that different combinations of modes for a transfer result in different values is external costs (of emissions) although they do not vary significantly (Winebrake et al, 2008b). The second reason is that, an explicit consideration of combination of modes in a transfer will require a different model, possibly with more variables, to represent the possible combinations. However, the number of such combinations might be large. For example, in instance with $|M| = 4$, there are six possible combinations, whereas if the number of modes increases to 10, there could be up to 45 different combinations. Given the figures obtained from the literature, and to simplify the representation, the unit handling cost at terminals is assumed to be fixed. An alternative model which distinguishes between transfer cost would be worth exploring in future research.
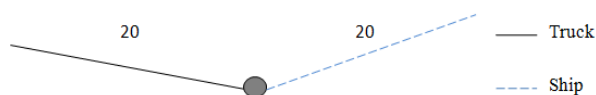
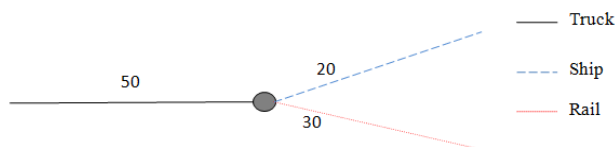**Fig. 1** Example 1 for how transfer cost occurred at intermodal node

Fig. 2 Example 2 for how transfer cost occurred at intermodal node
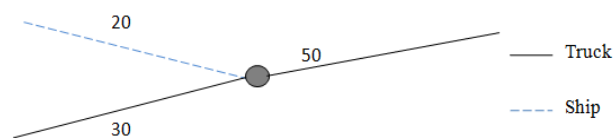
Fig. 3 Example 3 for how transfer cost occurred at intermodal node

The problem considered in this paper is to "design" the network by assigning a number of vehicles to links and ship commodities from their origin to destination by respecting constraints on the link capacities, flows and requirements for demands. The overall objective is to minimize a total cost function, including variable costs, fixed costs, emission cost and transfer cost.

We present three examples in Figure 1–3 showing how transfer occurs at an intermodal node. In Figure 1, 20 units of a commodity are transported by truck at first. When they reach an intermodal node, the transportation mode is changed to ship, so there is one transfer occurring. In Figure 2, 50 units of the commodity are transported to the intermodal mode by truck and they are split into two parts, 20 units are shipped by ship and 30 units are shipped by rail. There are two transfers occurring at this node for this commodity. In Figure 3, the commodity is brought into the terminal by ship and truck. One transfer occurs at the node. The transportation mode for the 20 units is then changed to truck.

3.3 Mathematical modeling

To formulate the green service network design problem described in the previous section as a mathematical programming formulation, we define the notation as shown in Table 1.

Table 1 Mathematical notation and the explanation in our model

Notation	Explanation
$G = (N, A)$	Transportation network, where N corresponds to the set of nodes and A represent the set of arcs
$N_i^+ = \{j \in N : (i,j) \in A\}$	The set of outward neighbors for each node
$N_i^- = \{j \in N : (j,i) \in A\}$	The set of inward neighbors for each node
b_i^k	The difference amount for commodity $k \in K$ between coming out of and coming into node $i \in N$
c_{ij}^m	Unit variable costs for shipping commodities on arc $(i,j) \in A$ by mode $m \in M$
$d(k)$	The destination of commodity $k \in K$
d_{ij}^m	Distance of arc $(i,j) \in A$ by mode $m \in M$
f_{ij}^m	Unit fixed costs for shipping commodities on arc $(i,j) \in A$ by mode $m \in M$
h_i^k	The absolute value of b_i^k
l_{ij}^{km}	Function of minimum flow of commodity $k \in K$ on arc $(i,j) \in A$ by mode $m \in M$
$o(k)$	The origin of commodity $k \in K$
p^m	Cost of emissions for mode $m \in M$
r^k	The quantity of commodity $k \in K$ that is to be sent from $o(k)$ to $d(k)$
u_{ij}^m	The maximum capacity for arc $(i,j) \in A$ by mode $m \in M$
w	The unit transfer cost for commodities
x_{ij}^{km}	Flow variable for commodity $k \in K$ on arc $(i,j) \in A$ by mode $m \in M$
y_{ij}^m	Number of vehicles transported on arc $(i,j) \in A$ by mode $m \in M$

Using the notation in Table 1, a mathematical model for the problem can be written as follows:

$$\text{Minimize} \sum_{k \in K} \sum_{(i,j) \in A} \sum_{m \in M} c_{ij}^m x_{ij}^{km} \tag{2}$$

$$+ \sum_{(i,j) \in A} \sum_{m \in M} f_{ij}^m y_{ij}^m \tag{3}$$

$$+ \sum_{k \in K} \sum_{(i,j) \in A} \sum_{m \in M} d_{ij}^m p^m x_{ij}^{km} \tag{4}$$

$$+ \frac{1}{2} w \sum_{i \in N} \sum_{k \in K} \left(\sum_{m \in M} \left| \sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} \right| - h_i^k \right) \tag{5}$$

subject to

$$\sum_{j \in N_j^+} \sum_{m \in M} x_{ij}^{km} - \sum_{j \in N_j^-} \sum_{m \in M} x_{ji}^{km} = b_i^k \qquad \forall i \in N, \forall k \in K \tag{6}$$

$$\sum_{k \in K} x_{ij}^{km} \le u_{ij}^m y_{ij}^m \qquad \forall (i,j) \in A, \forall m \in M \tag{7}$$

$$x_{ij}^{km} \ge 0 \qquad \forall (i,j) \in A, \forall k \in K, \forall m \in M \tag{8}$$

$$y_{ij}^m \in \{0, 1, 2...\} \qquad \forall (i,j) \in A, \quad \forall m \in M. \tag{9}$$

In this model,

$$b_i^k = \begin{cases} r^k, & i = o(k) \\ -r^k, & i = d(k) \\ 0, & \text{otherwise,} \end{cases} \tag{10}$$

and

$$h_i^k = \begin{cases} r^k, & i = o(k) \text{or } i = d(k) \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

The model (2)–(11) presented above is a non-linear, multi-commodity multi-modal service network design formulation. The objective function measures the total transportation costs. Components (2), (3), (4) and (5) are variable costs, fixed costs, the emission cost and the intermodal transfer cost, respectively.

A bundle of flow conservation constraints is shown by equation (6), which also expresses the demand requirements. In this case, each commodity has only one origin and one destination. Constraint set (7) introduces the capacity constraints. Constraint set (8) guarantees that the total flow on arc (i,j) using mode $m \in M$ must not exceed the product of the capacity of each vehicle and the number of vehicles used of mode $m \in M$. If the arc (i,j) is not chosen in the shipping network or the mode $m \in M$ is not used on arc (i,j) (i.e., $y_{ij}^m = 0$), the flow on arc (i,j) has to be 0. Constraint sets (8) and (9) are to make sure the decision variables x_{ij}^{km} for the flow of each commodity flow for each commodity $k \in K$ and y_{ij}^m for the number of vehicles of mode $m \in M$ on each link are non-negative and integer, respectively.

The non-linear nature of the model due to the objective function makes it chalenging to solve as it is known that non-linear mixed integer programming models are much more difficult to solve compared to their linear counterparts. To overcome this difficulty, we present a linearization in the next section.

3.4 Linearization

The second part of the objective function shown by component (5) is non-linear, due to the absolute value used to model transfers. To linearize, we use a variable z_i^{km} defined for each $i \in N$, $k \in K$ and $m \in M$. More specifically, z_i^{km} shows the transferred amount of commodity $k \in K$ by mode $m \in M$ at node $i \in N$ if there is a transfer at this node.

Proposition 1 The component $\left| \sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} \right|$ for $\forall i \in N, \forall k \in K, \forall m \in M$ can be linearized using the following constraints:

$$\sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} \le z_i^{km}, \forall i \in N, \forall k \in K, \forall m \in M, \tag{12}$$

$$\sum_{j \in N_j^-} x_{ji}^{km} - \sum_{j \in N_j^+} x_{ij}^{km} \leq z_i^{km}, \forall i \in N, \forall k \in K, \forall m \in M, \qquad (13)$$

where $z_i^{km} = \left| \sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} \right|$.

Proof First, notice that $\sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} = -(\sum_{j \in N_j^-} x_{ji}^{km} - \sum_{j \in N_j^+} x_{ij}^{km})$. Namely, if $\sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} \geq 0$, then $\sum_{j \in N_j^-} x_{ji}^{km} - \sum_{j \in N_j^+} x_{ij}^{km} \leq 0$. If $\sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} < 0$, then $\sum_{j \in N_j^-} x_{ji}^{km} - \sum_{j \in N_j^+} x_{ij}^{km} > 0$.

Now we consider two cases. If $\sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} \geq 0$, then constraint (12) and the minimizing objective function (2)–(5) will guarantee that $z_i^{km} = \sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km}$. In the other case where $\sum_{j \in N_j^+} x_{ij}^{km} - \sum_{j \in N_j^-} x_{ji}^{km} < 0$, then constraint (13) along with the minimizing objective function (2)–(5) will guarantee $z_i^{km} = \sum_{j \in N_j^-} x_{ji}^{km} - \sum_{j \in N_j^+} x_{ij}^{km}$.

With the new variable z_i^{km}, the formulation can be rewritten as:

$$\text{Minimize} \sum_{k \in K} \sum_{(i,j) \in A} \sum_{m \in M} c_{ij}^m x_{ij}^{km} \qquad (14)$$

$$+ \sum_{(i,j) \in A} \sum_{m \in M} f_{ij}^m y_{ij}^m \qquad (15)$$

$$+ \sum_{k \in K} \sum_{(i,j) \in A} \sum_{m \in M} d_{ij}^m p_m x_{ij}^{km} \qquad (16)$$

$$+ \frac{1}{2} w \sum_{i \in N} \sum_{k \in K} (\sum_{m \in M} z_i^{km} - h_i^k) \qquad (17)$$

subject to (6)–(9), (12), (13).

Now our model is a linear mixed integer program, which can be solved using any available optimization software. In the following section, we present results of computational experiments using this linearized formulation on a hypothetical case study from the UK.

4 Computational Experiments

4.1 Description of the Case Study

To demonstrate the application and guide the further development of our intermodal model, this section presents a hypothetical but realistic UK intermodal transportation case study. The network consists of 11 nodes, of which nine are important ports in the UK, namely Edinburgh, Newcastle, Liverpool, Milford Haven, Bristol, Felixstowe, London, Folkestone and Southampton. Two of the nodes are important inland cities, Birmingham and Manchester. A geographical representation of the nodes in the network is shown in Figure 4. There are

1. Edinburgh
2. Newcastle
3. Liverpool
4. Manchester
5. Milford Haven
6. Bristol
7. Birmingham
8. Felixstowe
9. London
10. Folkestone
11. Southampton
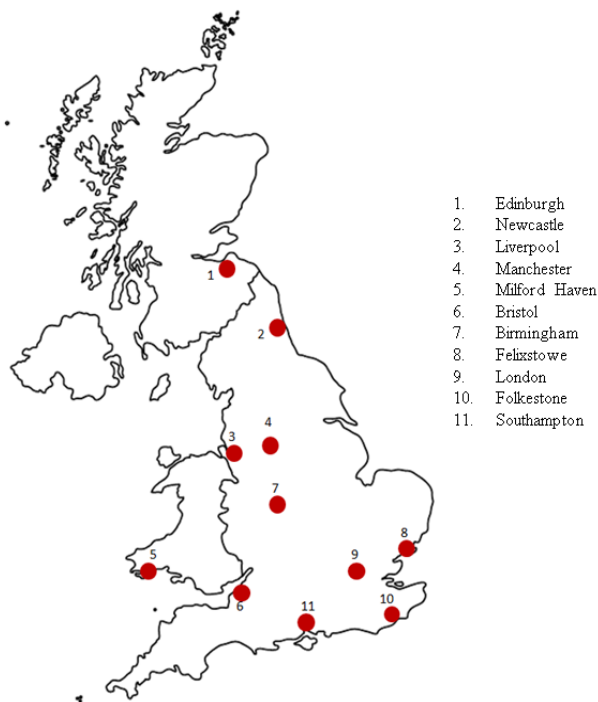
Fig. 4 11 UK cities and ports in the network

three transportation modes assumed to be running in the network: truck, rail and ship. For Birmingham and Manchester, only rail and truck available, while for other nodes, all transportation modes are available. The service network design case study therefore comprises 292 possible directed arcs between 11 nodes. We consider actual route distance in stead of straight-line distance to make the computational results more realistic. For road and rail journeys, the distance is provided by Travel Footprint Limited (travelfootprint.org), where road distances come from Google Maps using best route road algorithms and will apply to all road vehicles, while for rail, distance is calculated according to main rail line distances using the most common rail interchanges, see Lane (2006). For sea journey, distances between pairs ports are provided by sea-distance.com. There are 30 different commodities to be transported in the network. We randomly generate the origin, destination and demand requirement for each commodity, which is shown in Table 2. The data for capacity, unit variable cost, unit transfer cost and CO_2 emissions factor for each mode are found from the literature, see Department for Transport (2005), Andersson et al (2011), Faulkner (2004), Winebrake et al (2008a) and McKinnon and Piecyk (2010), summarized in Table 3. As can be seen from this table, the capacities, variable costs and emissions tend to vary from one mode to another, although the transfer cost is in this instance the same across all modes (Wine-

Table 2 Origins, destinations and demands for 30 commodities

No.	Origin Node	Destination Node	Required demand (tonne)
1	5	3	212
2	11	9	1182
3	2	11	794
4	5	4	128
5	2	9	182
6	4	6	99
7	7	3	150
8	7	1	343
9	4	9	168
10	3	8	567
11	9	10	960
12	1	3	240
13	2	4	790
14	6	7	83
15	6	8	570
16	6	10	150
17	4	2	1220
18	10	8	110
19	8	6	350
20	9	6	410
21	3	2	300
22	5	2	130
23	11	6	225
24	5	7	850
25	6	7	500
26	2	1	275
27	8	4	150
28	10	11	800
29	5	3	175
30	10	9	87

Table 3 Parameters used in the case study

Transportation mode	Capacity (Tonne)	Variable Cost (£per ton-mile)	Transfer Cost (£per tonne)	CO_2 (g/tonne-km)
Truck	29	0.036	1.391	62
Rail	397	0.0425	1.391	22
Ship	2970	0.025	1.391	16

brake et al, 2008b). As for the unit cost of emissions, we use the aforementioned value of £71.6 per tonne (The World Bank, 2012).

Since there are three modes used in our case study, there are three corresponding fixed cost. Estimates of fixed cost in the literature varied significantly. Instead we decide to look at a range of scenarios and investigate how these scenarios influence the solution. Fixed cost is one possible mean by which government policy can influence the transportation goods. We denote fixed cost by f_t, f_r and f_s for truck, rail and ship. The relationships between them can be written as:

$$f_r = \alpha f_t, \tag{18}$$

$$f_s = \beta f_t, \tag{19}$$

where α and β are positive integers.

To see the impact of fixed cost at the optimal structure and send the correct economic signals, we test a number of scenarios by changing the values of α, β and f_t in our case study. When the value of f_t is fixed, the value of α and β are combinations of 1, 3 and 5. So for each f_t, there are nine different combinations. We assume the fixed cost for truck are £50, £100 and £150, respectively. The number of instances and corresponding fixed costs given different f_r and f_s are shown in Table 4. In total there are 27 combinations.

Table 4 Fixed costs(£) for instances with different α and β

Instance No.	α	β	$f_t = 50$		$f_t = 100$		$f_t = 150$	
			f_r	f_s	f_r	f_s	f_r	f_s
1	1	1	50	50	100	100	150	150
2	1	3	50	150	100	300	150	450
3	1	5	50	250	100	500	150	750
4	3	1	150	50	300	100	450	150
5	3	3	150	150	300	300	450	450
6	3	5	150	250	300	500	450	750
7	5	1	250	50	500	100	750	150
8	5	3	250	150	500	300	750	450
9	5	5	250	250	500	500	750	750

4.2 Computational Results and Analysis

Based on the data set introduced in Section 3.1, the computational testing for our model is performed using CPLEX Interactive Optimized 12.4.0.0 on a Lenovo ThinkPad T410 laptop computer with Intel Core i5 CPU and 4G RAM. For each instance, the resulting integer linear programming formulation has 8760 continuous and 292 integers. The computational time required to solve the integer model to optimality is 1.89 seconds for each instance.

4.2.1 The Effect of Emission and Transfer Costs

In this section, we provide results of nine experiments when $f_t=$£50 to show the effect of incorporating transfer and emission costs into the model. For this purpose, we first solve the model without the emission cost (4) and transfer cost (5), and denote this by M. The total cost generated by M is the total operational transportation cost, including variable cost and fixed cost. Using the solutions obtained, we calculate the resulting emission cost M+G and transfer cost M+T, as a consequence of solving M. Then we solve the model

with objective (4) denoted M(G), with objective (5) denoted M(T) and with both, denoted M(G+T). Finally, the percentage savings obtained by M(G), M(T) and M(G+T) over the solutions provided by M+G, M+T and M+G+T are calculated. The results of these experiments are represented in Tables 5–7, along with the averages calculated across the nine instances.

Table 5 Computational results of models with and without emission cost

	M+G		M(G)		Savings	
	Operational Cost (£)	Emission Cost (£)	Operational Cost (£)	Emission Cost (£)	Emission Cost (%)	Total Cost (%)
1	77849	6545	78458	5015	23.38	1.09
2	78949	6545	79558	4991	23.74	1.11
3	79949	6545	80558	4991	23.74	1.09
4	80098	6518	81053	5148	21.02	0.48
5	81235	6744	82190	5158	23.52	0.72
6	82235	6845	83190	5168	24.50	0.81
7	82020	7167	82581	6016	16.06	0.66
8	83134	7076	83696	6016	14.98	0.55
9	84134	7076	84696	6016	14.98	0.55
Average	81067	6785	81776	5391	20.66	0.78

Table 6 Computational results of models with and without transfer cost

	M+T		M(T)		Savings	
	Operational Cost (£)	Transfer Cost (£)	Operational Cost (£)	Transfer Cost (£)	Transfer Cost (%)	Total Cost (%)
1	77849	3392	78266	2708	20.17	0.33
2	78949	3396	79466	2498	26.44	0.46
3	79949	3392	81516	1308	61.44	0.62
4	80098	3263	81316	1774	45.63	0.33
5	81235	3431	82755	1315	61.67	0.70
6	82235	3264	83655	1315	59.71	0.62
7	82020	3278	83478	1315	59.88	0.59
8	83134	3435	84415	1315	61.72	0.97
9	84134	3452	85315	1315	20.17	0.33
Average	81067	3367	82242	1651	51.97	0.64

As shown in Table 5, M generated at least £6545 emission cost for each instance. Considering GHG emissions in the objective function significantly decreases the emission cost, with an average saving of 20.66%. Since operational cost accounts for most of the total cost, the savings are between 0.48% and 1.11%, which is around £4300–£8000. In Table 6, it can be seen that M generated around £3400 transfer cost for each instance. In contrast, M(T) yields an average savings of 51.97%. The significance of the results shown in both tables is that that solutions of similar cost to M+G and M+T can be

Table 7 Computational results of models with and without emission and transfer costs

	M+G+T			M(G+T)			Savings		
	Operational Cost (£)	Emission Cost (£)	Transfer Cost (£)	Operational Cost (£)	Emission Cost (£)	Transfer Cost (£)	Emission Cost (%)	Transfer Cost (%)	Total Cost (%)
1	77849	6545	3392	78527	5920	2806	9.55	17.28	0.61
2	78949	6545	3396	79727	5900	2596	9.85	23.56	0.75
3	79949	6545	3392	80627	5900	2596	9.85	23.47	0.85
4	80098	6518	3263	80930	6066	2708	6.93	17.01	0.19
5	81235	6744	3431	82217	6075	2498	9.92	27.19	0.68
6	82235	6845	3264	83217	6075	1498	11.25	54.11	1.68
7	82020	7167	3278	82925	6336	2708	11.59	17.39	0.54
8	83134	7076	3435	84039	6336	2708	10.46	21.16	0.60
9	84134	7076	3452	85039	6336	2708	10.46	21.55	0.61
Average	81067	6785	3367	81916	6105	2536	9.98	24.75	0.72

obtained with our models, but those that are with significantly less emission and transfer costs. Table 7 shows the comparison of results between M+G+T and M(G+T). In this case, emission cost in M(G+T) is reduced by between 6.93% and 11.59% compared to that generated by M. Similarly, intermodal transfer cost is also reduced by up to 54.11%. The average savings in the total cost obtained by using M(G+T) is 0.72% on average. However, it is noteworthy that these solutions again exhibit an average savings of 9.98% on emission cost and 24.75% on transfer cost.

4.2.2 Intermodal vs. Unimodal Transportation

In our next set of experiments, we seek to compare unimodal with intermodal transportation. Since Birmingham and Manchester are inland, transportation by ship is not available for these nodes. As a result we only test truck only and rail only models for uni-modal transportation. We test scenarios for unimodal and intermodal transportation models with $f_t=f_r=f_s=£50$, $f_t=f_r=f_s=£100$ and $f_t=f_r=f_s=£150$, to delete the effects of different fixed cost when comparing the result. Computational results are summarized in Table 8. The third column displays the total cost for shipping commodities. The fourth, fifth, sixth and seventh columns display the variable costs, fixed costs, emission cost and intermodal transfer cost, respectively.

When the fixed cost is £50, the total costs for truck only, rail only and intermodal transportation are £112513, £98778 and £87253. Intermodal transportation is 22.4% and 11.7% less costly than truck only and rail only transportation. When the fixed costs increase to £100 and £150, the total savings that intermodal transportation affords is up to 41.2%.

Variable cost of the three truck only scenarios changes from £75730 to £75775, which is a 0.06% change. For rail only scenarios, variable cost stays the same. Unlike uni-modal results, variable cost of intermodal scenarios changes from £75327 to £77705, which is 3.1% increase when fixed cost increases from £50 to £100. A larger range of change indicates that when fixed cost is less

Table 8 Comparison of the results of the uni-modal and intermodal transportation

	Modal Type	Total Cost(£)	Variable Cost(£)	Fixed Cost(£)	Emission Cost(£)	Transfer Cost(£)
$f_t=f_r=f_s=$£50	Truck only	112513	75730	21550	15233	0
	Rail only	98778	91326	2100	5352	0
	Intermodal	87253	75327	3200	5920	2806
$f_t=f_r=f_s=$£100	Truck only	134019	75775	43000	15244	0
	Rail only	100878	91326	4200	5352	0
	Intermodal	89465	77705	3900	5020	2840
$f_t=f_r=f_s=$£150	Truck only	155519	75775	64500	15244	0
	Rail only	102978	91326	6300	5352	0
	Intermodal	91415	77705	5850	5020	2840

than £100, it has a greater effect on variable cost in intermodal transportation than that in uni-modal transportation. When fixed cost increases from £100 to £150, variable cost of uni-modal and intermodal models do not change. It is possible that variable cost reaches its maximal value and will not be affected by the change of fixed cost.

Since the emission factor of truck is the highest, followed by ship and rail, the emission cost for truck only transportation is nearly three times costly than that of rail only and intermodal transportation. We notice that there is only a slight change for emission cost in truck only transportation by adjusting fixed cost, while for rail only transportation, emission cost stays the same. In intermodal transportation, emission cost decreases from £5920 to £5020, a 15.2% decrease. When fixed cost keeps increasing, emission cost does not change. Reducing emission cost can be obtained by adjusting fixed cost when fixed cost is less than £100.

Transfer cost is only occurred in intermodal transportation. It is the smallest part of the total cost. When fixed cost increases from £50 to £150, the transfer cost increases slightly from £2806 to £2840. More details on this are provided in the next section where intermodal transportation results are discussed.

In sum, even if transfer cost is incurred in intermodal transportation, the total costs can be reduced by 11.3%–41.2% by using intermodal transportation as opposed to uni-modal transportation. By adjusting fixed cost, variable cost and emission cost can be reduced in intermodal transportation, while they rarely change in uni-modal transportation. These results indicate that intermodal transportation is more flexible than uni-modal transportation.

4.2.3 Intermodal Transportation Results

The results presented in Figure 5–7 show the total cost, including variable cost, fixed cost, emission cost and intermodal transfer cost, for 9 intermodal instances when $f_t=$£50, £100 and £150, respectively. From these figures, we notice that variable cost, which is around £75000, takes up the largest proportion of the total cost and it does not change greatly across the 27 instances. Intermodal transfer cost takes up the least proportion. For each f_t, the total
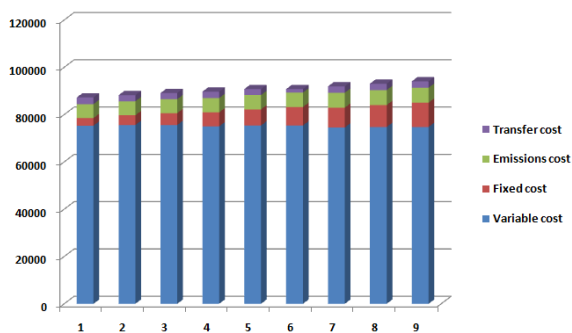
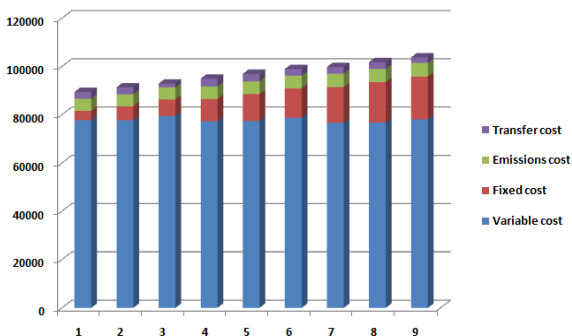**Fig. 5** Computational results for 9 intermodal instances when f_t=50

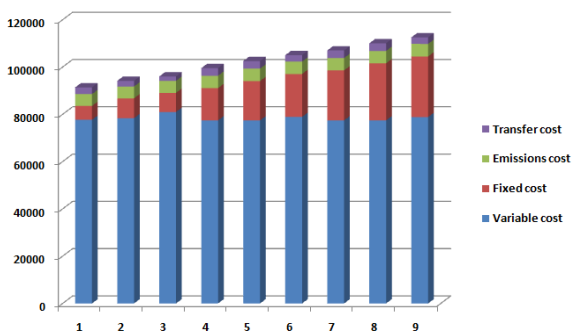**Fig. 6** Computational results for 9 intermodal instances when f_t=100

Fig. 7 Computational results for 9 intermodal instances when f_t=150

fixed cost increases when f_r or f_s is increasing. Hence, the total cost is also increasing. More details about the total cost and its components are presented in Table 9, which shows costs that are normalized to 1 against base case scenarios of f_t=f_r=f_s, for all 27 instances.

Table 9 shows that when f_t=£50, total cost for 9 instances is normalized to a range of 1.000–1.078. For each f_t, the total fixed cost is increasing when f_r

Table 9 Normalized costs for intermodal instances

f_t	f_r	f_s	Total Cost	Variable Cost	Fixed Cost	Emission Cost	Transfer Cost
		£50	1.000	1.000	1.000	1.000	1.000
	£50	£150	1.011	1.004	1.281	0.997	0.925
		£250	1.021	1.004	1.563	0.997	0.925
		£50	1.028	0.996	1.844	1.025	0.965
£50	£150	£150	1.041	1.001	2.125	1.026	0.890
		£250	1.041	1.001	2.438	1.026	0.534
		£50	1.054	0.990	2.609	1.070	0.965
	£250	£150	1.067	0.993	2.891	1.070	0.965
		£250	1.078	0.993	3.203	1.070	0.965
		£100	1.000	1.000	1.000	1.000	1.000
	£100	£300	1.021	1.000	1.487	0.996	1.000
		£500	1.039	1.023	1.744	1.003	0.559
		£100	1.062	0.995	2.359	1.044	1.129
£100	£300	£300	1.084	0.997	2.846	1.042	1.129
		£500	1.106	1.013	3.128	1.057	0.963
		£100	1.115	0.987	3.795	1.103	0.982
	£500	£300	1.138	0.988	4.282	1.101	0.982
		£500	1.160	1.005	4.564	1.116	0.816
		£150	1.000	1.000	1.000	1.000	1.000
	£150	£450	1.030	1.009	1.436	0.998	0.840
		£750	1.050	1.042	1.385	1.017	0.649
		£150	1.089	0.997	2.333	1.042	1.129
£150	£450	£450	1.122	0.997	2.846	1.042	1.129
		£750	1.149	1.016	3.103	1.042	0.963
		£150	1.171	0.997	3.615	1.042	1.129
	£750	£450	1.204	0.997	4.128	1.042	1.129
		£750	1.231	1.015	4.385	1.057	0.969

or f_s is increasing. It is interesting that the variable cost almost stays the same when fixed cost changes. The difference is between 0.1% and 2.3%. For most of the instances, the emission cost slightly increases when f_r or f_s is increasing. The emission cost increases up to 11.6%. We have mentioned in Section 3.1 that emission cost is measured by the product of distance, amount of load and emissions factor. We also know that emissions factor for truck is the highest, followed by ship and rail. So when f_r or f_s is increasing, total truck tonne-miles increase, which leads the result that total emission cost increases. Since rail and ship have lower emissions factors than truck, reducing f_r and f_s helps reducing emission cost in intermodal transportation. Transfer cost also does not change significantly. From Table 8, we already know that the transfer cost is aroung £2800 when $f_t=f_r=f_s$. Except two instances out of 27, the change of transfer cost is between 18.4% and 3.1%, which means intermodal transfer is a very important component in intermodal tansportation chain. Consolidation of loads or incentivizing certain low emissions forms of transportation can be efficiently achieved in intermodal transportation.

Table 10–12 list the total tonnage shipped and the capacity utilization of three transport modes when f_t=£50, £100 and £150 with the commodities shown in Table 2. From instance 1 to 9 in each table, either f_r or f_s is increasing, as shown in Table 4. We notice that more trucks are used and greater total

Table 10 Comparison of the capacity utilization for 3 modes when f_t=£50

	Truck			Rail			Ship		
	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)
1	26	741	98.28	27	8265	77.11	11	6306	19.30
2	26	741	98.28	29	9375	81.43	9	5196	19.44
3	26	741	98.28	29	9375	81.43	9	5196	19.44
4	34	939	95.23	24	7666	80.46	12	6323	17.74
5	34	939	95.23	24	8063	84.62	10	6013	20.25
6	34	939	95.23	24	8063	84.62	10	6013	20.25
7	45	1253	96.02	22	7352	84.18	12	6496	18.23
8	45	1253	96.02	22	7352	84.18	10	6410	21.58
9	45	1253	96.02	22	7352	84.18	10	6410	21.58

Table 11 Comparison of the capacity utilization for 3 modes when f_t=£100

	Truck			Rail			Ship		
	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)
1	0	0	N/A	29	9035	78.48	10	6257	21.07
2	0	0	N/A	31	9748	79.21	9	5544	20.74
3	0	0	N/A	33	10095	77.06	7	4463	21.47
4	6	174	100.00	25	8613	86.78	11	6939	21.24
5	6	174	100.00	25	8613	86.78	10	6766	22.78
6	7	186	91.63	25	8589	86.54	8	6647	27.98
7	17	476	96.55	24	8141	85.44	11	6641	20.33
8	17	476	96.55	24	8141	85.44	10	6468	21.78
9	18	488	93.49	24	8117	85.19	8	6349	26.72

Table 12 Comparison of the capacity utilization for 3 modes when f_t=£150

	Truck			Rail			Ship		
	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)
1	0	0	N/A	29	9035	78.48	10	6257	21.07
2	0	0	N/A	32	9848	77.52	8	5033	21.18
3	0	0	N/A	34	10772	79.80	4	4078	34.33
4	6	174	100.00	25	8613	86.78	10	6766	22.78
5	6	174	100.00	25	8613	86.78	10	6766	22.78
6	3	87	100.00	26	8688	84.17	8	6647	27.98
7	6	174	100.00	25	8613	86.78	10	6766	22.78
8	6	174	100.00	25	8613	86.78	10	6766	22.78
9	6	174	100.00	25	8613	86.78	8	6671	28.08

tonnage of commodities are transported by truck when f_r or f_s is increasing. Except for six instances in total, in which no trucks are used for shipping, the capacity utilization for other instances stays above 91%. In eight out of these 22 instances, the capacity utilization reaches 100% for truck. By adjusting f_t, we could avoid the situation that there are no trucks used in the transportation network and at the same time, get a relatively high capacity utilization. For rail, when f_r increases, both total tonnage and total number of vehicles used decreases, while the capacity utilization increases. One reason might be that it is more cost effective to travel further to consolidate onto fewer vehicles when f_r is high. When f_r is low, using more vehicles on direct routes could be more attractive. The capacity utilization of rail across the 27 instances is greater than 77% for all. In 17 out of 27 instances, it is greater than 84%. When f_t increases, the total tonnage transported by rail is increasing. By changing f_t or f_r, we might roughly control the total tonnage for rail. Since ships have large capacity, the average capacity utilization of ship is much less than that of truck and rail, with values around 20%. Due to its large capacity, the number of ships used and total tonnage of commodities transported also do not change as much as that of trucks and ships.

As part of the computational experiments, we have conducted further tests where costs of rail are changed and demands are increased. In the case that the variable cost and capacity of rail are changed to £0.017 per ton-mile and 3360 tonnes (Forkenbrock, 2001), the results with the intermodal model suggested a uni-modal transportation plan with rail being the only mode of transport used and ship very rarely. The capacity utilization for rail is 18% to 32%. In the event that demands are increased 10-fold, the results do not significantly change although the capacity utilization of rail and ship has increased. Rail has a much higher capacity utilization of more than 96% and ship being more used with capacity utilization of between 76% and 88%. Computational results for this case can be found in Table 13–15 in the Appendix.

5 Bi-criteria analysis

In this paper, the multimode multicommodity network design problem has so far been treated as a single-objective optimization problem. This was made possible by aggregating the two objective functions, one relevant to operational activities, and the other emissions, by attaching suitable cost coefficients to each. In this section, we show how the model can be used to produce non-dominated solutions with regard to the two objectives, if they are incommensurable. This analysis is particularly relevant if costs are not a prevailing factor, or are not readily available, as might be for emission costs. In multiobjective optimization, a *non-dominated*, or *Pareto-optimal*, solution is where no objective can be improved without worsening at lease one other objective (Coello et al, 2007). The set of Pareto-optimal solutions form the *Pareto-frontier*. Decision-makers usually select a particular Pareto-optimal solution based on their preferences on the objectives (Ghoseiri et al, 2004).

In order to find the trade-offs between minimizing total transportation cost and the amount of CO_2 emissions in the multicommodity multimodal service network design problem, we use the notation shown in Table 1 and define the two objective functions below:

$$(OBJ1) \qquad f_1(x, y, z) = \sum_{k \in K} \sum_{(i,j) \in A} \sum_{m \in M} c_{ij}^m x_{ij}^{km} \tag{20}$$

$$+ \sum_{(i,j) \in A} \sum_{m \in M} f_{ij}^m y_{ij}^m \tag{21}$$

$$+ \frac{1}{2} w \sum_{i \in N} \sum_{k \in K} \left(\sum_{m \in M} z_i^{km} - h_i^k \right) \tag{22}$$

$$(OBJ2) \qquad f_2(x) = \sum_{k \in K} \sum_{(i,j) \in A} \sum_{m \in M} d_{ij}^m e^m x_{ij}^{km}. \tag{23}$$

In the above, $f_1(x, y, z)$ measures the total transportation cost, including variable cost, fixed cost and transfer cost, which are detailed in Section 3.2. On the other hand, $f_2(x)$ measures the total CO_2 emission for all activities. Let S denote the feasible set defined by the equality and inequality constraints (6)–(9), (12) and (13) as described in Section 3.3.

A number of methods have been suggested to generate the Pareto frontier in multi-objective programming, such as goal programming, bound objective function formulations and genetic algorithms. In this paper, we use the ϵ-constraint method, which is easy to implement and effective. In this method, one of the objectives is optimized, subject to other objective converted into a constraint by imposing appropriate upper bounds on its value. The ϵ-constraint method can be implemented as follows (Mavrotas, 2009; Engau and Wiecek, 2007). We first solve the following single-objective optimization problem:

$$\text{Minimize} \qquad f_2(x) \tag{24}$$

$$\text{subject to} \qquad x \in S. \tag{25}$$

Let an optimal solution vector of (24)–(25) be denoted by (x_2^*, y_2^*, z_2^*). The minimized amount of CO_2 emissions is then fixed as $f_2(x_2^*) = \epsilon$. Following this step, we solve following next single-objective optimization model:

$$\text{Minimize} \qquad f_1(x, y, z) \tag{26}$$

$$\text{subject to} \qquad f_2(x) \le \epsilon \tag{27}$$

$$x, y, z \in S. \tag{28}$$

Let (x_1^*, y_1^*, z_1^*) denote an optimal solution to (26)–(28). Furthermore, let q be the number of Pareto-optimal solutions that a decision-maker wishes to produce. Then, the value of ϵ is to be increased by ς at every iteration where:

$$\varsigma = (f_2(x_1^*) - f_2(x_2^*))/(q - 1). \tag{29}$$

The method iterates by increasing the value of ϵ in this way (see Table 13), where each iteration generates another optimal solution. By repeatedly

relaxing the upper bound on f_2, and resolving f_1 each time, solutions can be obtain to construct the Pareto-frontier.

Table 13 Value of ϵ in ϵ-constraint approach

Iteration No.	Value of ϵ
1	f_2^*
2	$f_2^*+\varsigma$
3	$f_2^*+2\varsigma$
...	...
$q-1$	$f_2^*+(q-2)\varsigma$
q	$f_2(x_1^*)$

We now present a numerical example to illustrate the application of the ϵ-constraint method on the multimode multicommodity network design problem. The method is implemented in C and each sub-problem is solved to optimality by ILOG CPLEX Interactive Optimized 12.4. Therefore, the solutions generated are Pareto-optimal. The instances is based on the data presented in Section 4.1 with the fixed-cost scenario where f_t=£50, f_r=£150 and f_s=£250.

Assuming $q = 45$, the stepsize is calculated as ς=0.7 tonne. The resulting set of Pareto-optimal solutions are shown in Figure 8.
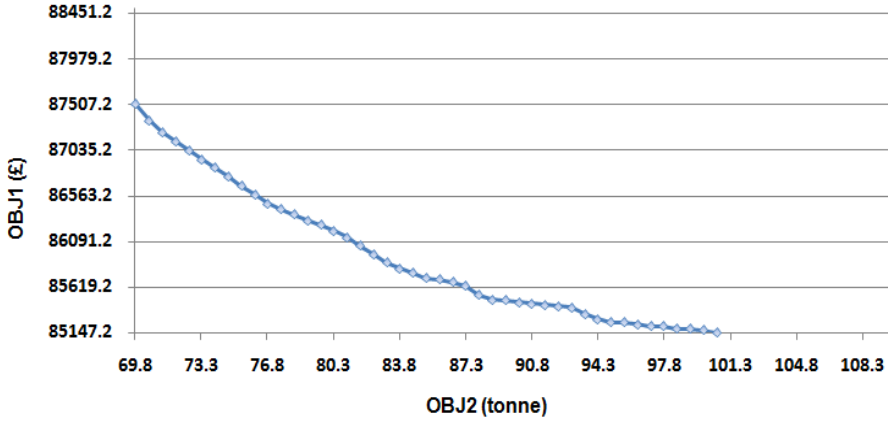

Fig. 8 Pareto optimal curve of MOO model

To select the most preferred solution from this set of non-dominated solutions, we have also implemented a normalized distance method, for which the two objectives are normalized as follows:

$$\bar{f_1}(x,y,z) = \frac{f_1(x,y,z) - f_1(x_1^*,y_1^*,z_1^*)}{f_1(x_2^*,y_2^*,z_2^*) - f_1(x_1^*,y_1^*,z_1^*)} \in [0,1], \tag{30}$$

$$\bar{f_2}(x) = \frac{f_2(x) - f_2(x_2^*)}{f_2(x_1^*) - f_2(x_2^*)} \in [0,1], \tag{31}$$

where $\bar{f}_1$ and $\bar{f}_2$ are the normalized value of OBJ1 and OBJ2, respectively. Assuming an ideal point $(0, 0)$, as shown in Figure 9, the solution that is closest can be considered as the most preferred solution.
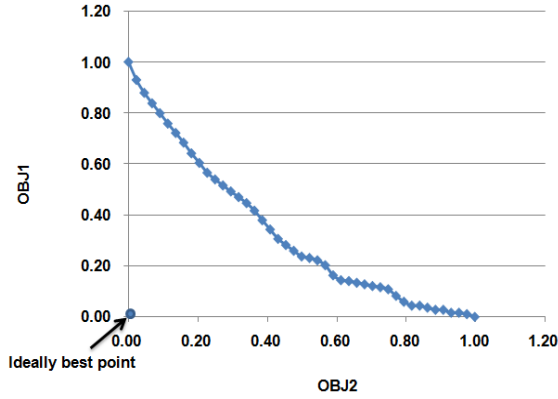

Fig. 9 Normalized Pareto optimal curve of MOO model

As seen in Figure 9, the normalized solution that yields the minimum distance from the ideal point is $\bar{f}_1 = 0.31$ and $\bar{f}_2 = 0.43$. Mapping this on the original functions, the values of the corresponding solutions are OBJ1=£85869.2 and OBJ2=83.1 tonne.

6 Conclusions

In this paper, we have described an intermodal freight transportation model, which also extends current service network design models by taking GHG emission cost into account. The model also includes a nonlinear expression for transfer cost at intermodal nodes, which can be linearized. We have also shown how the problem can be formulated as a bi-objective optimization model. The computational results have suggested that the proposed model provides cost-efficient and emission-efficient ways for transporting commodities. This makes it interesting for practical applications.

One important detail to remember is that the adjusted fixed costs are used for the purpose of sending the correct economic signals. We believe that it provides an opportunity for considerable cost reduction while adjusting fixed costs. By changing the value of fixed cost for three modes of transport, performance indicates emission cost, variable cost, capacity utilization for truck, rail and ship, and the tradeoffs between operational, emission and transfer costs can be analyzed.

Acknowledgements

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Appendix

Table 13–15 list the capacity utilization for 3 transport modes when f_t=£50, £100 and £150 with 10 fold of commodities in Table 2.

Table 14 Comparison of capacity utilisation for 3 modes when $f_t = £50$ and demand is increased 10-fold

	Truck			Rail			Ship		
	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)
1	241	6970	99.73	207	79080	96.23	27	64370	80.27
2	245	7105	100.00	210	80624	96.71	25	62629	84.35
3	245	7105	100.00	211	80624	96.25	25	62614	84.33
4	289	8365	99.81	199	77805	98.48	28	63427	76.27
5	290	8380	99.64	200	77775	97.95	27	63355	79.01
6	292	8437	99.63	199	77718	98.37	27	63298	78.94
7	428	12370	99.66	188	73697	98.74	28	63120	75.90
8	430	12428	99.66	188	73630	98.65	27	63064	78.64
9	430	12443	99.78	188	73634	98.66	27	63092	78.68

Table 15 Comparison of capacity utilisation for 3 modes when $f_t = £100$ and demand is increased 10-fold

	Truck			Rail			Ship		
	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)
1	0	0	N/A	225	86050	96.33	28	65670	78.97
2	0	0	N/A	229	87638	96.40	26	64100	83.01
3	0	0	N/A	229	87638	96.40	24	63042	88.44
4	10	279	96.21	220	85773	98.21	29	65583	76.14
5	11	308	96.55	220	85767	98.20	27	65211	81.32
6	10	279	96.21	221	85796	97.79	26	64625	83.69
7	22	627	98.28	217	85429	99.16	29	65671	76.25
8	39	1119	98.94	216	84935	99.05	27	65122	81.21
9	39	1119	98.94	216	84935	99.05	27	65122	81.21

Table 16 Comparison of capacity utilisation for 3 modes when $f_t = £150$ and demand is increased 10-fold

	Truck			Rail			Ship		
	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)	Total No.	Total tonnage	Capacity utilization(%)
1	0	0	N/A	225	86050	96.33	28	65670	78.97
2	0	0	N/A	229	87638	96.40	24	63042	88.44
3	0	0	N/A	229	87638	96.40	24	63042	88.44
4	5	134	92.41	220	86028	98.50	29	65865	76.47
5	12	337	96.84	219	85738	98.61	27	65324	81.46
6	5	134	92.41	220	86028	98.50	26	64530	83.57
7	15	424	97.47	217	85325	99.04	29	66285	76.96
8	16	453	97.63	217	85294	99.01	27	65919	82.20
9	16	453	97.63	217	85294	99.01	26	65125	84.34