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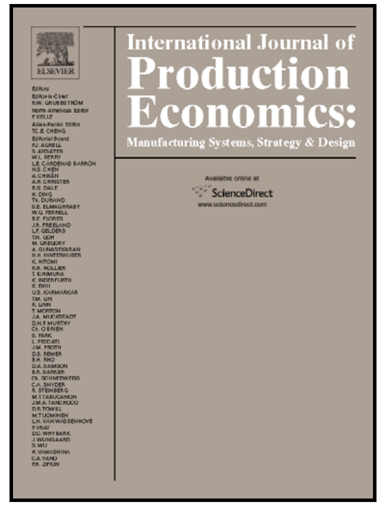

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Assessing the Impact of Cost Optimization Based on Infrastructure Modelling on CO_2 Emissions

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Abstract

Traditionally, logistics design is driven by a need to reduce costs and improve customer service. Recently, the environmental concerns from transport have been increasingly discussed. The traffic levels and associated energy consumption are influenced by supply chain structure, modal split and vehicle utilization. This paper aims to assess the impact of the traditional cost optimization approach to strategic modelling on overall logistics costs and CO_2 emissions by taking into account the supply chain structure (number of depots) and different freight vehicle utilization ratios (90%, 75%, 60%). The simulation model, based on a European case study from the automotive industry, considers strategic and operational level decisions simultaneously. The analysis shows that the optimum design based on costs does not necessary equate to an optimum solution for CO_2 emissions, therefore there is a need to address economical and environmental objectives explicitly as part of the logistics design.

Keywords: Sustainable logistics, Strategic decision making, Simulation, Case study.

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1. Introduction

The threat of climate change has been increasingly discussed at an international level, with greenhouse gas emissions from fossil energy sources being at the forefront of governmental concerns. Transportation, industrial processes and other commercial sectors have been linked to an increase in the greenhouse effect through their release of carbon dioxide, even though the influence of other gases should not be underestimated. The annual carbon dioxide (CO_2) emissions from all transport increased by 17 million tones of carbon in the UK during the period from 1970 to 2004 (DfT, 2006a). Although the growth rate has slowed down considerably since 1990, clearly the Government would like to see the trend reversed and emissions cut. *Figure 1* shows a particular concern in the rise of CO_2 emissions over the past decade from heavy goods vehicles (HGV) and light duty vehicles (LDV), by 33 % and 19 % respectively (DfT, 2007b).

The past 20 to 30 years have seen a significant restructuring of logistics networks for many companies, as they strive to reduce costs while improving customer service levels. In the context of transport, there has been a particular focus on improving vehicle fill and reducing the distance vehicles travel. While traditionally, attention has concentrated on outbound logistics, increasingly inbound distribution is also considered (Cubitt, 2002). Not only do these changes bring about internal benefits to companies, but also create wider benefits to society, leading to a reduction in external costs and its impact on the environment.

Logistics network redesign involves different decisions that attempt to optimize the number, location and allocation of service providers, flow of goods and modal selection etc. Interestingly, reduced environmental impact frequently results as direct aim, or as a by-product of a more cost-efficient distribution system (Aronsson and Huge Brodin, 2006). Nevertheless, there is an increasing need to treat logistics design as a whole by integrating economic and environmental objectives. Aronsson and Huge Brodin (2006) point out that:

"There is an agreement in literature that decisions on different organisational levels have different impact on operative efficiency, from strategic decisions of how to source material to operational decisions of what truck to use for a specific transport (Abrahamsson and Aronsson, 1999). There is also an agreement that strategic decisions should have a larger impact on emissions than operative decisions. There is, however, a disagreement on what specific decisions have the largest impact, and what those decisions really will lead to regarding environmental impact."

Figure 1. UK Carbon dioxide emissions for road transport (DfT, 2007b).

This paper aims to explore the relationship between total logistics costs and environmental impact, using a traditional cost-based optimization approach on a Pan -European case study from automotive industry (Hammant *et al.*, 1999). This data was previously evaluated from an economic perspective only and identified the optimum network design at two distribution centres. Taking an environmental perspective gives us new insights. We will consider the impact of strategic and operational level decisions simultaneously, focusing on inventory and transportation costs versus the environmental impact in terms of CO_2 emissions from transportation and non-domestic buildings such as depots. The calculation of CO_2 emissions from transportation considers vehicle type, utilization and vehicle speed. We use a supply chain network design application for our simulation with optimization based on costs alone. Attention is also paid to the sensitivity of our solutions when changes in key model parameters, such as vehicle utilization ratios (90%, 75%, 60%) and supply chain structure (number of depots), occur.

The paper is organized as follows. In Section 2 we present the literature review regarding logistics restructuring and how this affects the wider environment. Environmental impact from transportation and depots is also discussed. In Section 3 we present an overview of the case study, along with details of the method adopted for calculating CO_2 emissions. This leads to the presentation and analysis of the results, from which wider implications for management and policy makers are highlighted. Finally, conclusions are drawn.

2. Literature Review

2.1 Logistics restructuring and the environment

Since the 1980s, the development of supply chain management has resulted in managers becoming increasingly focused on the demands of their customers. Initiatives such as lean production have resulted in companies looking to deliver ever higher levels of customer service, while minimising the cost impact (Towill, 1996). Logistics operations have been required to handle smaller and smaller shipments through their networks while maintaining efficiency. As a consequence of this, it has been necessary for companies to reconfigure their logistics operations. These have been categorised by McKinnon (1998) into four main areas:

- Logistics structures – relates to the configuration of the distribution network and the choice of distribution channel. Control of this network also comes within this area.
- Pattern of trading links – determines the geographical spread of the logistics structure. Recently, moves towards outsourcing abroad have seen supply chains lengthen.

- Scheduling of product flow – affects the movement of products through the network and determines the size of the shipments to be made. Developments in this area include continuous replenishment and just-in-time deliveries.
- Management of transport resources – decides the actual transport requirements for particular shipments, and may include issues relating to modal choice.

All of the above decisions are likely to affect the transport requirements for an individual organisation, in terms of the distance, speed, frequency and timing of deliveries (Drewes Nielsen *et al.*, 2003). Traditionally, such changes would only influence the outbound logistics operations of a business (Gustin *et al.*, 1995), with inbound movements being viewed as the responsibility of the supplier. However, nowadays, there is a focus on this inbound network, as companies recognise the potential synergies that exist between them (Cubitt, 2002).

There are a number of examples within the published literature of how the efficiency of logistics operations can be improved, while also delivering environmental benefits. The consolidation of small shipments is a popular approach to reducing transport costs, and has particularly been used within the grocery industry in the UK (Fernie *et al.*, 2000). Consequently, load consolidation has resulted in a reduction in the distance vehicles travel of around 20% (McKinnon, 1998).

2.2 Infrastructure modelling for network design.

Physical infrastructure of the network, such as numbers, locations and capacities of depots has a direct affect on freight transport operations (McKinnon and Woodburn, 1994). Infrastructure modelling is not new to academic research and has a very rich literature. ‘Undesirable’ locations, such as those for chemical plants and nuclear reactors have been studied since the 1970's when the environmental impact of airborne pollutants first became an issue. The need for 'desirable' environmentally friendly networks is becoming ever more important and some research has started to consider both the economic and environmental impact of network design.

Traditionally, logistics redesign is driven by a need to reduce total logistics costs and improve customer service levels. Companies contribute to the environmental improvements as a direct aim, or as a by-product, of their logistics infrastructure. Aronsson and Huge Brodin (2006) describe three case studies, where companies had undergone different but similar changes in their distribution structures, noting a positive effect, and not just on cost reductions but also on the environment (reduced emissions). Typical changes involve new distribution structures with fewer nodes, larger warehouses, or changes in transport mode. Other examples show that changes made for economic reasons also produced environmental benefits (reduced congestion and number of vehicle-kms) when the Factory Gate Pricing concept was analysed for the Dutch (Le Blanc *et al.*, 2006) and UK (Potter *et al.*, 2003) retail industry. However not all infrastructure changes necessarily have a positive impact on the environment. Kohn (2005) describes a case study of a manufacturer of submersible pumps and mixers where he analyses the effects of changing from a decentralised to a centralised network and reveals that lowering costs and improving service performance produce a negative impact on the environment. The overall analysis of direct effects from road transport indicates increase in both tonne - kilometres and CO_2 emissions. These findings correlate UK statistics, that the centralisation of warehousing which was done to reduce inventory has had a direct impact on transportation, increasing the average length of haul from 79 km in 1990 to 87 km in 2004 (DfT, 2004). On the other hand, through the centralization the company managed to decrease the amount of emergency deliveries that lowered the emissions related to these transportations. Their analysis also opened new opportunities for the company to make decisions that improve environmental performance of the network.

Therefore, although it would appear that a reduction in environmental impact frequently occurs as bonus following a cost reduction exercise, this is by no means always the case. When creating an environmentally friendly network it is important to consider economic and environmental trade-offs of logistics redesign. For this reason, it is prudent to model environmental issues as part of the design objectives rather than as constraints. This way more information is available to help balancing cost versus environmental impact (Current *et al.*, 1990). There is evidence that some researchers have already started incorporating environmental objectives into strategic modelling. For example, Khoo *et al.* (2001) used a simulation approach to select plant locations concerned with the distribution of raw aluminium metal. They attempted to balance the following: low total market costs, low transport pollution, fast deliveries between plants, the promotion of recycling for scrap metal and the conservation of energy. Hugo and Pistikopoulos (2005) present a generic mathematical programming model for assisting the strategic long range planning and design of a bulk chemical network. Their multi-objective mixed-integer programming problem is formulated to minimize the environmental impact resulting from the operations of the entire network and maximize the Net Present Value (NPV) of the investment which is required to install and operate the plants. The Eco-Indicator 99® method (Pré Consultants, 2000), is used to model potential environmental damages on a European scale according to three categories: human health, ecosystem quality and resource depletion.

2.3 Environmental impact from transportation and depots. Bloemhof-Ruwaard *et al.* (1995) point out that the extent of the environmental problems over the last few decades has shifted from the local and regional level to a continental and global level. The environmental changes expand from the air quality and health at the local level to climate change and depletion of the ozone layer on the global level. Greenhouse gasses, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) contribute to climate change and the temperature rise near the surface of our planet. Therefore the greenhouse gasses from transport and energy need to be addressed urgently.

Carbon dioxide emissions are produced by burning fossil fuel and from a transportation point view are caused by different modes of transport such as road, rail, water and air. Different factors have an impact on the actual levels of emissions from road transportation and can be grouped under the following categories according to the *National Research Council* (NRC, 1995):

- Travel-related factors – these depend on the trip taken and distances travelled and vary for different vehicle operating modes. The speed and acceleration of the vehicle and load on the engine over the distance of the trip also have impact.
- Driver behaviour, such as smoothness and consistency of vehicle speed.
- The physical highway network characteristics, such as long grades, signalized intersections and volumes of traffic entering the traffic flow.
- Vehicle characteristics such as fuels, engine size, vehicle condition.

There are different formulations available for calculating road related emissions. The *National Atmospheric Emissions Inventory* (NAEI, 2002) provides a spreadsheet which contains a complete set of speed-emission factor coefficients for CO_2 and other greenhouse gas for different types and sizes of vehicles in the UK fleet travelling at average speeds. The *Department for Environment, Food and Rural Affairs (*DEFRA, 2005*)* provides greenhouse gas (GHG) conversion factors to convert existing data sources, e.g. freight fuel consumption, electricity/gas consumption etc. into CO_2 equivalent data. Their carbon dioxide formulation also takes into account the diesel lorry type and percent of weight laden of the lorry, which is the maximum carrying laden capacity of the loaded vehicle. Kohn (2005) uses an equation from the *The Network for Transport and Environment (Sweden)*, which allows the calculation of carbon dioxide emissions per tonne- kilometre for a particular vehicle type. Some researches calculate CO_2 emissions directly (Kohn 2005) and others use different methods for assessing the potential environmental damage. *Table 1* shows examples of papers which include different methodologies for assessing environmental impact. Also the importance of monitoring green supply chain management practices with factors such as green purchasing, design of products for reduced consumption of material/energy and others is discussed by Zhu *et al.* (2008). For the present study we are using the DEFRA (2005) formulation because it is widely used as guidelines to help UK businesses to calculate CO_2 emissions and thus identify and address environmental impact. Our environmental model takes into account CO_2 emissions from both transportation and depots.

Table 1. Examples of papers using different methods for calculating environmental impact.

McKinnon (2007) presents an analytical framework incorporating all the factors, which influence traffic level and related energy consumption, to review the opportunities for the reduction of CO_2 emissions from the freight sector at a macro level. The framework links the weight of the goods produced/ consumed to CO_2 emissions from freight operations. Handling factor (no. of links in the supply chain), average length of haul, modal split, average load on laden trips, average % empty running, fuel efficiency and CO_2 intensity of energy source (fuel-specific) are seven critical key ratios which affect the overall CO_2 intensity of the freight sector. Determinants such as supply chain structure, choice of transportation mode, vehicle utilization on laden trips and others have a direct impact on the respective key ratios for reducing CO_2 emissions. The report illustrates the sensitivity to total CO_2 emissions from the freight sector when hypothetical changes have been applied to the key ratios. McKinnon (2007) observes that modal split, average payload weight, the proportion of empty running and fuel efficiency have been moving in a direction which reduces CO_2 emissions per tonne-km over the period 1990-2004.

Depots have a very important role in the logistics network design. They are used for stocking products or as an exchange point for transportation modes to service their stores or customers. Greenhouse gas emissions in buildings arise from direct burning of fossil fuels to produce electricity and heat. The energy consumption of non-domestic buildings, such as depots or warehouses depends on the type of the product being stored. The storage of frozen and chilled goods would involve having a special storage space, which would involve higher energy consumption. DEFRA (2005) provide UK conversion factors for different fuel types, such as electricity and natural gas to convert available energy data into CO_2 equivalent data. In the UK electricity is generated mainly by the burning fossil fuels such as coal, natural gas and oil; whereas in other countries the main supply could come from different sources. For example, nuclear power dominates electricity production in France. Therefore, different electricity conversion factors need to be applied to the available energy data.

3. Method

To explore the relationship between total logistics costs and environmental impact in terms of CO_2 emissions for strategic modelling in the logistics network, there is a need for an appropriate methodology for both assessments. The method and data we use for evaluating economic costs is based on the case first presented in Hammant *et al.* (1999). One of the objectives of that study was to describe the use of a simulation-based decision support system to establish the impact of restructuring the physical infrastructure of the Pan-European supply chain. The authors indicated the benefits of using a simulation approach for assessing network design. The optimum network design at two distribution centres was determined by minimizing the total overall logistics costs (transportation and inventory costs) while ensuring an appropriate customer service level. Subsequently Lalwani at al. (2006) used the data to present a new method, which combines simulation and the Taguchi technique to identify the factors that the structure of the distribution network is sensitive to. Their analyses indicated that the optimum design is most at risk from the uncertainties associated with inventory holding stocks and delivery frequencies rather than customer volume changes and transport tariffs.

3.1 Modelling economic costs.

To model our logistics networks, we use a commercially available supply chain design application CAST-dpm® (by Radical, nowadays known as CAST-NV by Barloworld Optimus). This is the same package that was used in the original study by Hammant *et al.* (1999) and Lalwani at al. (2006). The software allows the decision-maker to evaluate different scenarios and aims to identify the optimum network infrastructure, such as the location and number of depots. It uses a heuristic approach to estimate the transportation costs of the network, distance run by the vehicles and the number of the vehicles needed for the particular output period. The Square Root Law (Maister, 1975) was used to estimate the inventory costs that are needed in the network.

As previously mentioned, the simulation model is based on the case study of an automotive aftermarket Pan-European distribution network. The network operates through different countries such as the UK, France, and Spain involving a large number of businesses and substantial operating distance. Throughout Europe, the company has around 550 suppliers and 10,000 customers. The case study is purely road transport based and does not take into account freight movements by sea or rail, although to join up with the UK road network a ferry or rail/tunnel journey would be used. All the input data, which was used in our model, was taken from the original case study, apart from the transportation data that we generated ourselves, as it was not available from the original source. *Table 2* summarizes the input data used for the simulation model. Note that the total logistics costs derived from our design, are different to the original paper because we used different transportation data. The aim of this research is not to replicate the original case study, but to show our methodology and analysis of the trade-offs between the total costs and their environmental impact of cost-based optimization.

Table 2. Simulation model's input data based on Hammant et al. (1999).

To analyse the relationship between total logistics costs and their environmental impact from transportation and depots, two different scenarios were considered for strategic modelling. For the first scenario, we used a centre of gravity method to determine the centroid locations of the distribution centres in the network. For the second scenario, the original locations from Hammant *et al.* (1999) were used to derive network related costs and distances travelled. The original locations are the real physical depots existing in the network. In this scenario, we aimed to replicate the total logistics costs curve from the original case study, which identifies the optimum network design at two depots.

According to Coyle *et al.* (2003), there are three principal modelling approaches in logistics network design: optimisation, simulation and heuristic methods. The optimisation approach guarantees to find optimum solution and is based on a mathematical formulation of the problem. Different techniques, such as linear, integer, mixed-integer linear programming are used to solve optimisation models. The simulation method allows the decision-maker to test the effect of alternative locations on cost and service level. The current network modelling software is based on the static approach, which could make it an overdue requirement for a constantly changing market. The simulation model is not intended to find the optimum solution; it evaluates different options, which are put in into the system. Heuristic approaches use "rules of thumb" and can provide a good approximation of least-cost solution to a complex problem quickly.

3.2 Centre of gravity modelling

Two different scenarios were considered for current study for strategic modelling: original published locations with optimum design of two depots and centre of gravity scenario. The centre of gravity approach is one of the well-known heuristic methods in facility location analysis. It indicates the centroid locations that minimize the total transportation cost. Traditionally, transportation rate and the point of volume are the only location factors in this approach (Ballou, 1998). The method provides a good estimation to the least-cost solution. However, a certain amount of location flexibility has to be exercised by the decision-maker because of geographical obstacles, such as sea, mountains etc. The current network modelling software offers two alternatives for centre of gravity modelling: cost centre of gravity and volume centre of gravity. The cost centre of gravity model attempts to minimize the total transportation cost; whereas the volume centre of gravity attempts to minimize the total distance travelled (Radical, 1999). There has been much research on centre of gravity techniques to try and overcome the inherent problem of finding sub optimal locations (Ballou, 1973). These techniques generally focus on an individual depot and therefore do not take into account inter depot movements. CAST-dpm® allows for the use of multiple depots, but does not account for inter depot movements in the centre of gravity modelling. The cost based centre of gravity was used with a limited number of scenarios, but these generated similar results to the volume centre of gravity. Therefore, due to time constraints and the similarity of results the latter technique was used. As can been seen from *Figure 2* the centroid depots locations for UK and France have not moved too far from the original locations due to the high supply and demand volumes in those areas. The other distribution centres have changed locations, which reflect current customer's and supplier's demands.

Figure 2. Depots locations (five depots scenario).

3.3 Modelling CO_2 emissions.

After establishing the base design for each scenario, we used two determinants, supply chain structure and vehicle utilization factor as key decision variables for this research, to analyse the potential for reducing CO_2 emissions at the micro level. These factors and others impact on the respective key ratios identified by McKinnon (2007) to influence CO_2 from freight transport. Supply chain structure has a direct impact on the two key ratios: handling factor and average length of haul. Handling factor is a crude measure of the number of the links in the supply chain, where the weight of the goods is converted into freight tonnes-lifted. Therefore, for our research, the supply chain structure was reflected in the reduction of the total number of depots in the network: from five depots down to one depot, decrementing in steps of one. Vehicle utilization has a direct impact on reducing vehicle traffic. Increasing vehicle utilization allows businesses to cut the number of vehicles on the road, which brings both economic and environmental advantages. The average weight-based utilization in 2005 in UK of rigid lorries on laden trips was 52% and for articulated vehicles 58% (DfT, 2006b). Average deck utilization of the vehicles, for pallet networks was 73%, for non-food 51%, and for food retail 53% (DfT, 2007a). Therefore, as the purpose of this research is to analyse the trade-offs between total costs and emissions, we used vehicle utilization factors at 90% (the 'ideal' vehicle utilization); at 75% (approximation from the average deck utilization for pallet network) and at 60% (average weight-based utilization for articulated vehicles).

When using strategic modelling techniques to calculate CO_2 emissions from transportation and depots, it is important to establish boundaries for those estimations. To calculate CO_2 emissions from transportation, we will only consider the amount of goods being transported over the distance travelled. Our method does not take into account the life cycle assessment of the product from "the cradle to grave". For the present work, we use the outputs from the supply chain network design application, which runs over a particular period of time and establishes the network related costs and travelled distances for different vehicles types for a particular output period of 52 weeks. Hence, our estimates for CO_2 emissions cover the same period of 52 weeks. As mentioned previously, the case study described in this paper is purely road transport based and does not take into account freight movements by sea or rail. *Figure 3* represents the overall method with data requirements for each scenario.

Figure 3. Input/Output diagram of the method for each scenario.

Due to the complexity of correctly estimating CO_2 emissions from transportation, some assumptions and simplifications have to be made with respect to driver's behaviour, volume of the traffic on the road, and so on. It is very difficult to take account of all the described factors, which have an impact on fuel consumption to calculate CO_2 emissions from road freight. Assume that two types of diesel lorry are used for delivering goods across the network: a 5 tonne gross weight lorry and a 40 tonne gross weight lorry. To calculate CO_2 emissions from transportation for each vehicle type, we used a distance-based formulation (1) from DEFRA (2005).

$$\textit{Total}\ \mathrm{CO2}\ (kg) = \textit{total km travelled} * \textit{litres fuel per km} * \textit{fuel conversion factor} \quad (1)$$

where a fuel conversion factor of 2.63 kg/litre was used for diesel fuel; litres fuel per km (LFPK) is the fuel consumption (litres/km) of the vehicle.

The fuel consumption (litres/km) figure for equation (1) is calculated depending on the vehicle speed, vehicle type and vehicle payload. The following methodology was used to define fuel consumption accordingly:

1. Establish fuel consumption (litres/km) for the base case (with average vehicle speed at 54 mph). For a 40 tonne lorry we used data from Kohn (2005), where a figure of 0.27 litres/km for fuel consumption unladen and 0.38 litres/km for fuel consumption with a full load was used for a vehicle speed of 54 mph. For a 5 tonne lorry we estimated that fuel consumption unladen is 0.157 litres/km and 0.275 litres/km for fuel consumption with a full load from the statistics of fuel consumption data by vehicle type from DfT (2004). Equation (2) presents a formulation which we used for calculating fuel consumption depending on the vehicle payload. Linear correlation

between payload and fuel consumption correspond to the recent investigation by DfT (2007c).

$$LFPK = LFPK(unladen) + \frac{(LFPK\ (unladen) - LFPK(unladen) * (\%\,weight\ laden))}{100} \quad (2)$$

The result of all calculations for different vehicle types, with an average speed of 54 mph is presented in *Table 3*.

Table 3. Fuel consumption (vehicle speed 54 mph).

2. Calculate fuel consumption (litres/km) from the base case (vehicle speed 54 mph) to a vehicle speed of 45mph, 36mph and 30mph, which reflects different road types for different vehicle types. *Table 4* presents the breakdown of road class and road traffic for HGV (DfT, 2007b). To calculate the percentage difference in fuel consumption between different vehicle speeds we used data from NAEI (2002), where the user can estimate CO_2 emissions depending on the vehicle type and the vehicle speed. The conversion of vehicle speeds from miles per hour to kilometres per hour was performed to calculate the emissions. For example, an articulated heavy goods vehicle with Euro II engine class produces around 5.53% less CO_2 emissions travelling at 45 mph compared to travelling at 54 mph. Because CO_2 emissions is determined mainly by fuel consumption (Romilly, 1999), we assumed the same percentage difference for fuel consumption for each vehicle type in our model (*Table 4*). The same assumptions were applied to data generated for other countries. Therefore, the fuel consumption for each vehicle type, vehicle payload and road class was adjusted accordingly to the percentage of difference shown in *Table 4* from the base case described in step 1.

Table 4. Road traffic, speed and fuel consumption articulated for HGVs.

To calculate CO_2 emissions from electricity used at depots we need to estimate the average annual electricity consumption (kWh/m^2) per depot. In our automotive network, the product is of a nature that does not need a specialised storage environment requiring cooling or heating. The depot data was only available regarding the size of the buildings in m^2. Therefore, an average figure of 2 kWh/m^2 was used from the British Land Company PLC (2005). To convert energy data to CO_2 emissions for UK-based depot, we used a conversion factor of 0.54 kgCO_2/kWh (DEFRA, 2005), which gives CO_2 emissions of 1.08 kg/m^2. For depots in other countries we used the following conversion factors: in France we used 0.083 kgCO_2/kWh, in Italy 0.525 kgCO_2/kWh, in Germany 0.539 kgCO_2/kWh (EIA, 2007), in Spain 0.4556 kgCO_2/kWh (CENEAN, 2008).

4. Results

Identifying the optimum number of depots and their positions is of fundamental importance, if one is to lower total costs and ensure an appropriate level of customer service. In the current study, delivery, collections and inter depot movements are taken into account for calculating overall transportation costs and distances. There is a trade-off between inventory and transportation. *Figure 4a* and 4*b* show the results of Pan-European distribution network modelling and the effect that decreasing the number of the depots in the logistics network has on the transportation and inventory costs. Transportation costs are a function of both distance and time related factors, which include fixed and operational (distance related) costs. We can observe that the transportation costs decrease as the number of facilities decreases until it is reaches the point when it starts increasing again, due to the longer travel distances to the nearest depot. The inventory costs decline as the number of facilities decreases due to the lower levels of inventory. As you can see from *Figure 4a,* the optimum number of depots for cost-based optimization in the centre of gravity scenario equated to three depots. *Figure 4b* shows the optimum number of depots for cost-based optimization equated to two in the original locations scenario, where depots are located at the real physical locations. By changing the vehicle utilization from 60% to 90% for the optimum design in the centre of gravity scenario we observe a decrease in total logistics costs of 8.9 %. A slightly larger decrease of 12.9 % is seen in the optimum design for original locations scenario. Unfortunately, 90% vehicle utilization is not a very realistic figure in the real world. By comparing the more practical levels of 60% and 75% vehicle utilization, we can see a 5.5% total logistics cost decrease for the centre of gravity locations scenario and 7.5% decrease for the original locations scenario.

Figure 4a. Logistics costs related to number of depots and vehicle utilization parameters for centre of gravity locations

Figure 4b. Logistics costs related to number of depots and vehicle utilization parameters for original locations.

Figure 5a and *5b* represent an overview of the transportation distances related to the number of depots and 90 % vehicle utilization parameters for both case studies. The figure shows that inter-depot distance is reducing as the number of depots decreases and the supplier and delivery distance travelled is increasing. Note that the optimum design based on travelled vehicle kilometres is three depots for both scenarios and all vehicle utilization parameters; while the optimum based on distribution costs is three depots for the centre of gravity locations scenario and two depots for the original locations scenario. Similar observations are produced for 75% and 60% vehicle utilization. Note, that in the latter scenario, for 90% vehicle utilization the difference between the three and two depots design resulted in a reduction of total logistics costs by 8.8%; transport costs decreased by 1.4% and total vehicle kilometres travelled based on % laden weight of the vehicle increased by 0.67%, which is almost negligible.

Earlier we discussed the impact of vehicle utilization on total logistics costs. Now we will assess the impact of cost-based optimum network design on the total vehicle kilometres travelled based on % weight laden of the vehicle. For the centre of gravity locations scenario, changing from 60% to 90% in vehicle utilization show a decrease of 22% in distance travelled (km) and 27% for the original locations scenario. Changing the vehicle utilization from 60% to 75% has produced a reduction of 13.1% in distance travelled (km) for the centre of gravity scenario and 16.1% for original scenario.

Figure 5a. Transportation distance breakdown related to number of depots and 90% vehicle utilization for centre of gravity locations.

Figure 5b. Transportation distance breakdown related to number of depots and 90% vehicle utilization for original locations.

Figure 6a. Total CO_2 emissions from transport and electricity related to number of depots and vehicle utilization parameters for centre of gravity scenario.

Figure 6b. Total CO_2 emissions from transport and electricity related to number of depots and vehicle utilization parameters for original scenario.

As discussed in Section 2.3, levels of emissions directly relate to different factors, including distances travelled, the load of the engine over the distance and the speed of the vehicle. The described factors are incorporated into our calculations of the emissions which give more accurate figure of estimating the impact. As you can see from *Figure 6a* the optimum design based on total CO_2 emissions for the centre of gravity scenario is three depots for all vehicle utilization ratios. The increase in vehicle utilization from 60% and 90% shows a reduction of 10.6% in transport related CO_2 emissions and for vehicle utilization from 60% to 75% a reduction of 6.8% can be observed. *Figure 6b* shows that for the original locations scenario the optimum design based on CO_2 emissions is two depots for 90% vehicle utilization and three depots for 60% and 75 % vehicle utilization. Analysing the difference in CO_2 emissions between three and two depots for the original scenario, we can see that there is only a 0.57% decrease for 90% vehicle utilization, which is almost negligible. For 75% vehicle utilization, an increase of 0.55% in CO_2 emissions can be seen and for 60% vehicle utilization an increase of 1.62 % can be observed. The analysis shows that for cost-based optimum design at two depots for the original locations scenario, the changes from 60% and 90% in vehicle utilization produce a reduction of 16.3% in transport related CO_2 emissions. For vehicle utilization from 60% to 75% there is a reduction of around 10%.

From our analysis we identified that environmental impact from electricity in depots in our case study was negligible and had little effect on the overall result of calculating CO_2 emissions. This was mainly due to the product not requiring any specific storage temperature.

5. Conclusion

This paper aimed to analyse the relationship between total logistics costs and their environmental impact in terms of CO_2 emissions from transportation and electricity usage in depots when using a traditional cost-based optimization approach. Our simulation model was based on a Pan-European network from the automotive sector taken from an original study by Hammant *et al.* (1999). The present paper describes a specific case study and does not attempt to generalize the results of the analysis. Nevertheless, we believe that our results highlight the following issue: the optimum solution for reducing costs does not necessarily equate to the optimum solution for reducing CO_2 emissions. Furthermore, our findings indicate the optimum design of a distribution network is highly sensitive to the level of vehicle utilization. Due to the increasing global climate change, the paper makes a case for considering environmental and economical objectives simultaneously.

To analyse the relationship between total logistics costs and their environmental impact from transportation and depots we considered two different scenarios for strategic modelling: a centre of gravity locations scenario and a scenario using the original published locations with optimum network design consisting of two depots. The cost-based optimization for the centre of gravity scenario identifies the optimum number at three depots based on total logistics costs and CO_2 emissions. In the original locations scenario, the optimum design of cost-based optimization equated to two depots for total logistics costs and two/three depots for CO_2 emissions. The latter proved to be sensitive to the vehicle utilization ratios, even though there is a very small difference in transportation costs and vehicle kilometers between three and two depots. The methodology for calculating CO_2 emissions takes into consideration speed of the vehicle, vehicle type and vehicle utilization. The study based on original location also indicates that increasing vehicle utilization by 15% could bring economic savings in total logistics costs (7.5%) as well as environmental benefits reflected in reduction of total vehicle kilometers traveled (16.1%) and reductions of transport related CO_2 emissions of around 10%. Therefore, due to the increasing environmental concerns, it’s important to incorporate environmental objectives as part of logistics design and correctly estimate vehicle utilization ratio factors for emissions calculations, to allow the decision-maker to make an informed and objective decision regarding network design.

The current study has several limitations. Firstly, only one case study has been analysed, which makes results dependent on the data used for evaluating CO_2 emissions. Secondly, the assumptions regarding transportation data also limits the study because in the supply chain a wider variety of vehicles are used to transport commodities. Also, the lack of specific fuel consumption figures for transportation makes the study dependent on information available in the public domain.

In our current research we are investigating the building of a multi-objective optimization decision support tool for strategic modelling, where traditional objectives, such as cost and improving service level and environmental impact are considered simultaneously (Harris *et al.*, 2009). The approach allows the decision maker to evaluate a set of viable alternatives, in contrast to traditional methods where environmental impact is calculated as a constraint or requires the user to prioritize objectives. The approach could potentially find excellent solutions which could be missed by other methods, but generating a large number of solutions could be considered as a disadvantage. Therefore it is important to involve the decision-maker in the evaluation of the solutions according to the potential criteria needed.

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Methodology	Reference
Carbon dioxide emissions per tonne-kilometre (The Network for Transport and Environment (Sweden))	Kohn (2005)
Life cycle assessment model (Eco-Indicator 99® method (Pré Consultants, 2000))	Hugo and Pistikopoulos (2005)
Life Cycle Analysis (LCA)	Quariguasi Frota Neto *et al.* (2008)

Customer (original data)	Name, location Annual demand by product group Number of deliveries per year Transportation mode
Supplier (original data)	Name, location Annual supply by product group Number of deliveries per year Transportation mode
Transport	Vehicle information: physical and distance constraints: Transportation costs functions
Warehouse locations (original data)	Location Throughput, total area (square meters)

Weight laden(%)	Fuel consumption (litres/km) 40 tonne lorry	Fuel consumption (litres/km) 5 tonne lorry
90 %	0.369	0.263
75 %	0.353	0.245
60 %	0.336	0.228

Road type	Road traffic (HGV)	Average speed limit	% difference in fuel consumption compare to driving at 54 mph
Motorway	42 %	54 mph	
Rural “A” roads	35 %	45 mph	- 5.53 %
Urban “A” roads	10 %	36 mph	- 5.55 %
Minor roads	13 %	30 mph	- 2.91 %

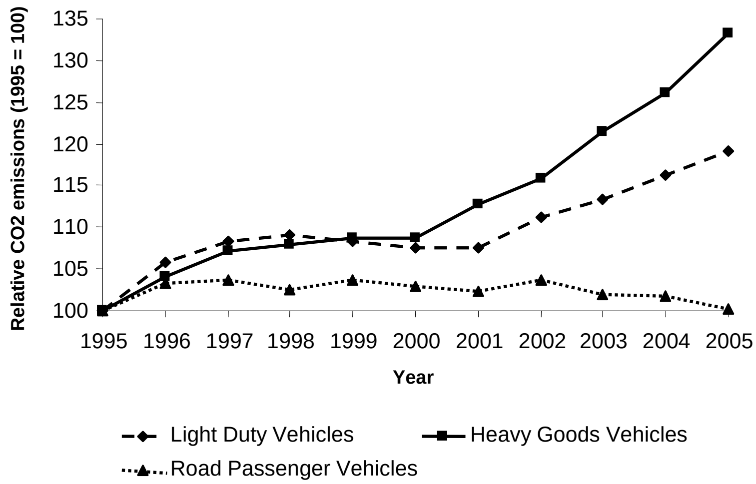
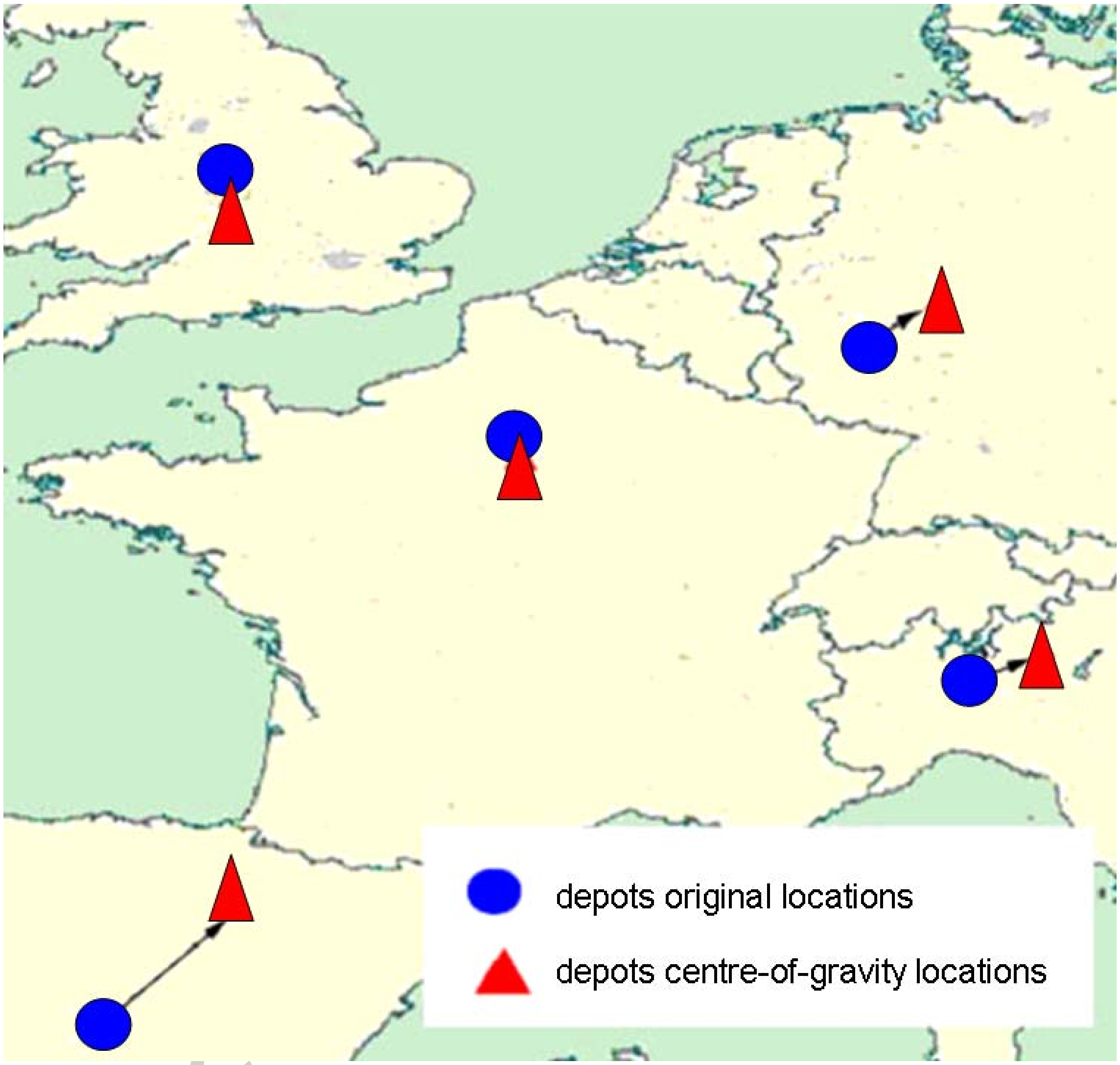
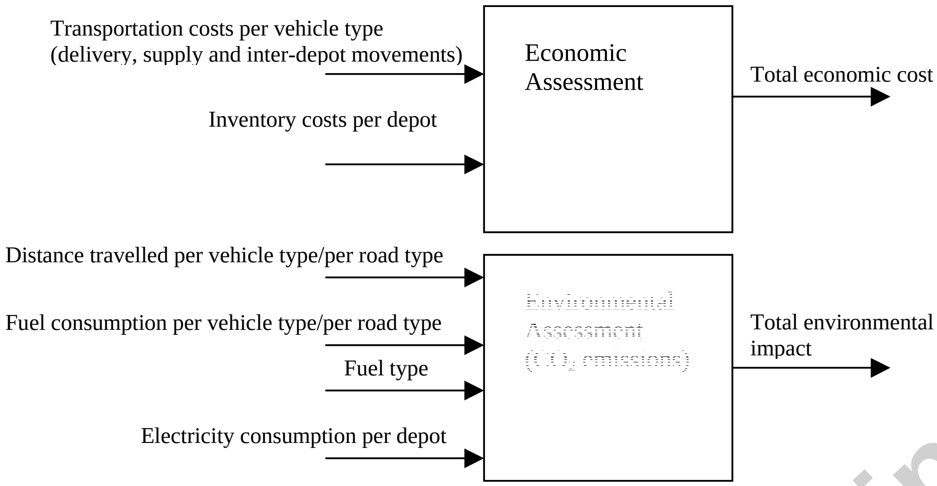


Figure 1. UK Carbon dioxide emissions for road transport (DfT, 2007b).

Fig 2


depots original locations
depots centre-of-gravity locations


Transportation costs per vehicle type
(delivery, supply and inter-depot movements)
Inventory costs per depot
Economic
Assessment
Total economic cost
Distance travelled per vehicle type/per road type
Fuel consumption per vehicle type/per road type
Fuel type
Electricity consumption per depot
Environmental
Assessment
(CO_2 emissions)
Total environmental
impact

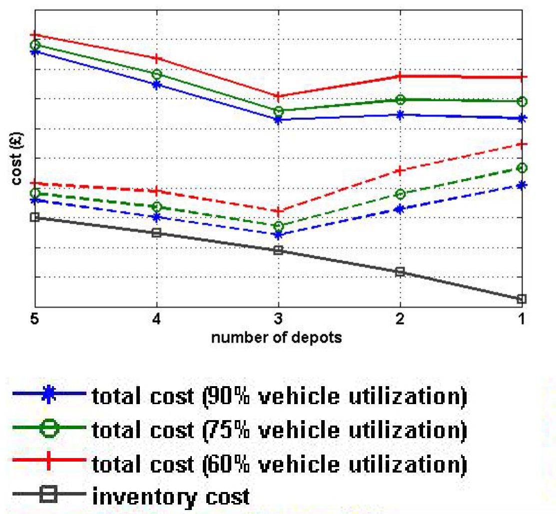


Figure 4a. Logistics costs related to number of depots and vehicle utilization parameters for centre o - gravity locations

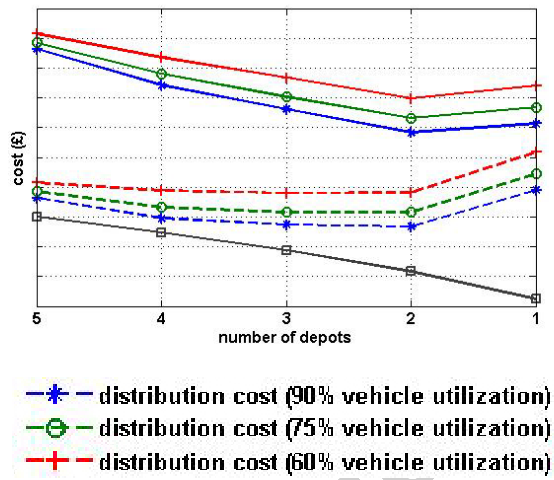


Figure 4b. Logistics costs related to number of depots and vehicle utilization parameters for original locations.

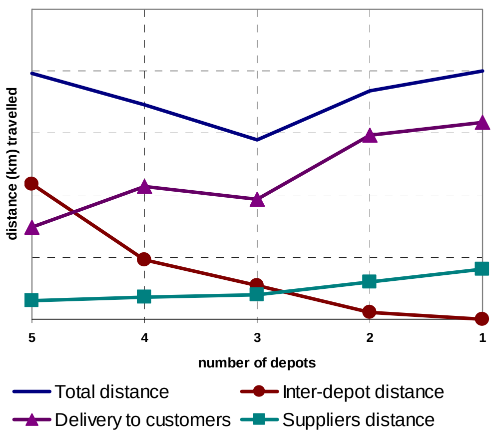


Figure 5a. Transportation distance breakdown related to number of depots and 90% vehicle utilization for centre of gravity locations.

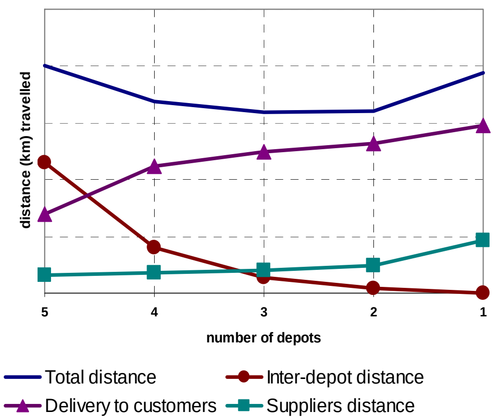


Figure 5b. Transportation distance breakdown related to number of depots and 90% vehicle utilization for original locations.

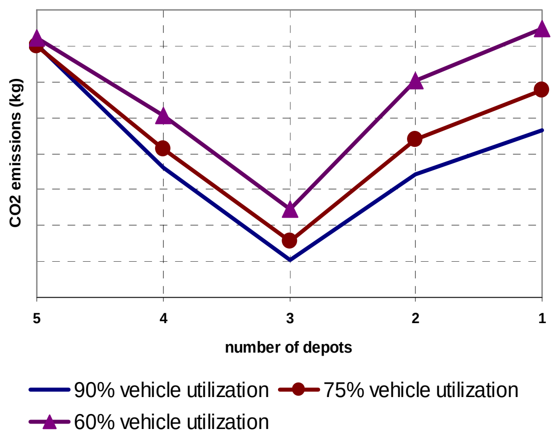


Figure 6a. Total CO_2 emissions from transport and electricity related to number of depots and vehicle utilization parameters for centre of gravity scenario.

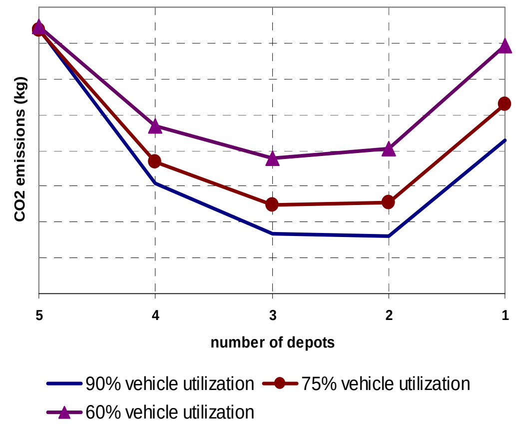


Figure 6b. Total CO_2 emissions from transport and electricity related to number of depots and vehicle utilization parameters for original scenario.