A REVIEW OF INFRASTRUCTURE MODELLING FOR GREEN LOGISTICS

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Abstract

Infrastructure modelling is a strategic level activity to make one or more decisions on the optimum location, number and allocation of service providers. This problem has been intensively researched in academic literature and traditionally focuses on minimizing total logistics costs or maximizing profit. But in many cases the optimum may involve dealing with multiple and sometimes conflicting objectives. Recently, climate change and environmental concerns in logistics network design have been increasingly discussed, and such 'green issues' are the main concern of the present paper. Our aim is to critically examine current techniques for infrastructure modelling and/or performance evaluation on Green Logistics.

A comprehensive literature review provides an overview of supply chain modelling and their objectives. In particularly we are interested in techniques that consider both economic (gold) and environmental (green) criteria simultaneously. This paper argues that there is a need to incorporate environmental aspects into the logistics design so as to obtain a balanced sustainable assessment of supply chain infrastructure performance.

Keywords: Sustainable logistics, Strategic decision making, Optimization

Introduction

Over the last few decades the focus of environmental impact has changed from the local to a global level. There is a general consensus that rising temperature is contributing to disappearing glaciers and increasingly unstable weather patterns around the globe. It is well known that greenhouse gasses, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) raise the temperature near the surface of our planet. The greenhouse gasses from transport and energy need to be addressed. Some companies are already trying to help the environment through the use of rail and depot consolidation (Chistensen 2002). Under the Kyoto Protocol, the UK is now legally required to reduce greenhouse gas emissions by about 12.5 % by 2012.

This paper covers two areas: infrastructure modelling and Green Logistics. Infrastructure modelling determines the optimum number, location and allocation of the facilities; whereas Green Logistics implies "an environmentally friendly and efficient transport distribution system" (Rodrigue et al. 2001). The objective of the paper is to critically examine current techniques for infrastructure modelling as applied to 'real-world' supply chains. In particularly we are interested in the models that consider both economic (gold) and environmental (green) criteria simultaneously as their objectives.

Traditionally, changes in logistics infrastructure have been driven by a need to reduce total costs and improve customer service levels. Until recently environmental benefits have not been a major concern. Nevertheless, a reduced environmental impact frequently results as a by-product of a more efficient distribution system (Aronsson and Brodin, 2006). In the last ten years several major companies have restructured their storage and distribution systems with a view to reducing their costs, and have subsequently reduced their CO_2 emissions as a result of those changes. For example Le Blanc et al. (2006) analyze the benefits of Factory Gate Pricing (FGP) for Dutch retail industry and the reductions in costs have brought significant environmental benefits (reduced congestion and number of kilometres) in addition to the planned economic savings. But not all infrastructure changes lead to a positive impact on the environment. Kohn (2005) analyzes the effects of changing from a decentralised to a centralized network and reveal that lowering costs and improving service performance produce a negative impact on the environment. The analysis of direct effects indicates considerable increase in both tonne-kilometres and CO_2 emissions. Hence, the structural changes reveal the opportunity to make environmental improvements in its logistics operations. Thus, although it is clear that environmental benefits are frequently a welcome result of an infrastructure redesign process aimed at reducing costs, this is not always the case. For this reason, there is a need to address environmental objectives explicitly as part of the logistics design process.

A comprehensive literature review provides an overview of optimization supply chain modelling and their respective objective functions, our main focus being multi-objective design for Green Logistics. Our techniques include a key word search, on ‘supply chain’, ‘network’, ‘design’, ‘performance measure’, ‘environment’ and ‘green’, using a number of journal databases such as Scopus, ABI/INFORM and Business Source Premier. Google search is also used to identify commercial software for environmentally friendly network design.

OR and Green Logistics

Operations Research (OR) uses mathematical methods for analysis, optimization and decision making in real-world problems. A problem is formulated as a set of mathematical expressions with objective function(s) and constraints. The objective function, such as cost minimization, measures a system’s performance whereas the constraints enforce realistic conditions, such as service level, to generate feasible solutions. Today the need for ‘desirable’ environmentally friendly networks is becoming ever more urgent. Bloemhof-Ruwaard et al. (1995) address the need for an integrated assessment model to consider all aspects of the system, to identify the causes, measure the emissions, and assess the efficiency of transportation systems from a global perspective. They claim that the added value of OR consists of evaluation (efficiency) and improvement (effectiveness) of emission and waste reduction scenarios. It is also important to model environmental issues as objectives and not as constraints because it can generate more information regarding cost and implications of environmental impact (Current et al. 1990).

Performance measures

An important part of infrastructure modelling is the establishment of appropriate qualitative and quantitative performance measures (objectives) to quantify the efficiency and effectiveness of the logistics network (Beamon, 1999). Shepherd and Gunter (2006) present the latest taxonomy of performance measures in general and classify them as quantitative or qualitative; by what they measure (cost and non cost); by their strategic, operational or tactical focus and the process they are related to in the supply chain. Current et al. (1990) classify the objectives specifically for facility locations into four categories: cost minimization, demand oriented, profit maximization and environmental concerns. Environmental objectives such as air quality, risk to surrounding population, quality of life and low-flow stream augmentation are included in their literature review.

(Bloemhof-Ruwaard et al. 1995) address the increasing need to incorporate quantitative environmental measures into the OR modelling. Beamon (1999) outlines a range of sustainable performance measures, such as emissions, total energy consumed and others for green supply chains. Taplin et al. (2006) propose a list of indicators for a sustainable metal production system for the simulation of production, transportation and recycling activities. More efficient use of energy and raw materials, reducing CO_2 emissions, scrap and waste and higher productivity made sustainable development practical and measurable.

Potter et al. (2002) propose a list of potential performance indicators for sustainable distribution which they refine using a quasi-delphi study. Emissions per item, amount of payload used (measure of vehicle utilization) and energy use per item are the top three ranked performance indicators. Khoo et al. (2001) use the balance of low total market costs and low transport pollution, fast deliveries between plants, promotion of recycling of scrap metal and conservation of energy in modelling of a supply chain concerned with the distribution of raw aluminum metal. Aronsson and Brodin (2006) also discuss in their comprehensive literature review that a commonly suggested performance measure of the logistics systems’ environmental performance is emissions.

Infrastructure modelling

Infrastructure modelling is not new to academia and has a very rich literature. It is a strategic decision process which influences tactical and operational level decisions for the long term efficient operation of a network. It determines the optimum number, capacity, location and allocation of facilities (such as warehouses, distribution centers and consolidation centers) to ensure efficient commodity flows from service providers to the market. Infrastructure modelling techniques can be used with single or multiple objectives for simple single or multiple product networks. A large range of techniques have been applied to infrastructure modelling, from linear, integer, dynamic, mixed-inter linear programming to heuristic methods and genetic algorithms. Coyle et al. (2003) describe the principle modelling approaches such as mathematical optimization, simulation and heuristic models. Mathematical optimization aims to find optimum solutions based on precise mathematical procedures. Heuristic approaches, on the other hand, do not guarantee optimal solutions but can produce an acceptable solution in a reasonable amount of time. Simulation allows a user to test the effect of alternative locations on costs and service levels.

Infrastructure modelling for Green logistics

The location analysis for facilities such us nuclear reactors and chemical plants that produce hazardous materials has been studied since the 1970's, when the environmental impact of airborne pollutants first became an issue. Today the need for 'desirable' environmentally friendly networks is becoming ever more urgent. Aronsson and Brodin (2006) discuss that there is an agreement among researches that strategic decisions should have a larger impact on emissions than operative decisions. However they point out that there is a disagreement on which particular decisions have the largest impact, and what effect of those decisions will have on environmental impact. From our research we identify only a small number of papers which explicitly relate to multi-objective infrastructure modelling for Green Logistics with some of these specifically addressing hazardous network structures.

Khoo et al. (2001) use a simulation approach to select plant locations that balances low total market costs and low transport pollution, fast deliveries between plants, promotion of recycling of scrap metal and conservation of energy in a supply chain concerned with the distribution of raw aluminum metal. They use ProcessModel 2000® to demonstrate the consequences of ignoring resource preservation and recycling activities as part of the network design.

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 method for impact assessment, the Eco-Indicator 99 method (Pré Consultants 2000), is incorporated within the quantitative life cycle assessment model to formulate an appropriate environmental performance objective to guide strategic decision- making. The Eco-Indicator 99 method attempts to model potential environmental damages on a European scale according to three categories: human health, ecosystem quality and resource depletion.

Le Blanc et al. (2006) describe the methodology for solving the FGP optimization problem for Dutch retail industry. They follow a two-phased heuristic approach consisting of interrelation of seven scenarios. The optimization of delivery frequency is based on single objective, supply chain costs. The reductions in costs have brought significant environmental benefits, such as reduced congestion and number of kilometres.

Aronsson and Brodin (2006) describe how companies contribute to the environmental improvements as a direct aim, or as a by-product, of their logistics infrastructure. Three case studies, where companies' had undergone different but similar changes in their distribution structures had a positive effect and not just on the environment (reduced emissions) but also cost reductions. Typical changes involve new distribution structures with fewer nodes, larger warehouses, or a switch in transport mode.

An example of an available commercial application, CAST (Radical 2007), which is widely used for supply chain network design has a carbon emissions optional module, 'CAST-FE'. In this application the network modelling is performed first and then the carbon footprint as CO_2 emissions is calculated from transport operations and storage facilities. To reduce carbon emissions and take into account the impact on overall costs and service level, the user must perform different simulations with alternatives supply chain strategies.

<u>Applications of supply chain infrastructure techniques</u>

Traditionally, infrastructure modelling mainly focuses on a single objective function such as cost minimization or profit maximization with all customer demands satisfied to a certain minimum level and without exceeding the capacities of the facilities. With environmental concerns and customer service levels considered to be more critical for infrastructure design there is a need to deal with multiple and sometimes conflicting objectives. When multiple objectives are involved then, conventionally, companies will try to adjust the various parameters under their control in order to simultaneously maximize profit (or minimize costs) and optimize customer service, for example. But, the two objectives are frequently in conflict and devising a single performance measure that weights the two objectives in a satisfactory way is a challenge. An added complication arises when we wish to incorporate appropriate quantifying environmental measures into the model. There are three principle methods of dealing with multiple objectives which have a wide variety of algorithms:

1. Combine all the objectives into a single scalar value, typically as a weighted sum, and optimize the scalar value.
2. Solve for the objectives in a hierarchical fashion, optimizing for a first objective then, if there is more than one solution, optimize these solutions for a second objective, and repeat for a third and so on as appropriate.
3. Obtain a set of alternative, non-dominated solutions, each of which must be considered equivalent in the absence of further information regarding the relative importance of each of the objectives.

Methods 1 and 2 both depend on making a priori assessments to weigh up the relative importance of the various objectives. Method 3 on the other hand, involves no such, perhaps arbitrary judgments, and produces a set of viable alternatives, called a Pareto set, from which a decision maker can make an informed selection at a later stage. This approach has the advantage that excellent solutions can be found that may be missed by the other methods. The potential disadvantage of the Method 3, however, is that it may generate a very large number of potential solutions.

Model description	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Traditional objectives									
Minimizing costs	*	*	*	*			*	*	*
Maximizing service level		*	*			*	*	*	*
Maximizing the net present value					*	*			
Minimizing investment in opening facilities							*		
Minimizing capacity utilization ratio									*
Minimizing financial risk						*			
Fast deliveries between plants				*					
Quality of living	*								
Traffic access	*								
Market opportunity	*								
Local incentives	*								
Site characteristics	*								
Flexibility (volume and delivery)		*							
Green objectives									
Minimizing transport pollution (CO, NO_x, VOCs, PM)				*					
Promotion of recycling				*					
Conservation of energy				*					
Minimizing impact on environment from entire supply chain (including transportation emissions)					*				
Techniques									
Method 1 and 2	*	*	*	*			*		
Method 3 (Pareto-based)					*	*		*	*

References: [1] (Min and Melachrinoudis 1999),[2] (Sabri and Beamon 2000), [3] (Nozick and Turnquist 2001),[4] (Khoo et al. 2001), [5] (Hugo and Pistikopoulos 2005), [6] (Guillen et al. 2005), [7] (Selim and Ozkarahan 2006), [8] (Villegas et al. 2006), [9] (Altiparmak et al. 2006)

Table 1. Multi-objective infrastructure modelling with techniques as applied to specific scenarios

Table 1 represents an overview of infrastructure modelling in terms of multiple objectives and techniques. As can be seen from the Table 1, we do not differentiate between Method 1 and 2 because they depend on making a priori assessments. For example, the analytic hierarchy process (AHP) has been used to assign different weightings to quantitative and qualitative measures for strategic modelling. Min and Melachrinoudis (1999) use the AHP method to evaluate multiple objectives: minimization of relocating cost, quality of living, traffic accessibility, maximization of market opportunities, local incentives and site characteristics to relocate manufacturing/distribution facility.

Classic multi-objective optimization methods such as the ε-constraint have been used to transform a multi-objective problem into a single objective one, producing just one solution per simulation run. For example, Sabri and Beamon (2000) develop an integrated multi-objective model involving strategic and operational planning under production, delivery and demand uncertainty. The ε-constraint method is used to minimize cost, while ensuring a sufficient amount of volume flexibility and service level (fill rates).

Recently, Method 3, which is based on Pareto-optimal solutions, has been considered by a small number of researchers for infrastructure modelling. This method allows the decision makers to investigate trade-offs and select a particular network design that best satisfies their compromise. For example, Altiparmak et al. (2006) use a genetic algorithm to design a supply chain for the product with three objectives: minimizing total costs, maximizing customer services and the maximization of capacity utilization balance for the producer of plastic products in Turkey.

Villegas et al. (2006) present the bi-objective (minimizing overall cost and maximizing coverage) incapacitated facility location problem to redesign a Colombian coffee network. They design an algorithm based on the Nondominated Sorting Genetic Algorithm, an algorithm based on the Pareto Archive Evolution Strategy and an algorithm based on mathematical programming with one of the objectives treated as a constraint and compare them for the quality of the approximation to the Pareto frontier.

Earlier discussed the ε -constraint method can generate Pareto based solutions when its run several times with different allowable levels. For example, Guillen et al. (2005) use the ε -constraint method with a branch and bound technique to solve a multi-objective stochastic mixed integer linear programming model to determine optimal supply chain configuration. The multiple objectives are the maximization of the NPV and the demand satisfaction, and the minimization of the financial risk. Hugo and Pistikopoulos (2005) use a multi-objective optimization framework with the ε-constraint method for environmentally friendly network design with two objectives: maximising the NPV and minimizing impact that the network has on the environment.

Conclusion

The main conclusion of our research is that if environmental assessment is incorporated as part of infrastructure modelling then there is a possibility of achieving both economic and environmental savings. Every logistics design should include industry specific environmental assessment to prevent pollution and save the environment. Some tools and techniques are already available to researchers to help achieve this goal, but there is still much work to be done.

From the literature review we identify the need to create environmentally friendly logistics systems where strategic decisions and the transport distribution system are considered together as part of design. In our literature review we found only two applications of multi-objective infrastructure modelling in a Green logistics context (Hugo and Pistikopoulos 2005, Khoo et al. 2001). Khoo et al. (2001) use simulation software for modelling whereas (Hugo and Pistikopoulos 2005) use the classic multi-objective optimization method. We also discussed in this paper an optimization methodology where a two-phased heuristic approach with scenarios is used to analyze FGP (Le Blanc et al. 2006). The single objective function based on supply chain costs is used to optimize the delivery frequency in the scenarios. Thus highlighting a fruitful area for our future research where environmental and economic concerns need to be modelled as explicit objective to generate more information about cost and implications of ecological impact.

Classic optimization methods, such as the ε -constraint method, which transform a multi-objective problem into a single objective and find only one Pareto based solution in one simulation are not sufficient for evaluating trade-offs. Another disadvantage of these methods is that not all Pareto-optimal solutions can be found in this way. In our literature review we found that only Hugo and

Pistikopoulos (2005) use multi-objective techniques in a Green Logistics context. Other multi-objective optimization techniques, such as evolutionary algorithms, are available to generate Pareto optimal solutions which allow the decision makers to investigate trade-offs between economic and environmental objectives. In practice, there is a wide range of algorithms that come under the Pareto-based category. Therefore there is a need to investigate these techniques for efficient infrastructure modelling for Green Logistics.

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