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A multi-objective meta-heuristic approach for the design and planning of green supply chains - *MBSA*

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ABSTRACT

Supply Chains are complex networks that demand for decision supporting tools that can help the involved decision making process. Following this need the present paper studies the supply chain design and planning problem and proposes an optimization model to support the associated decisions. The proposed model is a Mixed Integer Linear Multi-objective Programming model, which is solved through a Simulated Annealing based multi-objective meta-heuristics algorithm – MBSA. The proposed algorithm defines the location and capacities of the supply chain entities (factories, warehouses and distribution centers) chooses the technologies to be installed in each production facility and defines the inventory profiles and material flows during the planning time horizon. Profit maximization and environmental impacts minimization are considered. The algorithm, MBSA, explores the feasible solution space using a new Local Search strategy with a Multi-Start mechanism. The performance of the proposed methodology is compared with an exact approach supported by a Pareto Frontier and as main conclusions it can be stated that the proposed algorithm proves to be very efficient when solving this type of complex problems. Several Key Performance Indicators are developed to validate the algorithm robustiveness and, in addition, the proposed approach is validated through the solution of several instances.

1. Introduction

Traditionally the design and planning of supply chain networks (SCN) has been undertaken based on individual concepts and applying only economic objectives, such as cost minimization or profit maximization. However, the increasing market competition, the customers' change expectations, on the value of goods and services, combined with advances in technology and fast access to information demanded for an integrated view when managing supply-chain (SC) networks (Papageorgiou, 2009). In addition, the worldwide extension of business led to the availability of sets of alternative resources, as well as to a vast array of potential customers, justifying the current need of efficient SC management. Simultaneously, society has been developing an increasing level of awareness for environmental sustainability and companies have been realizing that economic objectives ought no longer to be the single concern of supply chains as environmental impacts resulting not only from their structures, but also from their operation need to be minimized (Seuring, 2013; Mota, Gomes, Carvalho, & Barbosa-Povoa, 2015). Dekker, Bloemhof, and Mallidis (2012) state that "Improving environmental quality comes at a cost, so the question is which trade-offs occur between the environmental impacts of an economic activity and its costs, and what are the best solutions for balancing ecological and economic concerns?". This raises the concept of building eco-efficient solutions. Thus it becomes necessary to define an efficient integration of these SC main aspects when planning and designing SC so as to minimize environmental impacts while maximizing profit and responsiveness.

Some research has already been done towards this identified goal, where the most used methodologies have been based on exact approaches, as MILP and MINLP (Papageorgiou, 2009), but focusing in single objectives. The inclusion of several objectives requires a multi-objective approach, which adds to the already high computational burden characterizing SC problems resolution (Papageorgiou, 2009; Barbosa-Póvoa, 2014). Thus new solutions approaches are to be explored to overcome this drawback. Some of them may be problem oriented, such as heuristics, evolutionary algorithms, meta-heuristics, hybrid methods or even math-heuristics.

This paper follows this need and aims to contribute to fulfill this gap by proposing a *multi-objective, multi-start, meta-heuristics algorithm*, MBSA, for the design and planning of supply chains (SC) where

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both economic and environmental objectives are taken into account. At the strategic level the algorithm provides the location and capacities of facilities, warehouse and distributions centers and selects the best multipurpose technology to be allocated to each facility. To cope with realistic problems multiproduct characteristics are considered, triggering flexible and multipurpose facilities. At the tactical level, the algorithm, defines the production planning, material flows, inventory profiles and distribution strategies allowing for X-docking. Moreover, the environmental aspects are integrated at the design level by using an end-point indicator, where all the emissions associated to products productions and distribution are quantified. The multi-objective approach where profit maximization and environmental impacts minimization are considered simultaneously uses small amounts of computation time. This appears as quite innovative having in mind the complexity of the problem in study. Such performance is based on the use of an efficient multi-start local search algorithm that trough a Simulating Annealing meta-heuristic is able to search the entire objective space. The quality, robustness and variability of the algorithm solution are analyzed through a sensitive analysis followed by a comparison with the exact approach.

As main result the proposed approach presents to the decision-maker a set of non-dominated solutions that define the Pareto frontier, where for each solution the strategic and tactical aspects are characterized.

This remain of this paper is organized as follows; in Section 2 a literature review is presented, followed by the problem description in Section 3. Section 4 characterizes in detail the solution approaches developed and in Section 5 Key Performance Indicators (KPI) are proposed and explored in detail. The instance characterization is shown in the Section 6, followed by algorithm results analysis and discussion in Section 7. To finalize Section 8 presents the conclusion and some final remarks on future work.

2. Literature review

Supply Chain optimization is nowadays an important and thriving research area of modern enterprises as their supply chains are becoming more and more complex systems demanding for supporting tools to inform the involved decision making processes (Grossmann, 2012). From strategic to operational decision levels this need has been clearly identified by academics and industrials (Papageorgiou, 2009). The most common developed approaches to tackle this problems are based on exact formulations (e.g. Cardoso, Barbosa-Povoa, & Relvas, 2013; Pasandideh, Niaki, & Asadi 2015; Salema, I., Barbosa-Povoa, & Novais, 2010), which when applied to real case problems often present solution difficulties associated with large computational times. Thus the development of alternative solutions methodologies that prove efficient is still a challenge research area where much has still to be done (Melo, Nickel, & Saldanha-da-Gama, 2009; Barbosa-Póvoa 2014). Recently some authors have been trying to address this problem using methodologies that embed the problem characteristics resulting in heuristics algorithms.

In, Wang, Makond, and Liu (2011) addressed a location–allocation problem through a bi-level stochastic formulation of a two-echelon supply chain considering uncertainty in the demand. The authors developed a genetic algorithm with greedy heuristics and the results reveal that the algorithm can efficiently yield nearly optimal solutions against stochastic demands. Later on, Kadadevaramath, Chen, Shankar, and Rameshkumar (2012) explored several variations of particle swarm algorithms for solving a constrained multi echelon supply chain network considering the minimization of the total supply chain operating cost. One year later, Shankar, Basavarajappa, Chen, and Kadadevaramath (2013) developed a multi-objective hybrid particle swarm algorithm that considered simultaneously the costs minimization, defined by facilities location and shipment costs, and the maximization of the customer demands. The problem involves a single-product, four-echelon supply chain architecture. Zhang, Li, Qian, and Cai (2014) also explored the supply chain network design problem with the aim of defining the locations of the distribution centers and the assignment of customers and suppliers to the corresponding distribution centers. The formulation explored a Lagrangian relaxation based algorithm and the results were compared with the exact approach CPLEX showing that the proposed algorithm presented a stable performance and outperformed CPLEX for large-scale problems. Recently, Ren et al. (2015) developed a mixed-integer non-linear model with the aim of helping the decision-maker to select the most sustainable design and planning supply chain network. The SC structure considers multiple feed stocks, transport modes, regions for production and distribution centers. A sustainable measure was explored, which was based on the energy sustainability index trough a life cycle perspective. Fung, Singh, and Zinder (2015) developed a procedure with the aims of infrastructure expansion minimization cost to face future demand variability in a mineral supply chain. A matheuristic formulation was designed based on the hybridization of mixed integer linear programming (MILP) and a simulated annealing approach taking advantages of different levels of data aggregation. The procedure demonstrated the ability to solve industrial problems of different sizes. Camacho-Vallejo, Munoz-Sanchez, and Luis Gonzalez-Velarde (2015) considered in its work the production planning and distribution of a supply chain with the aim of operation and transport costs minimization in a four echelon supply chain. A heuristic algorithm based on Scatter Search that considers the Stackelberg's equilibrium was developed for the problem solution. The algorithm developed shown better results than the existing best known results in the literature,

The above works show the increasing investment on alternative solution techniques to support the development of expert systems able to solve real supply chains problems. Such works presented promising solution approaches but are still away from providing solution techniques that account for multi-objective SC problems where simultaneously with the SC modeling complexity both economic and environmental objectives are considered. Within this context the main contributions of the present work are twofold. On one hand, from a formulation viewpoint the SC decision complexity is modeled where simultaneously the design and planning problems are considered allowing for the location and sizing of different entities and associated technologies, while pursuing trade-offs between economic and environmental objectives. On the other hand and from an algorithm solution viewpoint an efficient solution approach is developed, which, from the best of our knowledge, explores for the first time a multi-objective approach using a multi-start strategy, to characterize and define the Pareto frontier solution.

3. Problem description

The work by Pinto-Varela, Barbosa-Povoa, and Novais (2011) presented a generic formulation for the design and planning of SCs, while considering simultaneously economic and environmental aspects. The supply chain network is characterized by n-echelons, where first and second level suppliers, manufacturers, wholesalers, retailers and markets are present. It includes a set of manufacturing facilities that employ a set of resources technologies that are multipurpose in nature (i.e. more than one product can be produced sharing the available resources). From a strategic point view, the network comprises several entities, namely production facilities, warehouses (WH) and distribution centers (DC) selected from a set of potential locations where the former employ the selected so-called resource technologies (i.e. production lines, storage resources, connections, etc.). At a tactical level the supply chain defines the capacities, the planning of each resource usage, as well as the materials flows within the