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A solution method for a two-layer sustainable supply chain distribution model

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ABSTRACT

This article presents an effective solution method for a two-layer, NP-hard sustainable supply chain distribution model. A DoE-guided MOGA-II optimiser based solution method is proposed for locating a set of non-dominated solutions distributed along the Pareto frontier. The solution method allows decision-makers to prioritise the realistic solutions, while focusing on alternate transportation scenarios. The solution method has been implemented for the case of an Irish dairy processing industry's two-layer supply chain network. The DoE generates 6100 real feasible solutions after 100 generations of the MOGA-II optimiser which are then refined using statistical experimentation. As the decision-maker is presented with a choice of several distribution routes on the demand side of the two-layer network, TOPSIS is applied to rank the set of non-dominated solutions thus facilitating the selection of the best sustainable distribution route. The solution method characterises the Pareto solutions from disparate scenarios through numerical and statistical experimentations. A set of realistic routes from plants to consumers is derived and mapped which minimises total CO_2 emissions and costs where it can be seen that the solution method outperforms existing solution methods.

1. Introduction

Increased consciousness amongst consumers, firms and governmental organisations towards the escalated deterioration of the environment caused by human actions has significantly increased the momentum in sustainable supply chain management. In reality, in a supply chain (SC) firms are now not only held responsible for themselves but also for the environmental and social performance of their suppliers [73]. In today's competitive environment it is essential that the logistical elements of sustainable-SC networks must operate on a combined platform of reduced carbon emissions and low operating costs. The operation of low-carbon SCs is one of today's most strategic challenges. When designing and developing modern SCs, transportation decisions are of major concern as they have substantial implications on the environmental performance of the SC and additionally the cost of product distribution significantly contributes towards the total SC cost. For this reason, one of the key success parameters presented for improved enterprise performance for local product sales markets is the efficacy of product distribution decisions [47], making low-carbon distribution system design a strategic priority for many businesses.

Carbon dioxide (CO_2) is one of the six greenhouse gases included in the Kyoto protocol. According to the United Nations Framework Convention on Climate Change [79], CO_2 is considered as the principal greenhouse gas in the "*carbon market*". Often the quantity of emitted greenhouse gases is expressed as CO_2 equivalent (CO_2e) in the carbon footprint. The "*total amount of CO_2e emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product*" is described as the carbon footprint [87]. More precisely, CO_2e gases emitted across a SC for a single unit of a product is referred to as its carbon footprint [67]. Therefore, to enhance the efficiency of green-SC networks it is recommended that the total amount of CO_2e should be evaluated in order to identify mechanisms by which the SC carbon footprint can be reduced. In this article the term "low-carbon" is delineated as a descriptor for the performance associated with a "carbon footprint". A number of recent studies in this domain have reported on the integration of low carbon emission issues with operational decision-making for procurement, production and inventory management [7] and on the relevance of carbon footprint taxation schemes, and such studies can have effect on the optimal choice in sourcing decisions [13–15].

There are a number of recommended low-carbon/green-SC principles in businesses, such as the in-depth discernment of the

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impact of the carbon footprint with manufacturing locations and raw material sources, alternative sourcing options, operating speed of SCs, reduction of the use of packaging, increases in proportional reverse logistics [25,4]) and the re-design of distribution channels. In a SC network, logistics service providers are required to contribute by increasing SC efficiency while simultaneously reducing associated costs and carbon emissions. Transportation in logistic activities is one of the most significant sources of air pollution and greenhouse gas emissions within a SC [85]. These activities leave harmful effects on human health and the environment [71]. Therefore, transportation activities of products from plants to retailers via roadways warrant more thorough investigation. Minimisation of the traversed distance [33] and maximisation of vehicle utilisation during transportation are potential solutions for emissions reduction. Considering the principles of low-carbon SCs and the effect of transportation activities on society, this article supports the need for a sustainable capacitated distribution model to manage both the carbon footprint and cost on the demand side of a SC.

Several approaches have been considered to date to tackle distribution system problems on the demand-side of SCs. Two-layer distribution system models are well known to be computationally NP-hard. There is no unique solution to these types of models but a feasible solution space. A variety of heuristics/meta-heuristics used to solve such models can be found in the literature in the form of one or multi-phase algorithms. In this article a novel Design of Experiment (DoE)-guided solution method is implemented on a two-layer sustainable distribution system. The DoE guides a Multi-Objective Genetic Algorithm of kind II (MOGA-II) optimiser towards the selection of the best optimal realistic solution sets from a large number of available optimal feasible solutions. The decision-makers' prioritisation is encapsulated in the analysis and subsequent ranking of the realistic solutions using TOPSIS [3]. The implementation of this efficient solution method as presented in this paper is focused on the case of an Irish dairy manufacturing SC.

This remainder of the article is organised as follows. A comprehensive literature review on distribution system methods and their solution approaches is provided in Section 2. The next section elucidates the holistic solution method for the sustainable distribution system optimisation. In this section the DoE-guided MOGA-II solution method is described and its implementation in an Irish dairy manufacturer's SC discussed. Section 4 delineates the results obtained from the DoE-guided solution method, which are then analysed in Section 5. This section illustrates the final results and discusses the characteristics and efficacy of the solution method. Finally, Section 6 concludes the research indicating the scopes for future research.

2. Literature survey

Distribution decisions consider a number of constraints in order to satisfy the demands of retailers while simultaneously minimising total costs. The total costs include routing costs, fixed costs of the vehicle, fixed costs and operating costs of the facility [39]. Distribution systems are modelled as NP-hard combinatorial optimisation problems [54,49,90]. The nature of NP-hard problems is such that the computational effort required for solution attainment grows exponentially with increasing problem size [21]. Therefore, there is a need for an effective and robust solution method for distribution system models. A detailed survey of different distribution systems can be found in [42].

Table 1
Solution approaches to distribution system models.

Publications	Solution approaches
[50]	Hybrid particle swarm optimisation; multiple phase neighbourhood search – greedy randomized adaptive search procedure
[89]	Sequential and iterative procedure using particle swarm optimisation
[46]	Multi-objective particle swarm optimisation combined with grey relational analysis and entropy weight
[26]	Tabu search heuristic with a generalised insertion procedure
[78]	Two-phase Tabu search algorithm coded in C
[12]	Set partitioning approach and tabu search algorithm
[52]	p-Median approach to find an initial feasible solution and a meta-heuristic integrating variable neighbourhood search and Tabu search to improve the solution
[2]	Tabu search metaheuristic solution with CPLEX 6.5 solver
[44]	A combined Tabu search and simulated annealing metaheuristics
[9]	Multi-objective combinatorial optimisation based on tabu search
[68]	Reactive Tabu search method based metaheuristics approach
[72]	A neural network approach based on a self-organising map
[45]	Metaheuristics approach based on threshold accepting and simulated annealing
[88]	Simulated annealing
[90]	Simulated annealing
[75]	Simulated annealing
[64]	Greedy randomised adaptive search procedure
[20]	Greedy randomised adaptive search procedure
[56]	Greedy randomised adaptive search procedure
[28]	Variable neighbourhood search algorithm
[19]	Variable neighbourhood search algorithm
[6]	Ant colony optimisation
[8]	Ant colony optimisation
[77]	Ant colony optimisation
[35]	Genetic algorithm
[65]	Genetic algorithm
[92]	Genetic algorithm
[49]	Genetic algorithm
[50]	Genetic algorithm
[38]	Genetic algorithm
[40]	Genetic algorithm
[51]	Honey bees mating optimisation
[5]	Bacterial metaheuristics