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Discrete Optimization

Distributed supply chain management using ant colony optimization

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ABSTRACT

Successful supply chain management requires a cooperative integration between all the partners in the network. At the operational level, the partners individual behavior should be optimal and therefore their activities have to be planned using sophisticated optimization tools. However, these tools should take into account the planning of the remaining partners, through the exchange of information, in order to allow some kind of cooperation between the elements of the chain. This paper introduces a new supply chain management technique, based on modeling a generic supply chain with suppliers, logistics and distributers, as a distributed optimization problem. The different operational activities are solved by the optimization meta-heuristic called ant colony optimization, which allows the exchange of information between different optimization problems by means of a pheromone matrix. The simulation results show that the new methodology is more efficient than a simple decentralized methodology for different instances of a supply chain.

1. Introduction

Supply chain (SC) systems are nowadays entering the age of adaptive and intelligent supply chains, a new generation of networks that features collaboration and visibility features across the different partners to deal with the system dynamics, such as supplier failures or demand uncertainty [6,21]. Supply chains systems are a set of separate and independent economic entities more interested in their local objectives than in the global system performance. Therefore, *centralized management* approaches, where a single partner such as the logistic center optimizes the global performance, are becoming less realistic and being replaced by *decentralized management* approaches, where each member optimizes its own performance, albeit knowing that collaboration with other partners can improve the individual and global performance. In any case, the key issue is to align the members objectives and coordinate their decisions to optimize the supply chain performance, but this is particularly more difficult to attain with a decentralized management approach [13].

At the operational level, supply chain management (SCM) is now seeking to determine the stock levels at the logistic centers depending on the demand, or the size and frequency of batches produced at the suppliers to feed the producers in time, or even the delivery planning that minimizes the transportation costs and environmental impacts [8]. The coherence between the different decision making centers in the chain can be easily accomplished by a multi-agent framework [17]. These systems are based on explicit communication between specialized agents assigned to structural elements of the chain (e.g. supplying or logistic agents) about their tasks and using an interaction protocol with a specific message structure, conversation rules, action and reaction behaviors [1].

The research in this field has tackled mainly the interaction between the agents and the optimization issues are usually solved through some simple dispatching rules. However, these methods are usually not sufficient to deal with the complexity of the real-world problems and the agents need to use more powerful optimization techniques [14]. Moreover, to take full advantage of the supply chain framework, the communication protocols should support the possibility of exchanging information during the optimization process, in order to allow agents to react to failures or other type of dynamic disturbances. However, it is necessary to take into account all sort of problems regarding level of disclosure and the asymmetry between the supply chain members that can generate opportunistic behaviors.

This paper introduces a multi-agent supply chain management methodology based on the description of the supply chain as a set of different distributed optimization problems and using the *ant colony optimization* (ACO) meta-heuristic [10] to achieve cooperation between different multiple partners. While optimizing, the ACO algorithm builds a *pheromone matrix*, which is an indirect record of the optimization steps. This matrix can be accessed at all times during the optimization process and contains no private

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information of any kind. If each system in a supply-chain is optimized by its own ant colony-agent, the pheromone matrices can be used to exchange information between the different systems as a multi-agent system, introducing in this way a coordination mechanism into the supply chain.

The paper proceeds as follows: Section 2 describes the SC model that is used in this paper. Section 3 presents a short literature survey on *decentralized* supply chain management and models the management problem as a distributed optimization problem. Section 4 shows how the ant colony optimization can be used to solve this problem as a multi-agent system. The simulation results are presented in Sections 6 and 7 concludes the paper and presents the guidelines for future work.

2. Decentralized supply chain modeling

We consider a generic supply chain model that comprised three systems: a *logistic* system, its *suppliers* and the *distributers*. A previous study considering only the suppliers and the logistic system was presented in [19]. The suppliers–logistics–distribution system proposed in the paper takes full advantage of the distributed optimization by considering all echelons of the supply-chain. The logistic system collects the orders from the customers, purchases the components from external suppliers and schedules the components delivered by the suppliers as orders. This system is also responsible to manage the cooperation between the partners in the network and for the communication between the clients and the supply chain. The supply system is a network of external suppliers that manufacture the components and deliver them to the logistic system. The distributers are responsible to pick up different items at the warehouses of the *logistic system* and distribute them to clients. Fig. 1 presents a schematic representation of such multiple echelon system.

The modeling approach proposed in this paper consists of describing each of the subsystems of the supply chain by a benchmark optimization problem: the logistic system is described by the general assignment optimization problem [20]; the supplying system by the manufacturing scheduling optimization problem [14]; and the distribution system by the vehicle routing problem [9].

2.1. Logistic system

At each day, the logistic system has an *order list* O of n orders waiting to be delivered. An order $o_j \in O$ with $j = 1,\dots,n$ is a set of ℓ different types of items, called the components c_i with $i = 1,\dots,\ell$, in certain quantities q_{ij}. Therefore, an order can be defined as an ℓ-tuple $o_j = (q_{1j},\dots,q_{\ell j})$. When a new order o_j arrives, it receives two labels: the arrival date or *release date* r_j and the desired delivery date or *due date* d_j, which is the date when the client wishes to receive the order. The order is delivered at the completion date C_j.

Assuming that the system does not deliver orders if they are ready before the due date, the difference between the completion date and the due date is called the *tardiness* $T_j = C_j - d_j$. The objective is to match both dates, i.e. to have for all orders $T_j = 0$. However, two disturbances may influence the system: the fact that suppliers service may not be respected and the fact that some clients ask for desired delivery dates not compatible with the supplier services.

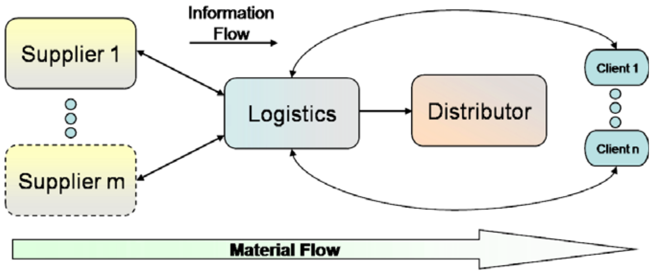

Fig. 1. Generic multi-echelon supply chain system.

In order to define the cost function that best describes the objective of the logistic system, consider the following definitions. Given the set O of orders in the system waiting to be delivered, the subset of orders that are going to be *delivered* is defined as $O_D \subseteq O$. The complementary subset of orders that are *not delivered* and remain in the system is defined as $O_{ND} \subseteq O$, such that $O_D \cup O_{ND} = O$. Consider further that the subset of orders that are delivered at the correct date is defined as $O^0_D \subseteq O_D$ and the subset of orders that are not delivered and are already delayed is defined as $O^d_{ND} \subseteq O_{ND}$. The optimization objective is to minimize the cost function given by

$$f_L = \frac{w_A\left(\sum_{j\in O} T_j\right) + w_B|O^d_{ND}|}{w_C|O^0_D| + \epsilon}, \qquad (1)$$

where $\sum_{j\in O} T_j$ accounts for the minimization of the tardiness of the total set of orders in the system O; $|O^d_{ND}|$ is the cardinality of the subset O^d_{ND} and refers to the minimization of the number of orders that are not delivered and are already delayed; and finally $|O^0_D|$ is the cardinality of the subset O^0_D and accounts for the maximization of the number of orders delivered at the correct date. The ϵ is a small constant that avoids the infinity value when no orders are delivered at the correct date. The weights w_A, w_B, w_C are used to convert the cost to the same unit, e.g. monetary units, or to balance the different variables in case the order of magnitude of the variables is very different. In this case, $w_A = 1/\text{day}$, $w_B = w_C = 1$. This decision step is done once per day, but different solutions for the same daily problem originate different next-day scheduling problems. The supply chain management is a dynamic succession of daily optimization problems, that are treated independently, even though they are not. Therefore, to evaluate the performance of the supply chain, larger periods of time, such as weeks or months, should be considered.

2.2. Supplying system

The supplying sub-system is a network of m different suppliers or manufacturers M_i with $i = 1,\dots,m$, each one producing its own set of jobs J_{M_i}, where each job refers to a type of component c_i requested by the logistic sub-system. Each supplier is independent and therefore it optimizes its own problem called the *local supplier* problem. However, from the point of view of the logistic system, the suppliers can be virtually considered as one single entity, and the optimization problem is called the *global supplier* problem.

2.2.1. Local supplier problem

The optimization problem of each M_i supplier, called here the local supplier problem, can be modeled as a single machine scheduling problem [14]. There is one machine that produces all the n_i jobs on the waiting list J_{M_i} of the supplier. The objective function to be minimized is the total tardiness of all the jobs

$$f_{M_i} = \sum_{j\in J_{M_i}} w_T \cdot T_j, \qquad (2)$$

where tardiness is defined as in the logistic system and w_T is a weight to convert the cost from days to other unit, such as monetary units.

2.2.2. Global supplier problem

The global supplier problem describes the supply system from the logistics point of view. The problem can be modeled as an open