THE TRADE-OFF BETWEEN CO$_2$ EMISSIONS AND LOGISTICS COSTS BASED ON MULTI-OBJECTIVE OPTIMIZATION

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ABSTRACT

This paper develops a decision-support tool for estimating the balanced market shares of given freight transport systems operating in a given network, satisfying both the minimum costs and the Carbon-Dioxide (CO2) emission requirements. Since CO2 constraints in logistics markets need to be realized in the near future, a modal shift in freight transport could be expected to reduce the CO2 emissions within the reasonable cost/time constraints. In order to clarify the relationship between freight costs and CO2 emissions, the technique of multi-objective optimization is used as the core of the decision-support tool. This tool enables the optimal modal market share to be found as well as the optimal trade-off between the costs and the CO2 emissions. The developed tool is applied to a simplified freight transport network connecting two large European ports – the port of Rotterdam (The Netherlands) and the port of Gdansk (Poland). The initial solution, based on the minimization of freight costs, shows that the mode share of freight is local/regional freight transport situations, while the other solutions balanced with CO2 emissions shows that the mode share is changed into intermodal freight system, which is based on the ‘Hub-and-Spoke’ network.

Key words: multi-objective optimization, multimodal freight transport, decision-support tool, Carbon-Dioxide (CO2) emissions, modal market share.
INTRODUCTION

In most logistics systems, minimizing the cost/time performance has always been the top priority objective. The efficiency-oriented logistics systems have created a high dependency on the truck-only system (the road freight market share amounts to about 44% in the European Union (1,2)). However, over the same time period, road freight transport has been one of the most rapidly growing CO₂ contributors, while other contributors have decreased, rather slowly though, over the past 10 years (1,3). Consequently, in order to reduce the CO₂ emissions from the road freight transport in Europe, international organizations as well as national and local governments have designed policies which aim to increase the market shares of the non-road freight transport modes, focusing on the inter-, or multi-, modal freight transport systems (4,5). A research question is then raised as to what the desired (well-balanced) freight mode share is? To what extent should intermodal freight systems be desirable to ensure freight market (and, in this study, container transport studying particular) and to reduce CO₂ emissions from freight transport. This study attempts to answer these questions by clarifying the relationship between the costs and the CO₂ emissions of different modes.

To estimate the share of particular freight transport modes, a decision-support tool based on the multi-objective optimization problem is developed. The detailed outcome being looked for is the ever-changing network assignment solution for each solution as well as the trade-off curve consisting of a certain number of assignment solutions. This outcome may be an answer to the research question asked above. The tool is applied to a simplified network consisting of two hubs and four spokes (i.e. 2 nodes for hubs and 4 nodes for local shippers/consignees).

MULTIMODAL HUB AND SPOKES NETWORK REPRESENTATION

This Section describes the representation of multimodal hub-and-spoke networks, consisting of two kinds of nodes, hub cities and local cities, and two kinds of arcs, internal flows and external flows. Figure 1(a) illustrates the internal and external flows. The internal flows consist of explicit internal flows and implicit internal flows. Explicit internal flows indicate the flows from/to any nodes in the network excluding a dummy node, which is the representative node for other cities in the network regions. Implicit internal flows, which influence the network but are not specifically expressed in the network, indicate the flows from/to the dummy node. For example, the implicit internal flows might use long-haul in an intermodal freight system but the destination is not explicitly indicated in the network region. The external flows are coming/outgoing from/to some places outside of the network. Specifically, if the supply of node 1 (O₁) is the sum of X₁external, X₁₂, and X₁dummy, only X₁₂ is considered. This is illustrated in Figure 1(b), where one more hub city and some more local cities are added to Figure 1(a). The arcs do not represent the homogeneous infrastructure (e.g. highway). For example, ARChub1hub2 can be railway, short sea shipping and roadway. Xhub1external can be the short/deep sea lines. Figure 1(c) presents the comprehensive network considering all possible modes in the network. For example, the long haulage from hub1 to hub 2, flows on ARChub1hub2, is the summation of the flows of three systems: truck, indicated as superscription ‘1’ of X; rail intermodal system, indicated as ‘1’, and SSS (Short Sea Shipping), indicated as ‘3’. Specifically, X₃₄+ X₃₂ +X₃dummy = (X₃₄ + X₃₂ +X₃dummy) + (X₃₄ + X₃₂ +X₃dummy) + (X₃₄ + X₃₂ +X₃dummy).
FIGURE 1 Freight network representation

(a) Description of internal and external flows

(b) Hub and Spokes network representation

(c) Multi-modal freight network representation

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**FIGURE 1** Freight network representation
For the truck only system, every local shipper/consignees can send/receive flows directly by truck. For example, the linear line from node 1 to 4 is $X_{14}$. In the same way, all the other flows can be presented in the network region. It is notable that the basic unit of freight transport is “system” instead of “mode” in Figure 1(c), in order to represent both truck-only systems and inter- (multi-) modal systems. Thus, drayage and terminal transshipments are regarded as parts of intermodal systems.

**MULTI-OBJECTIVE OPTIMIZATION**

The multi-objective optimization model is used as the core of the decision support tool for finding the optimal freight systems assignment (e.g. truck-only system, the rail-based intermodal system, and the vessel based short-sea system) and for estimating the trade-off between the freight costs and the CO$_2$ emissions. There are two types of multi-objective optimization problems that are applicable: preference-based and ideal (i.e. cooperative and competing, respectively)(6). The core of preference-based optimization problems is to internalize CO$_2$ emissions in the objective function. Thus, the solution is similar to one for single optimization problems. However, the ideal multi-objective optimization problem considers two issues (i.e. freight cost and CO$_2$ emission in this case) separately and estimates their relationship (i.e. trade-off). The relationship can be drawn as a trade-off graph and is called Pareto-optimal solutions (6).

The problem with the preference-based approach is that it is extremely difficult to estimate the CO$_2$ price (i.e. a converting factor (e.g. euro / kg of CO$_2$)). In other words, even though CO$_2$ emissions might be treated as a component of external costs, converting the emission into monetary terms should be done very carefully. The ideal multi-objective optimization approach chosen in this study is more flexible. In addition, as shown later, the converting factor can conversely be approximated by this approach once the trade-off has been estimated. The ideal multi-objective is presented in its general form and then applied to the relationship between cost and CO$_2$ emissions in freight transport systems in the following Subsections.

**General Multi-Objective Optimization Problem and Pareto Optimal**

Minimize/Maximize $f_m(x)$, 

\[
\text{s.t.} \quad g_j(x) \geq 0, \quad j = 1,2,\ldots,J; \\
\quad h_k(x) = 0, \quad k = 1,2,\ldots,K; \\
\quad x_i^L \leq x_i \leq x_i^U, \quad i = 1,2,\ldots,N.
\]

Where,

- $x$ is a vector of $n$ decision variables: $x = (x_1,x_2,\ldots,x_n)^T$
- $x_i^L$ and $x_i^U$ are the lower and upper bounds of $x_i$, respectively.
- $g_j(x)$ and $h_k(x)$ are the constraint functions of $J$ inequality and $K$ equality, respectively.

The $x_i^L$ and $x_i^U$ demarcates a decision variable space $D$. Thus, the number of axis of a decision variable space is $N$. The multi-objective space, $Z$, is the crucial difference between single objective optimization problem and multi-objective optimization problem since the latter has “multi-dimensional space” (for more details, see (6)).
Pareto optimal is defined as “a solution (call it A) to a multiple-objective problem is Pareto optimal if no other feasible solution is at least as good as A with respect to every objective and strictly better than A with respect to at least one objective” (7).

The Relationship between Cost and CO₂ Emission

The aim is to determine an appropriate freight modal split which ensures minimum freight costs with the minimum level of CO₂ emissions, subject to the demand and the capacity. Thus, the final solution might not be a single point but a curve or a line. We found the multi-objective optimization problem highly suitable for our aim. The objective functions in the problem are to minimize the total system operational costs and the quantities of the CO₂ emissions. The optimization constraints are: (a) the flow conservation constraints, (b) the freight systems availability constraints, (c) intermodal freight conservation, (d) the non-negativity constraints, (e) the CO₂ emission restriction constraints, defined as quota, for both the particular routes and the transshipment points. Highlighting the CO₂ quota, Kim, et al. recently developed CO₂ limitations based on the Kyoto protocol and other traffic characteristics (8). The quota is defined as the fixed target quantity assigned to the freight transport after considering all other sources of emissions of CO₂ such as from passenger transport sharing the same transport infrastructure. However, the CO₂ quota in this paper is defined as the relative magnitude updated iteratively from the initial CO₂ mass when the freight cost is minimized.

Notation used in the model is as followed:

- \( V \) is the set of nodes, i.e. the origins and destination of the freight transport flows;
- \( A \) is the set of routes connecting the origin and destination nodes of the freight flows;
- \( K \) is the set of the freight transport systems serving the given freight flows in the given region;
- \( O(k), k \in K \) is the set of origins of the freight system \( k \); 
- \( D(k), k \in K \) is the set of destinations of the freight system \( k \); 
- \( o^k_i, (i,j) \in A, k \in K \) is the demand of the freight system \( k \) from \( i \) to \( j \); 
- \( u^k_i, (i,j) \in A, k \in K \) is the service capacity of freight system \( k \) on the system; 
- \( x^k_{ij}, (i,j) \in A, k \in K \) is the flow of the freight system \( k \) on the route \( (i,j) \) (i.e. the decision variable); 
- \( C^k_{ij}(x^k_{ij}), (i,j) \in A, k \in K \) is the cost for transporting \( x^k_{ij} \) flow units by the freight system \( k \) on the route \( (i,j) \) ($/ton); 
- \( Q^k_{ij}(x^k_{ij}), (i,j) \in A, k \in K \) is the CO₂ emissions from the transport system \( k \) on the route \( (i,j) \) (ton); 
- \( Q^k_i, i \in T(k), k \in K \) is the CO₂ emissions at the transshipment point \( k \) (ton); 
- \( B^k_i, (i,j) \in A \) is the CO₂ emission quota for the route \( (i,j) \) including terminal operations (ton); 

It is notable that \( A \) in the notation above is not the ‘arc’ that connects individual nodes. The ‘route’ can be a series of arcs.

Although objective functions and the related constraints are not purely linear if we fully formulate the related freight costs and CO₂ emissions, this study attempts to express them in a
linear form and simplify the problem in order to avoid unnecessary complexities. Thus, the parameter estimation of $C^k_{ij}$ and $Q^k_{ij}$ is indeed crucial to finding the approximation of the Pareto optimal solution. The simplified objective functions and constraints are presented below.

The objective function 1 based on the total transport cost:

$$Z_1 = \text{Min} \sum_{i \in A, j \in A} C^k_{ij} x^k_{ij}$$

The objective function 2 based on the CO$_2$ emissions:

$$Z_2 = \text{Min} \left[ \sum_{k \in K} \sum_{i \in A} Q^k_{ij} x^k_{ij} + \sum_{k \in K} \sum_{i \in V} Q^k_i x^k_i + \sum_{k \in K} \sum_{j \in V} Q^k_j x^k_j \right]$$

Subject to

(a) The flow-conservation constraints:

$$\sum_{j \in V \setminus \{i,j \in A\}} x^k_{ij} = o^k_{ij}, \quad (i,j) \in A, \; k \in K$$

(b) The freight mode availability constraints:

$$\sum_{j \in V \setminus \{i,j \in A\}} x^k_{ij} \leq u^k, \quad i \in V, \; k \in K$$

(c) The intermodal freight conservation constraints:

$$\sum_{j \in V \setminus \{i,j \in A\}} x^k_{ij} \leq u^k, \quad k=2 \text{ and } 4$$

$$\sum_{j \in V \setminus \{i,j \in A\}} x^k_{ij} \leq u^k, \quad k=3 \text{ and } 5$$

(d) The non-negativity constraints:

$$x^k_{ij} \geq 0$$

(e) The CO$_2$ emission quota constraints:

$$\left[ \sum_{k \in K \setminus \{i,j \in A\}} Q^k_{ij} x^k_{ij} + \sum_{k \in K \setminus V} Q^k_i x^k_i + \sum_{k \in K \setminus V} Q^k_j x^k_j \right] \leq B^k_{ij}, \quad (i,j) \in A, \; k \in K$$

According to (c) the intermodal freight conservation constraints, it is assumed that the rail-based intermodal system and the 2nd level rail-based intermodal system use the same freight train service and accordingly share the limited capacity (i.e. train slots). The assumption is similarly applied to two options of short sea shipping.

**SOLUTION PROCEDURE AND MODEL IMPLEMENTATION**

**Procedure**
**Estimation of upper bound and lower bound of the second objective function**

Step 0: Initialization: set all parameters, objective functions and constraints (a), (b), (c), and (d)

Step 1: Run linear programming for $Z_1$ excluding $Z_2$ and get the initial solution for $Z_1$

Step 2: Substitute the initial solution to the second objective function ($Z_2$) and assume the current value of $Z_2$ as the upper bound of constraint (e)

Step 3: Run linear programming for $Z_2$ with the same constraints excluding $Z_1$, get the initial solution for $Z_2$, and use the current $Z_2$ as the lower bound of constraint (e)

**Estimation of Pareto optimal solution**

Step 4: Set Pareto Optimal set $= \{ \phi \}$ and the desired number of subset of Pareto Optimal points

Step 5: Estimate the increment of CO$_2$: increment = (upper bound – lower bound) / the number of Pareto Optimal points

Step 6: Update the constraint (e):

$$\sum_{i-k} \sum_{j-1} Q_i^k x_i^k + \sum_{i-k} \sum_{j-1} Q_i^k x_i^k + \sum_{i-k} \sum_{j-1} Q_i^k x_i^k \leq (\text{Initial Upper bound} – \text{increment})$$

Step 7: Run linear programming for $Z_1$ with the updated constraint and others

Step 8: Update the subset of Pareto Optimal set for ($Z_1, Z_2$), if all constrains and optimality conditions are satisfied and a solution is found

Step 9: If the current number of Pareto Optimal solution is less than the desired number of Pareto Optimal (in other words, the current upper bound is less than the global lower bound), go to Step 6

Step 10: end

Excel Solver was used to run LPs in the entire algorithms. The algorithms have been coded in Visual Basic. Lingo 11.0 was also used for the verification.

**Case Study**

**Study Area**

We explored a case study area where 3 different intermodal systems could be compared. In the study area, the freight systems may have the appropriate equipment for transshipment and can compete, at least potentially, with each other. The study area may have more than two major economic activity centers. As many manufacturing industries have recently been located in Eastern Europe, the port of Gdansk is one of the fastest growing ports, being a regional hub for Poland and Lithuania as well as connected to a freight rail-line. On the other hand, the Port of Rotterdam is one of the largest ports in Western Europe as well as a regional hub for the Netherlands and Northern Belgium. Thus, connecting two ports (i.e. rail and short-sea) as a long-haulage line, these two hubs are an appropriate study area satisfying the criteria mentioned above. Actually, this route has been recognized as one of the major freight corridors in Europe (9)

**Ranking of Cost and Emissions**
The freight transport cost and CO$_2$ emissions, as shown in Table 1, are estimated based on two European Commission researches: RECORDIT and MEET, respectively (10,11). Although there are many factors affecting CO$_2$ emissions, the most crucial one in the long-distance trips in this case study is the average cruising speed rather than the acceleration rate, cold start emissions, ambient temperature and so on. This case study assumes the average cruising speeds of trucks, railway, and short sea shipping to be 90km/h (60km/h in drayage), 90km/h, and 25km/h respectively. It is also worth noting that production emissions are included based on previous research (12-15). Those performance measures (i.e. cost and CO$_2$ emissions) being used as parameters (i.e. $C_{ij}^k$ and $Q_{ij}^k$) in linear programming are multiplied by the estimated shortest path distance based on different modal networks (i.e. road, rail, and short sea waterway) in GIS. Table 1 shows the complexity to decide “What is the best option in the network in terms of one of two objectives?” and the difficulty to generalize the freight costs for each freight system. In other words, one mode dominates one route (region), while it is not even comparative in another route (region). In addition, one mode is economically superior to the others in one route, while it can be significantly worse in the other route. One certain fact in the entire case study network is the worst freight system regarding CO$_2$ emissions is the truck-only system indicated as $\mathbf{1}$ as shown in Table 1.

### Table 1 Ranking of cost and CO$_2$ emission in the freight network in case study

<table>
<thead>
<tr>
<th>Origin – Destination</th>
<th>Best choice based on Freight Transport Cost</th>
<th>Best choice based on CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best choice</td>
<td>2$^{nd}$</td>
</tr>
<tr>
<td>Amsterdam – Warsaw (1-3)</td>
<td>$\mathbf{1}$ (€ 1,401)</td>
<td>$\mathbf{4}$</td>
</tr>
<tr>
<td>Amsterdam – Vilnius (1-4)</td>
<td>$\mathbf{4}$ (€ 1,596)</td>
<td>$\mathbf{1}$</td>
</tr>
<tr>
<td>Amsterdam – Gdansk (1-6)</td>
<td>$\mathbf{4}$ (€ 1,090)</td>
<td>$\mathbf{2}$</td>
</tr>
<tr>
<td>Brussels – Warsaw (2-3)</td>
<td>$\mathbf{4}$ (€ 1,484)</td>
<td>$\mathbf{1}$</td>
</tr>
<tr>
<td>Brussels – Vilnius (2-4)</td>
<td>$\mathbf{4}$ (€1,639)</td>
<td>$\mathbf{1}$</td>
</tr>
<tr>
<td>Brussels – Gdansk (2-6)</td>
<td>$\mathbf{4}$ (€ 1,169)</td>
<td>$\mathbf{2}$</td>
</tr>
<tr>
<td>Rotterdam – Warsaw (5-3)</td>
<td>$\mathbf{4}$ (€ 1,230)</td>
<td>$\mathbf{2}$</td>
</tr>
<tr>
<td>Rotterdam – Vilnius (5-4)</td>
<td>$\mathbf{4}$ (€ 1,385)</td>
<td>$\mathbf{2}$</td>
</tr>
<tr>
<td>Rotterdam – Gdansk (5-6)</td>
<td>$\mathbf{2}$, $\mathbf{4}$ (€ 915)</td>
<td>$\mathbf{1}$</td>
</tr>
</tbody>
</table>

**Mode(System) Choice Sets**

1. Truck-only system
2. Rail based Intermodal system (Truck drayage – Rail Long haulage – Truck drayage)
3. Short Sea based intermodal system (Truck drayage – Shortsea haulage – Truck drayage)
4. 2$^{nd}$ level Rail based Intermodal system
   - (Truck pickup – Rail drayage – Rail Long haulage – Rail drayage – Truck distribution)
5. Rail-Shortsea based Intermodal system
   - (Truck pickup – Rail drayage – Shortsea Long haulage – Rail drayage – Truck distribution)
It is worth mentioning that there are three types of drayage in the mode choice sets in Table 1: truck-drayage, rail-drayage, and truck pickup/distribution. The rationale dividing these types is that the distance of drayage in the study area seems to be longer than the practical drayage distance (i.e. 50 km or so). The truck-drayage is defined as the movement from senders to a terminal or a port by trucks. It exists in the rail-based intermodal system indicated as ② and the short sea based intermodal system indicated as ③. Rail-drayage, indicated as ④ and defined as the rail-rail (or rail-short sea shipping) connection system from the local freight train terminal to a hub terminal is shown in the 2nd level intermodal systems and the rail-short sea based intermodal system is indicated by ⑤. Thus, in the cases of the 2nd level intermodal systems, the truck pickup/distribution plays the role of picking up from the origin and distributing to destinations.

④ shows the quite competitive cost performance in terms of both freight costs and CO$_2$ emissions. Compared to ②, ④ has the lower freight cost and the lower CO$_2$ emissions although the terminal transshipment charges are twice as high. However, the route from Amsterdam to Warsaw was an exception. The rail- and short sea-based intermodal shortest path associated with the route both involve a considerable detour, while the truck-only system (①) has the shortest path without such a considerable detour. Thus, ① is the best option on the route 1-3 in terms of costs. In practice, there are several similar cases, in that ① has significant competitive advantage over the intermodal system, due to the detour on the given network.

**Network Assignment**

The demand of containers in each node and furthermore the OD matrixes were estimated using freight transport demand statistics issued by Eurostat (16). The summation of the demands for each arc was used as the RHS constraints ($a^b_{ij}$). The external flows and implicit internal flows are not considered in the case study (e.g. external containers to be loaded/ unloaded in the Port of Rotterdam are not taken into account). The issue on setting up the capacity, in particular for the road network, is quite challengeable because all situations on road links vary from country to country in Europe (e.g. the number of lanes, percentages of freights and passenger trips, the time variation, and so on). Thus, instead of setting up infrastructure capacity, the number of available freight vehicles in the logistics market is assumed to be that used in the RHS. For example, $x_{12} + x_{13} + \ldots + x_{99} \leq$ the number of trucks in the entire network region (i.e. the superscription indicates the freight system). This may be applied to each node if the market information is sufficiently satisfied.

Figure 2 (a) shows the demand. Each arc has three mode options. There are invisible arcs connecting spoke nodes (i.e. node 1, 2, 3, and 4) and hubs (i.e. 5 and 6). Those arcs have two mode options: road and rail, since 2nd intermodal systems are considered. The capacities for freight systems in the network are assumed to be 90TEU per day for rail, 200 TEU per day for short sea service, and 500 TEU for a truck-only system, reflecting the current freight system. Figure 2(b) is the first container assignment solution minimizing the freight cost in the network by the single LP running (i.e. Step 1 in the previous Section). This solution may represent the current freight market share if the inputs (i.e. demand and capacity) are accurate and the decisions in logistics are only made to minimize the freight cost. In addition, this solution is totally independent of the relation to CO$_2$ since currently there is no direct regulation of CO$_2$ emissions in the case study area.
FIGURE 2 The given flows and initial assignment solutions

Figure 2(c) shows the assignment of containers in terms of minimizing the CO₂ emissions generated from the freight systems in the entire network (i.e. Step 3 in previous Section). There are only a few shifts from one system to another in order to reduce CO₂ in the entire network. Specifically, for the arc (2, 3), 185 containers transported by road in Figure 2(b) are reduced to 153 in Figure 2(c) and are shifted to short sea shipping. However, since the short sea shipping has the capacity (i.e. 200 TEU per day), 25 containers from node 5 to node 4 are shifted from short sea shipping to rail, in that \( X_{54} + X_{54}' = 77 \) in Figure 2(b) is equal to \( X_{54}' = 13 \) in Figure 2(c). In terms of
satisfying the flow conservation constraint (a), this model appears to find the lowest costs as well as ensuring the lowest CO₂ emissions. As shown in Table 1, the truck-only system from 1 to 6 seemed to be the optimal choice in terms of costs if the rail-related services are excluded. This small change in the case study was caused by the capacities of each freight system being quite tight (i.e. total demands and capacity are assumed as 783 and 790 respectively). In other words, there is no room significantly to update the network too much. It was also shown that the binding constraints in Figure 2(b) were the truck-only system and the intermodal rail system while in Figure 2(c) it was rail based intermodal systems and short sea intermodal systems. It is also worth noting that the flows with superior truck-only system costs in arc (1, 3) are supposed to shift to less CO₂-emitting systems in Figure 2(b). However, the capacities of other intermodal systems are full. It is recognized that the capacity and demand of intermodal systems seems to be crucial in terms of minimizing CO₂ emissions. This issue will be fully discussed in the Scenario Analysis Section.

**Pareto Optimal (Trade Off)**

The solutions to the assignment problem estimated previously were the marginal points as shown in the Figure 3: the minimization of freight transport system costs (i.e. upper left side) and the minimization of CO₂ emissions (i.e. lower right side). Figure 3 shows 50 solutions, which are not a full set of Pareto optimal solutions but a subset. However, the algorithm can estimate less than 50 since there might be non-feasible solutions in iterations. The relationship between costs and CO₂ emissions in the entire network is not exactly linear. The linearity of Pareto Optimal is not necessary even if all the objective functions are linear. Specifically, the changed amount of costs is not necessarily proportional as the allowed CO₂ emissions are decreased.
SCENARIO ANALYSIS

Input Scenarios

In order to examine different market situations, 6 different scenarios related to demand and capacity are shown in Table 2.

TABLE 2 Scenarios in terms of OD flows and Service capacity

<table>
<thead>
<tr>
<th>Description</th>
<th>OD Sets</th>
<th>Total Demand</th>
<th>Service Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S 1</strong> The demand based on economical activity (Ams – War / Bru – War) and the capacity reflecting current market situation (2 train services per week / 1 short sea service per week)</td>
<td>Warsaw 315 Vilnius 27 Gdansk 25</td>
<td>783</td>
<td>truck 500</td>
</tr>
<tr>
<td></td>
<td>Amsterdam 315 Brussels 217 Rotterdam 25</td>
<td></td>
<td>rail 90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vessel 200</td>
</tr>
<tr>
<td><strong>S 2</strong> The demand based on economical activity (Ams – War / Bru – War) and the extended intermodal capacity (3 train services per week / 1 short sea service per week)</td>
<td>Warsaw 315 Vilnius 27 Gdansk 25</td>
<td>783</td>
<td>truck 500</td>
</tr>
<tr>
<td></td>
<td>Amsterdam 315 Brussels 217 Rotterdam 25</td>
<td></td>
<td>rail 270</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vessel 200</td>
</tr>
<tr>
<td><strong>S 3</strong> The demand based on economical activity (Ams – War / Bru – War) and infinite capacity</td>
<td>Warsaw 315 Vilnius 27 Gdansk 25</td>
<td>783</td>
<td>truck infinite</td>
</tr>
<tr>
<td></td>
<td>Amsterdam 315 Brussels 217 Rotterdam 25</td>
<td></td>
<td>rail infinite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vessel infinite</td>
</tr>
<tr>
<td><strong>S 4</strong> The fixed demand for all origins and the capacity reflecting the current market situation (2 train services per week / 1 short sea service per week)</td>
<td>Warsaw 87 Vilnius 87 Gdansk 87</td>
<td>783</td>
<td>truck 500</td>
</tr>
<tr>
<td></td>
<td>Amsterdam 87 Brussels 87 Rotterdam 87</td>
<td></td>
<td>rail 90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vessel 200</td>
</tr>
<tr>
<td><strong>S 5</strong> The fixed demand for all origins and extended capacity (3 train services per week / 1 short sea service per week)</td>
<td>Warsaw 87 Vilnius 87 Gdansk 87</td>
<td>783</td>
<td>truck 500</td>
</tr>
<tr>
<td></td>
<td>Amsterdam 87 Brussels 87 Rotterdam 87</td>
<td></td>
<td>rail 270</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vessel 200</td>
</tr>
<tr>
<td><strong>S 6</strong> The fixed demand for all origins and infinite capacity</td>
<td>Warsaw 87 Vilnius 87 Gdansk 87</td>
<td>783</td>
<td>truck Infinite</td>
</tr>
<tr>
<td></td>
<td>Amsterdam 87 Brussels 87 Rotterdam 87</td>
<td></td>
<td>rail Infinite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>vessel Infinite</td>
</tr>
</tbody>
</table>

Scenario 1, whose Pareto optimal was already presented in Figure 3, is more or less the base scenario to compare with the others. Thus, Scenarios 2 and 3 are the attempts to examine the change of relationship between freight costs and CO\textsubscript{2} emissions as the capacities of specific freight system(s) are changed.

In Scenario 4 to 6, the fixed number of containers (i.e. 87 containers) is the total number of containers divided by the number of nodes in the network region. These scenarios have been designed in order to avoid the effect of one exceptional route, which is Amsterdam to Warsaw. The route has greater demand (i.e. 315 containers) compared to other nodes and an exceptionally cheaper truck-only system cost compared to other arcs. In order to generalize, even though the
demand might be correlated with the costs, it is assumed that the same amounts of containers are transported.

**Results**

![Figure 4](image)

**FIGURE 4 Scaled Pareto Optimal Solution on given network and demand**

The trade-off graphs (i.e. Pareto optimal) in Figure 4 have the same scale of x- and y- axis. Figure 3 has been changed to the first graph (Scenario 1) in order to compare with other scenarios. It can be seen that pairs of two scenarios, (S1 and S4), (S2 and S5), and (S3 and S6), have similar shapes. Comparisons and interpretations are as follows:
The increment of CO₂ emission constraint of S1 and S2 is 527.16 and 10,941.28 respectively. (the increment is defined in Step 5 in the previous Section). The vertical length (i.e. CO₂) and horizontal width (Cost) of two graphs can be explained by the amount of increment. The greater increment means a longer and wider graph, which indicates that the changeable amount of cost and CO₂ in S2 is relatively greater than in S1. When it comes to absolute comparison, it makes sense that S2, adding two more railway services per day on the long-haulage arc (5, 6) provides a more economical and less CO₂-emitting service than S1 in the entire network region.

S1 vs S2 vs S3
S3 shows that both costs and CO₂ are reduced as the system capacity is infinitely increased. Actually, the graph does not seem to happen in reality due to congestion on the highway and the queues of containers in the port/terminals. Nevertheless, it is worth observing that the slope of the graphs is very different compared to S1 and S2. The shape indicates that it is feasible to reduce CO₂ emissions drastically as a relative small amount of costs are paid in the region where the intermodal system capacities are sufficient and other external impacts are negligible.

S1 vs S4
The slope of S4 is steeper than of S1 because the concentration of demand in the area where a cheaper truck service (i.e. flows from Amsterdam) is provided is relaxed.

S2 vs S5
The graph shapes are almost similar apart from the left upper part of S5, the minimized cost with the loosed CO₂ constraints. This part indicates the slightly expensive freight costs because the costs are increased across the entire network through the uniform distribution of the demand (i.e. 87 containers for all nodes) in that some flows use uneconomical freight systems. The steeper slope at the beginning is because the truck-only system services rapidly shift to the intermodal systems. As the uncompetitive expensive truck services in terms of route are removed from the network and the CO₂ emissions constraints get tighter, the slope in S5 is stabilized as S2.

S3 vs S6
In general, both costs and CO₂ are considerably decreased. The main reason is the initial unbalanced demand flows on the arc (5, 6).

Discussion

The comparisons of scenarios in Figure 4 make the evaluation of current tax policy possible. As mentioned previously, scenario 1 has been constructed based on the current demand and capacity in the case study area. The slopes of each scenario in Figure 4 could be an indication of the CO₂ tax price per ton since it is almost a line, which can be approximated in any point. Simple linear regressions are run in order to draw the generalized lines for 6 scenarios. Table 3 presents the scenarios, the estimated linear regressions and R², and CO₂ price per ton (€/ton of CO₂). According to R² values and t-values in the basket (e.g. [-92.62]), the regression lines fit well. However, it is surprising that CO₂ price ranges from 11 € / ton to 5,350 € / ton in terms of the input scenarios. Considering the practically recommended CO₂ price ranging 7 € / ton to 45 € / ton for 2010 (17) even though the approach for the estimation is different from this study, the
CO₂ price estimated in this study seems to be over-estimated. However, the opposite case is also possible in that the current recommended CO₂ price could be seriously underestimated.

**TABLE 3 Estimation of CO₂ price per ton**

<table>
<thead>
<tr>
<th>Demand</th>
<th>Linear Regression Equation</th>
<th>$R^2$</th>
<th>CO₂ price per ton (€ / ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 1</td>
<td>Current OD flows</td>
<td>Cost = 3,319,039 – 5.35 CO₂</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td>Base capacity</td>
<td>[92.62]</td>
<td></td>
</tr>
<tr>
<td>S 2</td>
<td>Current OD flows</td>
<td>Cost = 2,810,750 – 0.496 CO₂</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>Increased Rail Service</td>
<td>[-7945.5]</td>
<td></td>
</tr>
<tr>
<td>S 3</td>
<td>Current OD flows</td>
<td>Cost = 1,107,040 – 0.011 CO₂</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>Infinite</td>
<td>[-89079.5]</td>
<td></td>
</tr>
<tr>
<td>S 4</td>
<td>Equal flows in all O-D</td>
<td>Cost = 1,833,786 – 0.125 CO₂</td>
<td>0.919</td>
</tr>
<tr>
<td></td>
<td>Base capacity</td>
<td>[-23.4]</td>
<td></td>
</tr>
<tr>
<td>S 5</td>
<td>Equal flows in all O-D</td>
<td>Cost = 2,414,230 – 0.368 CO₂</td>
<td>0.993</td>
</tr>
<tr>
<td></td>
<td>Increased Rail Service</td>
<td>[-82.2]</td>
<td></td>
</tr>
<tr>
<td>S 6</td>
<td>Equal flows in all O-D</td>
<td>Cost = 1,055,150 – 0.011 CO₂</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>Infinite</td>
<td>[-24828.1]</td>
<td></td>
</tr>
</tbody>
</table>

**CONCLUSIONS AND FURTHER STUDY**

The quantitative relationship between CO₂ and freight costs has been gaining in importance in the logistics field due to global warming as well as rapidly increasing fuel costs. This study is an effort to estimate the relationship using the LP-based algorithm. This study clearly shows the trade-off curve generated by developing a decision-support tool. Since each solution composing the trade-off curve has the unique network assignment as well as modal share rate, the point (or range) could be found which fits with the social needs or decision makers’ wishes. Furthermore, examining six scenarios with different O-D sets and capacity constraints shows that the trade-off curves have almost a linear relationship in that freight costs should be paid more as CO₂ emissions should be reduced. However, the quantity of the relationship varies, ranging from 5,350€ / ton to 11€ / ton in terms of the input scenarios. In other words, the cost of CO₂ emissions cannot be estimated in general while it can be estimated only if several necessary conditions are fully considered (i.e. O-D sets, capacity and availability of freight systems, cost structure, CO₂ estimation and so on). The study also shows that increasing the lower CO₂ emitting system’s capacity would reduce the CO₂ emissions. In addition, this study has newly extended the concept of intermodality into 2nd level intermodal systems assuming that drayage can be performed by rail and considered as a different option.

Nevertheless, this study may be incomplete since one of the most crucial decision factors in logistics decision making, minimizing the lead time or ensuring Just-in-time, is not taken into account. The third/fourth objective functions could compensate for this incompletion in a future study. The objective functions minimizing those temporal concepts might be non-linear functions. In addition, the actual cost function and emissions function are not really linear. Although the unit-based performance measures are used as in this study, more precise formulations will lead this simple linear problem with feed-back to non-linear optimization problem. Accordingly, non-linear programming (NLP) would be a better option to finding a more accurate solution. Thus, more complicated algorithms such as evolutionary and generic algorithms should be used in order
to estimate the full set of Pareto optimal solutions. As mentioned previously, the Pareto optimal estimated in this study was a subset. There are some more details to be improved on in a future study. RECORDIT showed that the different type of loading units often caused the considerable different total costs. Thus, although the two types of containers are converted into TEU in this study, the attention of loading units should be paid. It is because the double size of the loading unit does not guarantee double weight, which crucially affects the costs as well as the CO₂ emissions. Road traffic congestion is also an important factor affecting both costs and CO₂ emissions.

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