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Multi-objective ant colony optimisation: A meta-heuristic approach to supply chain design

Luis A. Moncayo-Martínez [a], David Z. Zhang [a,b,*]

[a] Exeter Manufacturing and Enterprise Centre, School of Engineering, Computing and Mathematics, University of Exeter, Exeter EX4 4QF, United Kingdom
[b] State Key Laboratory on Mechanical Transmission, Chongqing University, Chongqing, PR China

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ABSTRACT

This paper proposes a new approach to determining the Supply Chain (SC) design for a family of products comprising complex hierarchies of subassemblies and components. For a supply chain, there may be multiple suppliers that could supply the same components as well as optional manufacturing plants that could assemble the subassemblies and the products. Each of these options is differentiated by a lead-time and cost. Given all the possible options, the supply chain design problem is to select the options that minimise the total supply chain cost while keeping the total lead-times within required delivery due dates. This work proposes an algorithm based on Pareto Ant Colony Optimisation as an effective meta-heuristic method for solving multi-objective supply chain design problems. An experimental example and a number of variations of the example are used to test the algorithm and the results reported using a number of comparative metrics. Parameters affecting the performance of the algorithm are investigated.

1. Introduction

Today's rapidly changing business environment requires corporations to continuously evaluate and configure their Supply Chains (SCs) to provide customers with high quality products/services at the lowest possible cost and within the shortest possible time (Zhang and Sharifi, 2007; Zhang, 2010). A supply chain is a network of optional resources through which materials (raw materials, work in progress, and finished products) flow along one direction while information (demand data, due date, delivery, and assembly cost and time) along both directions in order to satisfy demands for products from customers. The process of finding the best flow patterns (i.e., choices of resources) for a family of products is known as the optimisation of supply chain design (Goetschalckx et al., 2002).

The determination of a flow pattern for every product in a family requires the selection of a supplier (or suppliers) for every component used by the product mix, the selection of a manufacturing plant (or plants) for assembling every sub- or final assembly in the product mix, and the choice of transport options for delivering every product to customers. For a typical supply chain, there often exist many suppliers that could supply the same components, multiple optional manufacturing plants that could assemble each subassembly or product, and alternative transport options that could be used for every product–destination combination. These resource options are differentiated by the lead-time and cost associated with each option. Optimising supply chain design requires the selection of resource options across the supply chain to minimise the total cost for the supply chain while keeping total lead-times as short as possible (or within what customers are prepared to accept). This is a non-trivial task due to the complexity involved in optimising two different, often contradicting, objectives (cost and time) simultaneously. The involvements of multiple products of complex hierarchy, sharing common components and sub-assemblies, and the existence of a large number of resource options across a supply chain, add further complexity to the problem.

In the literature, there are basically two ways in which two or more objectives could be dealt with simultaneously. The first involves transforming the multi-objective problem into a single-objective problem that aggregates all the objectives through a procedure called weighted sum in which every objective is multiplied by a weighting factor and the objective function is calculated as the sum of the weighted objectives (Corner and Buchanan, 1995). This requires a-priori knowledge of the relative importance of different criteria (objectives) which is not always available. An alternative method is to accept several criteria (objectives) simultaneously and determine a non-dominated set. This set is a collection of alternative solutions that represent potential trade-offs among objectives. The advantage is to allow the decision-maker to choose between trade-offs based on situations.

This paper proposes a heuristic algorithm based on Pareto Ant Colony Optimisation for multi-objective supply chain design problem. With this algorithm, the supply chain design problem is formulated into an Ant Colony Optimisation problem, and a number of colonies of

* Corresponding author. Tel.: +441392 263641; fax: +441392 217965.
E-mail addresses: l.a.moncayo@ex.ac.uk (L.A. Moncayo-Martínez), d.z.zhang@ex.ac.uk (D.Z. Zhang).

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ants are used in a sequence to explore the solution space and search for successively better non-dominated set of supply chain designs. An experimental example and a number of variants are used to test the algorithm and illustrate the benefits of utilising multiple pheromone matrices and multiple ant colonies in multi-objective supply chain design problems. This paper is organised as follows. In Section 2, the literature related to the supply chain design problem is reviewed. In Section 3, the theory of Pareto Ant Colony Optimisation (P-ACO) is explained. Section 4 describes the problem representation and solution methodology for finding supply chain designs by P-ACO. In order to test the proposed method an experimental application is introduced and results of tests reported in Section 5. The paper is concluded in Section 6.

2. Literature

Many techniques and approaches have been used to solve problems related to supply chain design. These techniques include mathematical modelling, heuristics, and agent technology.

In mathematical modelling, the problem is represented by a Mixed-Integer Programming (MIP) model. Graves and Willems (2005) developed a MIP model where a supply chain is divided into stages each representing an activity or operation (the sourcing of a component, the assembly of a sub-assembly or final product, and the delivery of a product to customers) that could be performed by alternative resource options. Each resource option has a lead-time and cost associated with performing a corresponding operation, and the question considered is to determine which option is the optimum for performing each stage such that the cost of goods sold and inventory held are minimised. The network was considered as a spanning tree and the problem solved by dynamic programming. Cakravastia et al. (2002) proposed a two-part model for a three echelon supply chain. The first part is for optional suppliers to schedule the production to find the lead-time and cost for supplying a component to the manufacturer for a given order. The second part is for the manufacturer to select suppliers for the order using a MIP model. Guillén et al. (2005) formulated a supply chain design problem as a multi-objective stochastic MIP model in which uncertainty is represented with demand forecasting. This model is solved by branch and bound techniques. Objectives are to maximise profit over the time horizon, maximise demand satisfaction, and minimise financial risk. The advantage of mathematical approaches is that it is guaranteed that the optimum solution can be found. The disadvantage is that for NP-hard problems like this, with exponential complexity, the amount of computation will increase significantly when problem size increases, in this case, when a large number of stages and players are involved in a supply chain and when products are of a complex nature involving a large number of hierarchies and components.

Another technique used for such problems is the multi-agent technology. Swaminathan et al. (1998) suggested to structure a supply chain as a library of structural elements (production and transportation resources) and control elements (flow, inventory, demand, and supply) represented by agents that interact with each other to find the best configuration. Fox et al. (2000) proposed an agent building shell that permits agents to exchange messages, negotiate with other agents (peer-to-peer interaction), plan behaviour, and execute the planned activities. The agent building shell is a collection of reusable software components and interfaces that provide support for the development of application dependent agent services. Supply chain design was considered as an application. Zhang et al. (2006) proposed an agent-based architecture for supply chain design that has three layers, a static layer that models a supply chain structure as a multi-agent system where each agent represents an optional resource, a dynamic layer where agents bid and negotiate for taking part in an optimal set of supply chain resources for customer orders, and an evaluation layer that exists to evaluate the behaviour and stability of supply chain designs resulting from the dynamic layer. This work formed a key part of a broader concept of dynamically integrated manufacturing systems (Zhang et al., 2007; Anosike and Zhang, 2009; Goh and Zhang, 2003). Ahn et al. (2003) designed a flexible agent system for designing supply chains that can be adapted to changes, such as new product introduction or addition/removal of optional resources. The system consists of three procedures. The first is used to interpret new messages. The second permits exchanging of new conversation policies among agents. The third enables new policies to be used by new resources. Agent-based approaches are distributed problem solving methodologies. Compared to traditional centralised problem solving methodologies such as MIP, agent-based models are adaptive and can easily accommodate dynamic changes in a supply chain (e.g., the addition and removal of resources, capacity limit, and dynamic scheduling of resources) and its operational environment (e.g., changes of exchange rates and transport situation which affect lead-time and cost of resources). The problem is how to coordinate the behaviour of individual agents such that solutions emerging from agent interactions can be optimum or close to optimum. This has been a major challenge for research in recent years (Lim et al., 2009; Wang et al., 2002; Zhang and Zhang, 2007). Akanle and Zhang (2008), for example, proposed a Genetic Algorithm (GA) based coordination algorithm which is able to coordinate agents' interactions to optimise supply chain designs dynamically. The algorithm can also deal with situations where costs of resources performing a particular operation are functions of lead-times, in which case there are an infinite number of solutions to be evaluated for a supply chain design problem and it is impossible to solve the problem with mathematical approaches.

In recent years, alternative techniques have been used and one of the most widely employed is meta-heuristics. Although such techniques do not guarantee to find the optimum solutions, they provide a useful compromise between the amount of computation time necessary and the quality of the approximated solution space. Silva et al. (2005) modelled supply chain as a logistic process that includes order arrival, components request, components arrival, components assignment, and order delivery. The problem is to determine the sequence in which orders should be fulfilled. The resulting scheduling problem is solved using Genetic Algorithms (GA) and Ant Colony Optimisation (ACO). Altiparmak et al. (2006) proposed a procedure, based on GA, for designing a four-echelon supply chain (suppliers, plants, warehouses, and customers). It has three objectives to be minimised. The first is the cost that includes the fixed costs of operating and opening plants and warehouses plus the cost of supplying raw materials and delivering products. The second is the total customer demand that can be delivered within the orders' due date. The third is capacity utilisation for plants and warehouses. An approach that combines ACO and multi-agent system is proposed by Silva et al. (2004), in which, a supply chain is considered to have three sub-systems: (a) a logistic sub-system that has the task of receiving the orders requested by customers, purchasing different components from external suppliers, and starting the scheduling process, (b) a supplying sub-system that is a network of different suppliers that have to produce a sub-set of components and to find, cooperatively, a solution for the global supplying problem, and (c) a distribution sub-system that is modelled as a vehicle routing problem in which a delivery sequence is built for delivering every order on time. Every sub-system solves its own task by means of ACO. The approach breaks the overall supply chain system down into three sub-systems and attempts to find solutions for each of the subsystems.

Ant Colony Optimisation (ACO), particularly the Pareto Ant Colony Optimisation technique, is a relatively recent meta-heuristic in solving complex discrete optimisation problems. Since the introduction of the Ant System by Colorni et al. (1992), Dorigo (1992), and Dorigo et al. (1996), ACO has been applied to a number of NP-hard combinatorial optimisation problems including the