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A Corporate Supply Optimizer with Flow Network

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Abstract. *A holding or a multi-business corporate seeks to coordinate its supply for minimum overall costs. A Corporate Supply Optimizer (CSO), as a central entity taking advantage of the notion of flow networks, gathers necessary operational information from members of the corporate supply chain. The CSO then guides supply chain members on ordering decisions for a minimum overall cost for the entire supply chain. Its computational engine models the entire supply chain with multiple members in four stages to satisfy customer demand. The CSO seeks a solution with minimum total costs, unlike non-cooperative supply chains where individual members compete to optimize their local costs. The existing literature stays with restrictive assumptions on the number of supply chain stages, disallowing a case of multiple products. Simulation results indicate an approximately 26% reduction in total costs of the supply chain utilizing the CSO.*

Keywords: *Corporate supply; Coordination mechanism; Flow network; Linear programming; Optimizer.*

INTRODUCTION

After a period of focusing heavily on individual business specific results, many multi-business companies are again becoming concerned to take advantage of potential synergies between their businesses. A focus on opportunities to add value and on the distinctive resources possessed by the corporate parent that lead to added value, provides the basis for valid corporate strategies [1]. Many suppliers also enter into partnership or alliance agreements so that they can share the benefits of serving better customers in a particular market [2].

Outsourcing has become a hot topic for many companies in recent years. Some companies are pushing as many processes onto outside suppliers, while keeping control over the timing and mix of flow from each link. Although each supplier is a distinct business, the client persists in complete control on the timing and mix of the required supply [3].

It has become a widespread policy to organize multi-business firms into Strategic Business Units (SBUs). Each SBU is given the responsibility to serve the particular demands of one business area or to produce a particular supply for other units [4]. Even where resources, activities and product offerings are split along business unit lines, integration can be achieved by ensuring that coordination is carried out between business units. Such orchestration of work across business unit boundaries should result in the ability to operate as if the various parts were actually one unit [5].

Coordination among the stages or, in other words, among a network of buyers and sellers is a major challenge in cooperative supply chain, and generated much interest in the past several decades [6]. As the actual number of businesses related to manufacturing and distribution of products has increased in practice, the coordination issue has become immensely complicated. Lack of coordination may cause unfavorable effects such as longer lead times, higher operation (production, transportation or inventory) costs, degradation in the customer service levels and a negative impact on the relationships amongst members in a supply chain.

Although much formulation and quantitative analysis is developed in supply chain literature in the past two decades [7], a comprehensive model optimizing all aspects of cost and capacity for multiple stages

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and products is not found, which may additionally include customer priority or product inventory and shortage. For a cooperative or a corporate-managed supply chain, the overall optimization problem has not yet been addressed. Furthermore, such initial supply chain optimization models have not been extended into practice, employing an integrated real-time mechanism to match advances in electronic procurement.

The idea behind the proposed mechanism in this paper is to present the corporate supply chain as a flow network, and then formulate and solve a corresponding linear programming model in the flow network. Furthermore, a Corporate Supply Optimizer (CSO) system, which may be actually an electronic hub (e-hub), gathers needed information about operational costs and capacities from the supply chain members. CSO guides the cooperative supply chain members on ordering decisions, thus providing a minimum overall cost for the entire supply chain. Without such mechanism, every member makes decision on order quantities based on its local and accessible information, resulting in non-optimal performance of the corporate supply chain.

Organization of the paper is as follows. The next two sections review the literature on supply chain coordination and corporate-managed supply. Concept of flow network as a major player in the solution is investigated in the following section. Next parts provide definition and assumptions associated with the problem, and demonstrate how the proposed model can solve the problem. Evaluation of the model and conclusion have been presented at the end of the paper.

SUPPLY CHAIN COORDINATION

A supply chain is defined as a set of suppliers, manufacturers, distributors and retailers (supply chain stages) along with all their interrelationships [8]. A supply chain is composed of several stages with a number of members in each stage, which may be distinct businesses related to each other directly or indirectly to satisfy customer demand. Different types of products are produced from a set of supplied components in a supply chain.

A supply chain coordination scheme in practice may generally include coordination contracts, information sharing and negotiation. The most common mechanism for bilateral relationship between a buyer and a seller is to collaborate and agree on a contract. Supply network contracts include quantity-discounts, revenue-sharing, buy-back contracts, price-discounts, quantity-flexibility, sales-rebate, promotional allowances, cooperative advertising and franchise contracts [7,9-11]. Cachon provides a thorough study of coordination contracts [12]. Increase in the number of members of supply network transforms traditional contracts into inefficient coordination mechanisms. Li and Wang [6] provide a survey of traditional coordination mechanisms for supply network taking an inventory control approach.

Decision making based on shared operational information by members of a supply chain is the second major type of coordination mechanisms. Lee and Whang [13] describe inventory, sales, demand forecast, order status and production schedule as different types of information shared. While Lee et al. [14] and Cachon and Fisher [15] clearly show the significance of information sharing in a two-level supply chain, lack of information sharing aggravates the incurred cost in a supply chain with multiple members in several stages (see [16,17]). Usual choices for managing and sharing business information include Customer Relationship Management (CRM), Supplier Relationship Management (SRM), Electronic Data Interchange (EDI), e-marketplaces and e-chains [8,18-22].

Sahin and Robinson [23] provide a literature review in product flow and information sharing in supply chains based on the degree of information sharing. An absolutely significant question is that while members of the supply chain do not trust each other completely, why should they accept to share their own strategically important information via such coordination systems? Li [24] investigates the incentives for members of a two-level supply chain with one manufacturer and several retailers to share information horizontally. He concludes that voluntary information sharing is not rationally possible and therefore examines conditions under which information can be traded. Thus, it may be essential to restrict shared information as much as possible. The problem of a general supply chain with multiple levels and several members in each level still remains unexplained.

Many recent studies have focused on negotiation-based mechanisms for the supply chain coordination. Negotiation may be considered as a process with a special type of information sharing where less information is shared, and a protocol is used for conducting the negotiation process. Fox et al. [25] developed a high-level framework for supply chain functions with the idea of encapsulating these function in corresponding software agents. Consequently, Fox et al. [26] presented a general approach to supply chain management operations covering planning and execution of actions with different types of software agents. Dudek and Stadtler [27] study a two-member supply chain. By defining members' mathematical operational model, they proposed a negotiation mechanism to reduce total costs. Chen, et al. [28] propose a flexible negotiation-based multi-agent system in which new members can join the supply chain and its members may leave it.

Despite their nice approach to the problem, the issue of several agents' interactions remains unexplored. Fazel Zarandi et al. [29] attempt to provide an agent-based architecture based on fuzzy logic to realize a responsive and cooperative supply chain. Ding and Chen [30] consider using negotiation in return policy to coordinate a three-stage (with a single member in each stage) supply chain. Fink [31] proposes using a mediator software agent to conduct a bilateral negotiation process until both firms accept a contract. In general, limiting the number of supply chain members and concurrent interaction of multiple agents are the major obstacles in applying the current negotiation-based mechanisms to supply chains with multiple members.

Using linear programming techniques to formulate and analyze the various supply chain management problems has a long record in the research literature. In addition to inventory management and production-distribution planning problems, which make use of linear programming schemes extensively [32-38] designing distribution networks [39-41], models for facility location allocation [42-44], the facility capacity allocation problem [45] and the aggregate planning [8,46] represent this category of supply chain management problems. While dealing with different supply chain problems, mixed Integer programming provides more accurate description of the problem, but reaching the fast and exact solutions to the problem might be a challenge (e.g. [47]).

CORPORATE-MANAGED SUPPLY

Corporate headquarters (CHQ) play varying roles in large or multi-business companies. CHQ or the parent unit can help the other elements expand their size and scope of activities in, for example, globalization or product extensions [2]. In organizational economics, the role of CHQ is mostly limited to monitoring and incentive issues. However, this role may be expanded to assist in exploiting economies of scope and other synergies, in building up internal capital markets, and in directing mix of activities within each unit [48].

Headquarter or corporate strategy can be described as the identification of the purpose of the organization and the plans and actions to achieve that purpose amongst the business units [2]. Corporate strategies should facilitate the coordination of organizational actions and their interactions [49]. In a multi-business company, each business needs to have its own strategy to succeed in its particular product market arena. However, the corporate strategy must be more than simply the aggregation of these business strategies [50]. Otherwise, there is no justification for bringing the separate businesses together under the common ownership of a single corporate parent.

Corporate level strategy is about selecting an optimal set of businesses and determining how they should be integrated into the corporate whole. Deciding on the best array of businesses and relating them to one another is referred to as the issue of 'corporate configuration' [49]. Determining the configuration of a corporation can be disentangled into two main questions:

(a) "What businesses should the corporation be active in?" This is called the topic of 'corporate composition'.

(b) "How should this group of businesses be managed?"This function is labeled as the issue of 'corporate management'.

Centralization, coordination and standardization between business units can also be achieved without the use of hierarchical authority. Business units might be willing to cooperate because it is in their interest to do so, or because they recognize the overall collective interests. Corporate strategists interested in such integration, by mutual adjustment, will focus on creating the organizational circumstances under which such self-organization can take place [51]. Such coordination can result on lower overall costs shared by all business units.

Proff [52] developed a research concept to assess the consistency of corporate strategies. He formulated a research hypothesis that Return On Equity (ROE) increases with an increase in consistency between the corporate and lower-level business strategies. The research hypothesis was significantly confirmed by an empirical investigation of the corporate strategies, using a sample of the 35 largest German diversified firms [52].

A case in point is IKEA, which was founded over 60 years ago in Southern Sweden. It has since grown to become the world's largest furniture retailer. During its expansion in the 1960s, IKEA also laid the groundwork for its purchasing strategy, relying on long-term relationships with selected suppliers as external sources for its offerings. Today, its supply network spans the entire world and has become increasingly complex [53].

A pivotal role in this network is played by "IKEA of Sweden". This leading business unit not only manages IKEA's product range, but also supervises the entire IKEA universe and develops long-term marketing, logistics and purchasing strategies. IKEA designs and purchases products that entail low production and transportation costs by carefully taking into account all the activities performed in the network from raw materials to customer homes. Remaining faithful to its original external orientation, IKEA performs only a few of these activities internally while it intensively uses its relationships with suppliers to combine its internal and their external resources [53]. IKEA of Sweden in fact acts as a central unit to manage the suppliers.

Supply networks are widely publicized and researched phenomena, especially in high-tech sectors where the likes of Dell, Microsoft or Genentech pursue their network strategies through research and development joint ventures, cross-licensing or strategic alliances [54]. Networks are not only important for small firms that need to interact with their peers to supplement their limited resources, but they are fundamental for large companies as well. For instance, multinational companies in the steel, paper and automotive industries interact tightly with their suppliers, sub-suppliers, distributors and customers to develop new technologies or increase efficiency [55]. There are many examples of large firms from several sectors that relied strongly on networks for their rapid growth: Apple, Benetton, Toyota, Corning and McDonald's [56].

FLOW NETWORKS

Since the 'flow network' concept is an integral part of the proposed solution in this research, a brief overview of the concept is provided here. A flow network is a directed graph in which each node can produce, consume or pass a flow. Examples of the flow networks include electrical and urban transportation, telecommunication, railroad and oil product pipeline networks. Each directed arc is a one-way conduit for the flow with a defined capacity. Nodes are conjunction points of flow paths and can only pass the flow (not store or consume it) except for two special types of nodes: the source node(s) and the sink node(s). A source node has only outgoing arc(s) and produces the flow, while a sink node has only incoming arc(s) and consumes the flow. Several studies [57,58] provide comprehensive surveys of algorithms for solving network-flow problems.

A flow network $G = (V, E)$ is a directed graph in which each arc $(u, v) \in E$ has a nonnegative capacity, i.e. $c(u, v) \geq 0$. If $(u, v) \notin E$, it is assumed that $c(u, v) = 0$. In a typical flow network, consider two distinguished nodes: source node, s, and sink node, t. It is assumed that every arc lies on some path from the source to the sink. A flow is a real-valued function $f : V \times V \to \mathbf{R}$ that satisfies the following properties:

a) Capacity constraint: for all $u, v \in V$, $f(u, v) \leq c(u, v)$.

b) Skew symmetry: for all $u, v \in V$, $f(u, v) = -f(v, u)$.

c) Flow conservation: for all $u \in V - \{s, t\}$, $\sum_{v \in V} f(u, v) = 0$.

$f(u, v)$, which can be positive, zero or negative, is the flow from node u to node v. Furthermore, a flow network may have several sources and sinks rather than just one of each. In this case, the source and sink nodes should be replaced with a set of source nodes and a set of sink nodes in the aforementioned definition, respectively.

The multi-commodity flow problem consists of shipping several different commodities from their respective sources to their sinks through a common network so that the total flow going through each edge does not exceed its capacity. Associated with each commodity is a demand which is the amount of that commodity that we wish to ship through the network [58]. Given a multi-commodity flow problem, we would like to know if there is a feasible flow, i.e. a way of shipping the commodities that satisfies the demands as well as the capacity constraints. This problem can be solved using either exact algorithms or approximation algorithms [59,60] to speed up the solution.

OVERVIEW OF THE PROBLEM

Problem Definition

A supply chain is considered with multiple members in at least four stages, providing k different types of products to the customers. Supply chain stages include suppliers, manufacturers, distributors and retailers. Each product is manufactured from a number of basic components or raw materials provided by the suppliers. A manufacturer can potentially produce all products, limited by its production and delivery capacity or by its strategies. Any supplier has a restricted capacity for providing each kind of basic components. The distributors, according to their distribution capacity, are able to send the products from the manufacturers to the retailers. Finally the retailers sell the products to the customers. The aforementioned definition removes two simplifying assumptions in the previous works containing quantitative analyses, i.e. limited number of members in the supply chain and single-product case. Thus, a more general and realistic problem is investigated.

The proposed mechanism aims to minimize total operations costs for the entire supply chain. Distribution, transportation, lost sales, holding inventory, excess capacity and production are considered as different components of the total costs in the supply chain. In this way, higher competitiveness for the supply chain is achieved by lower overall cost of providing products to the end-customers. We develop a linear programming model for the problem considering single-period case.

Assumptions

Sale prices of the products are assumed to be independent of the chain performance because they are derived from the overall supply and demand in a competitive market and are not controlled significantly by individual members in a supply chain. The problem here, therefore exclusively concerns with minimizing costs of providing products to the customers.

The operation of the supply chain is focused here on a single planning period, as the decisions are in practice usually made at the beginning of each period. The members in the supply chain are assumed to follow the fixed interval policy for inventory control. Hence, an agreement exists on a fixed order placement period for the products. However, the model may be expanded in the future to include multiple periods. Members only make decisions about quantities and sources of their orders. Retailers are also provided, at the beginning of each period, with customer demand information for different types of products. Manufacturers use all of the received supplies to produce final products. Moreover, manufacturers and retailers can hold inventory of products. In practice, distributors given the demand information, first examine ways of providing products from the manufacturers to the retailers before placing order to them. Therefore, distributors are considered as unpreventable intermediate nodes and we do not consider a case in which excess inventory remain in distributor as the end of planning period. Contrary to distributors, holding inventory by retailers is commonplace.

Obviously, most real-world scenarios involve more intricate and complicated characteristics such as using different inventory management systems and stochastic nature of demand. However, this paper as an ongoing research aims to extend the previous studies by considering multiple stages and multiple products. Thus, as a primary step, the proposed coordination mechanism is studied with potential for more complex situations.

COORDINATION MECHANISM

Consider a directed graph $G = (V, E)$ in which each node represents a member of the supply chain and each directed arc represents a potential relationship between two members. Every directed arc (u, v) shows the possibility of providing basic components, raw materials or finished products from member u to member v. Arc capacities are given as capacities for supply, production, distribution and transportation (depending on nature of a relationship) from an organization to another for a planning period. Moreover, a cost factor is assigned to each arc representing the costs of supply, production, distribution and transportation for each unit of a product or component. These costs are assigned to the first member in a relationship (i.e. organization u).

Notation used in the model is listed below:

p: index for number of different types of components/materials;

k: index for number of different of types of products;

i: index indicating type of product, where $i = 1, 2, \cdots, k$;

j: index indicating type of component (or raw material), where $j = 1, 2, \cdots, p$;

a_{ij}: necessary quantity/amount of component/raw material type j necessary to produce every unit of product type i;

$A_i = \{a_{i1}, a_{i2}, \cdots, a_{ip}\}$: set of components/raw materials composing one unit of a product type i (for example, if $A_4 = \{0, 2, 1\}$, then every unit of forth type of products contains two units of component type 2 and one unit of component type 3. It is obvious that component type 1 is not needed to produce type of product);

$S\text{set} = \{sp_s, \forall s = 1, 2, \cdots, S\}$: set of suppliers;

$M\text{set} = \{\text{manu}_m, \forall m = 1, 2, \cdots, M\}$: set of manufacturers;

$D\text{set} = \{\text{dist}_d, \forall d = 1, 2, \cdots, D\}$: set of distributors;

$R\text{set} = \{\text{ret}_r, \forall r = 1, 2, \cdots, R\}$: set of retailers;

Network (I): a flow network with vertices consisting of Mset, Dset and Rset and arcs which connect these vertices;

Network (II): a flow network with vertices consisting of Sset and Mset and arcs which connect these vertices;

V_1: set of vertices of Network (I) ($V_1 = M\text{set} \bigcup D\text{set} \bigcup R\text{set}$);

V_2: set of vertices of Network (II) ($V_2 = S\text{set} \bigcup M\text{set}$);

V: set of vertices of directed graph G;

d_{ir}: quantity of customer demand for product type from retailer r (where $r = 1, 2, \cdots, R$);

$c_i(u, v)$: capacity of arc (u, v) for flow of product i (in Network (I));

$o_i(u, v)$: cost of flow of each unit of product i through arc (u, v) (in Network (I));

$f_i(u, v)$: value of flow of product type i in arc (u, v) (in Network (I));

$c_j(u, v)$: capacity of arc (u, v) for flow of component (or raw material) type j (in Network (II));

$o_j(u, v)$: cost of flow of component/raw material type j through arc (u, v) (in Network (II));

$f_j(u, v)$: value of flow of component/raw material type j through arc (u, v) (in Network (II));

QP_{im}: quantity of production of ith type of products in mth manufacturer;

$\text{Inv}(I)_{ir}$: inventory level corresponding to rth retailer and ith type of products at the beginning of the planning period;

$\text{Inv}(II)_{ir}$: inventory level corresponding to rth retailer and ith type of products at the end of the planning period;

$\text{Inv}(I)_{im}$: inventory level corresponding to mth manufacturer and ith type of products at the beginning of the planning period;

$\text{Inv}(II)_{im}$: inventory level corresponding to mth manufacturer and ith type of products at the end of the planning period;

H_{ir}: holding cost corresponding to rth retailer for every remained unit of ith type of products' inventory at the end of planning period;

H_{im}: holding cost corresponding to mth manufacturer for every remained unit of ith type of products' inventory at the end of planning period;

LS_{ir}: lost sale cost corresponding to rth retailer and every unit of ith type of products;

$\text{ECC}_i(u,v)$: excess capacity cost corresponding to arc (u,v) $(u,v \in V_1)$;

$\text{ECC}_j(u,v)$: excess capacity cost corresponding to arc (u,v) $(u,v \in V_2)$;

UC_{im}: production cost for each unit of ith type of product by mth manufacturer;

PR_{ir}: order fulfillment priority assigned to rth retailer and ith type of products $(0 < PR_{ir} \leq 1)$;

z: objective function representing the total cost incurred by the supply chain.

As it is clear from the notation, the original directed graph G representing the whole supply chain is logically decomposed into two parts: Network (I) which includes manufacturers, distributors and retailers, and Network (II) which covers suppliers and manufacturers. In Network (I) products flow, while in Network (II) components/raw materials flow. In Network (I), manufacturers and retailers are considered as sources and sinks of flow, respectively; while in Network (II), suppliers and manufacturers are considered to take these roles.

Parameters $c_i(u,v)$, $c_j(u,v)$, $o_i(u,v)$ and $o_j(u,v)$ are given as input data for each planning horizon for which the model is used. $c_i(u,v)$ is interpreted as maximum feasible capacity of organization u for providing (i.e. distributing and transporting) product i and delivering it to organization v with cost $o_i(u,v)$. $o_i(u,v)$ is considered as distribution transportation costs. $c_j(u,v)$ and $o_j(u,v)$ have similar interpretations replacing products with basic components (or raw materials). d_{ir} is another input parameter to the model. LS_{ir}, H_{ir}, $\text{Inv}(I)_{ir}$, $\text{Inv}(I)_{im}$, $\text{ECC}_i(u,v)$, $\text{ECC}_j(u,v)$ and UC_{im} are also predefined parameters or available from previous periods' data given as inputs to the model. Parameter PR_{ir} can be initially assigned value one. If there is no feasible solution for the model, it might be reduced for some retailers with less cooperative background and solve the model again. Application of PR_{ir} as well as other parameters are clarified further in the next section. Finally, $f_i(u,v)$, $f_j(u,v)$ and QP_{im} are decision variables.

The proposed model for the whole supply chain is provided as follows:

$$\begin{aligned}\min z = &\left(\sum_{u,v\in V_1}\sum_{i=1}^{k} o_i(u,v) f_i(u,v)\right)\\
&+\left(\sum_{u,v\in V_2}\sum_{j=1}^{p} o_j(u,v) f_j(u,v)\right)\\
&+\left(\sum_{r=1}^{R}\sum_{i=1}^{k}\left(\left(d_{ir}-\text{Inv}(I)_{ir}\right.\right.\right.\\
&-\left.\left.\left.\left(\sum_{u\in V_1} f_i(u,\text{ret}_r)\right)\text{LS}_{ir}\right)\right)\right)\\
&+\left(\left(\sum_{r=1}^{R}\sum_{i=1}^{k}(\text{Inv}(I)_{ir}H_{ir})\right)\right)\\
&+\left(\sum_{m=1}^{M}\sum_{i=1}^{k}(\text{Inv}(I)_{im}H_{im})\right)\\
&+\left(\sum_{u,v\in V_1}\left(\sum_{i=1}^{k}(c_i(u,v)-f_i(u,v)\text{ECC}_i(u,v))\right)\right)\\
&+\left(\sum_{u,v\in V_2}\left(\sum_{j=1}^{p}(c_j(u,v)-f_j(u,v)\text{ECC}_j(u,v))\right)\right)\\
&+\left(\sum_{m=1}^{M}\sum_{i=1}^{k} QP_{im}UC_{im}\right),\end{aligned} \tag{1}$$

subject to:

$$f_i(u,v) \leq c_i(u,v), \quad \forall i=1,2,\cdots,k, \quad \forall u,v \in V_1, \tag{2}$$

$$f_i(u,v) = -f_i(v,u), \quad \forall i=1,2,\cdots,k, \quad \forall u,v \in V_1, \tag{3}$$

$$\sum_{v\in V_1} f_i(u,v) = 0, \quad \forall i=1,2,\cdots,k, \quad \forall u \in D\text{set}, \tag{4}$$

$$\sum_{u\in V_1} f_i(u,\text{ret}_r) \geq (d_{ir} - \text{Inv}(I)_{ir})PR_{ir},$$

$$\forall i=1,2,\cdots,k, \quad \forall r=1,2,\cdots,R, \tag{5}$$

$$f_j(u,v)\leq c_j(u,v), \quad \forall j=1,2,\cdots,p, \quad \forall u,v\in V_2, \tag{6}$$

$$\sum_{u\in V_2} f_j(u,\text{manu}_m) \geq \sum_{i=1}^{k}(a_{ij}\sum_{v\in V_1} f_i(\text{manu}_m,v)),$$

$$\forall j=1,2,\cdots,p, \quad \forall m=1,2,\cdots,M, \tag{7}$$

$$QP_{im}+\text{Inv}(I)_{im} \geq \sum_{v\in V_1} f_i(\text{manu}_m,v),$$

$$\forall j=1,2,\cdots,p, \quad \forall m=1,2,\cdots,M, \tag{8}$$

$$(d_{ir} - \text{Inv}(I)_{ir} - \sum_{d=1}^{D} f_i(\text{dist}_d,\text{ret}_r)) \geq 0,$$

$$\forall hi=1,2,\cdots,k, \quad \forall r=1,2,\cdots,R, \tag{9}$$

$$f_j(sp_s,\text{manu}_m)\geq 0, \quad \forall s=1,2,\cdots,S,$$

$$\forall m=1,2,\cdots,M, \quad \forall j=1,2,\cdots,p, \tag{10}$$

$$f_i(\text{manu}_m,\text{dist}_d)\geq 0, \quad \forall m=1,2,\cdots,M,$$

$$\forall d=1,2,\cdots,D, \quad \forall i=1,2,\cdots,k, \tag{11}$$

$$f_i(\text{dist}_d,\text{ret}_r)\geq 0, \quad \forall d=1,2,\cdots,D,$$

$$\forall r=1,2,\cdots,R, \quad \forall i=1,2,k, \tag{12}$$

$$QP_{im}\geq 0, \quad \forall m=1,2,\cdots,M, \quad \forall i=1,2,\cdots,k. \tag{13}$$

Expression 1 describes objective function which indicates total operational costs of the supply chain. Is consists of eight terms logically separated by parentheses. The first and second terms indicate flow costs (i.e. purchasing and transportation costs) in Network (I) and Network (II), respectively. The third term shows cost of lost sales. The fourth and the fifth parentheses represent holding cost of remained inventory from the previous period. Costs incurred by the supply chain because of excess capacity in Network (I) and Network (II) are shown by the two subsequent terms. Finally, the eighth term stands for production costs.

There are also twelve constraint sets denoted by Relations 2 to 13 in the model. First three constraint sets (Relations 2, 3 and 4) are equivalent to capacity constraint, skew symmetry and flow conservation properties of flow networks (for Network (I)), respectively. Constraints 5 guarantees satisfying demand in retailers. Constraints 6 are equivalent to capacity constraint of flow networks (for Network (II)). Constraints 7 guarantee satisfying demand from the manufacturers for basic components to produce sufficient products.

Constraints 8 assure sufficient production by the manufacturers. Constraints 9 both assure non-negativity of lost sales and not having remained inventory at retailers (note that similar constraints for manufacturers are implicitly satisfied according to model). Finally, Constraints 10 to 13 are non-negativity constraints on the values of out flows and quantities of product.

Note that if supply chain members choose order quantities according to the solution of the model, they will not have any excess inventory. However, they may opt for holding inventory because of their own forecast of future demands or keeping safety stock (i.e. $\text{Inv}(II)_{ir}\geq 0$ or $\text{Inv}(II)_{im}\geq 0$). Therefore, $\text{Inv}(I)_{ir}$ and $\text{Inv}(I)_{im}$ are not necessarily zero at the beginning of the upcoming planning period.

Since the model is a linear programming model, existing polynomial-time algorithms such as Karmarkar's algorithm [61] can be used to solve them efficiently. Upon solving the model and informing the supply chain members of their respective flow values, the members are able to make decisions and place orders such that optimal situation for the whole supply chain would be attainable.

CORPORATE SUPPLY OPTIMIZER

To coordinate the supply chain in practice, a central software entity named Corporate Supply Optimizer (CSO) plays a central role whose architecture is described later in this section. The suppliers and manufacturers are asked to provide A_i sets information to the CSO. Whenever A_i changes, they can inform the CSO immediately. At the beginning of a planning period, for example at beginning of each month, the retailers also provide demand forecast information to the CSO. Every supplier, manufacturer and distributor in supply chain provides the CSO with names of connected organizations in its next stage along with associated capacity and cost parameters. In other words, a retailer ret_r sends d_{ir} and every non-retailer member of supply chain such as u specifies arcs (u,v) and values for $c_i(u,v)$ and $o_i(u,v)$ to the CSO. Formally, $\text{Info}(u)$ denoting information given to the CSO by member of the supply chain is defined for different members as follows:

$$\text{Info}(sp_s)$$

$$=\left\{\begin{array}{l}(c_j(sp_s,v),o_j(sp_s,v),\text{ECC}_j(sp_s,v):\\ j=1,2,\cdots,p \quad (sp_s,v)\in E\end{array}\right\}, \tag{14}$$

$$\text{Info}(\text{manu}_m) = \left\{ \begin{array}{l} (c_i(\text{manu}_m, v), o_i(\text{manu}_m, v), \\ \text{ECC}_i(\text{manu}_m, v), \\ \text{Inv}(I)_{im}, H_{im}, UC_{im}) : i = 1, 2, \cdots, k, \\ (\text{manu}_m, v) \in E, \end{array} \right\}, \quad (15)$$

$$\text{Info}(\text{dist}_d) = \left\{ \begin{array}{l} (c_i(\text{dist}_d, v), o_i(\text{dist}_d, v) \\ ECC_i(\text{dist}_d, v)) : i = 1, 2, \cdots, k, \\ (\text{dist}_d, v) \in E, \end{array} \right\}, \quad (16)$$

$$\text{Info}(\text{ret}_r) = \{(d_{ir}, \text{Inv}(I)_{ir}, H_{ir}, LS_{ir}) : i = 1, 2, \cdots, k\}. \quad (17)$$

Note that providing the CSO with information according to the above four sets is the most cooperative case. In minimum, only $c(u, v)$, $o(u, v)$ and d_{ir} would be sufficient to form the optimization model [62]. In the latter case, unknown parameters may be forecast based on previous periods' information. In the worst case in which no information is available these parameters and members do not want to announce them cooperatively, corresponding terms may be omitted from objective functions and constraints which results in a less actual but still quite helpful model.

Priority parameter PR_{ir} which is set by the CSO, reflects cooperative records of a member (the greater value means a more cooperative behavior). Cooperation is the degree to which a supply chain member abides by the order quantities declared by the CSO. This parameter might take initial value of one. If there is not any feasible solution for the model because of limited flow capacity, the CSO could reduce priority parameters for members with less cooperative records. As a result, tendency to become selfish, and act in a locally-optimum fashion, would be deterred over time.

Using gathered information, the CSO is then able to construct and solve the optimization model and send the flows' values to the corresponding supply chain members. These orders are placed to assure the entire supply chain operations with minimum feasible costs and satisfying customer demand. Necessary decision information provided by the CSO for manufacturer manu_m, distributor dist_d and ret_r retailer are denoted by Expressions 18, 19 and 20:

$$\text{Decision} - \text{Info}(\text{manu}_m, u, j) = \left\{ \begin{array}{l} (f_j(u, \text{manu}_m), QP_{im}) : \\ (u, \text{manu}_m) \in E; \\ i = 1, 2, \cdots, k, \ m = 1, 2, \cdots, M \end{array} \right\}, \quad (18)$$

$$\text{Decision} - \text{Info}(\text{dist}_d, u, i) = \{f_i(u, \text{dist}_d) : (u, \text{dist}_d) \in E\}, \quad (19)$$

$$\text{Decision} - \text{Info}(\text{ret}_r, u, i) = \{f_i(u, \text{ret}_r) : (u, \text{ret}_r) \in E\}. \quad (20)$$

AN APPLICATION

Iran Khodro is the oldest and the largest vehicle manufacturing company in Iran. Having an average share of 65 percent of domestic vehicle production market, Iran Khodro produced 550,000 vehicles in year 2008 (http://www.ikco.com/default.aspx). In the past, the company used hundreds of independent domestic and international suppliers for delivering parts and sub-assemblies to its multiple production lines. Frustrated by long delivery delays, uncoordinated and non-cooperative suppliers and local sub-optimized decisions by each supplier, the company moved towards developing a coordinated and empowered supply chain.

In 1993, Iran Khodro helped establishing SAPCO (Supplying Automotive Parts Company), a member of Iran Khodro Industrial Group with a mission of "the localization of automotive parts and development of Iran Khodro part supply chain". Its premier staff was a group of Iran Khodro employees who worked in Supply Chain department and helped establish the new company with a planned supply chain operation for the mother company (www.sapco.com).

A paradigm shift has occurred in Iran Khodro's Supply Chain operation, matching with a Just-in-time mentality learned from the Japanese counterparts [63]. SAPCO moved from a traditional adversarial competition among the suppliers towards a measured development of a supplier network in which various members are coordinated by the ultimate stakeholder, namely Iran Khodro. Although SAPCO is a Strategic Business Unit (SBU), it acts a corporate supply coordinator arm of Iran Khodro industrial group.

The problem in this paper is motivated and defined based on the type of actual operations in SAPCO, which manages the requirements of Iran Khodro for coordination of its supply chain. The members in various stages, though are independent and wish the highest throughputs with lowest costs locally, act in a coordinated fashion for the lowest overall costs of the supply chain. As in JIT paradigm, a one period planning horizon is used, as inventory or back-order are highly undesirable. The problem is formulated exactly with multiple customers, multiple stages and multiple products under stable and deterministic capacity and demand.

An initial version of the CSO was implemented at SAPCO in 2008, which was received well by the company and the suppliers. It allowed the company to obtain an initial optimum solution and various what-if simulation results for follow-up supply negotiation within the supply chain. A modified version of the system with expanded input-output designs is to be implemented in a near future, and is expected to be eventually integrated with the existing information systems. The above framework is not limited to Iran Khodro and Iran alone, but is the current norm in a widespread range of industries in Iran and in the World.

EVALUATION

In this section, sample computations have been provided to demonstrate the solution in depth. Furthermore, simulation results show how the solution would be useful in different situations.

Sample Computations

This section provides a numerical example to illustrate the mechanism. Consider a supply chain with two suppliers, three manufacturers, three distributors and four retailers. In this example, two types of products are manufactured from three types of basic components such that $A_1 = \{11, 4, 19\}$ and $A_2 = \{5, 6, 12\}$.

All of the illustrative computations in this section are based on this example. Finally all priority factors are considered having value one. Tables 1 to 4 represent the supply chain parameters with regard to flow network description of a sample supply chain described before.

Using ILOG CPLEX 11.0 standard mathematical programming solver, the results appear in Tables 5, 6 and 7.

The minimized total cost equals 46295.63. Note that in this example there is no lost sale. This fact

Table 1. Network (I) specifications.

Network (I)						
Arc	$c_1(u,v)$	$c_2(u,v)$	$o_1(u,v)$	$o_2(u,v)$	$\mathrm{ECC}_1(u,v)$	$\mathrm{ECC}_2(u,v)$
$(m1, d1)$	13	18	15	14	3	3
$(m1, d3)$	12	10	24	15	1	1
$(m2, d1)$	16	15	16	19	2	3
$(m2, d3)$	19	13	35	10	1	2
$(m3, d1)$	12	16	24	13	3	6
$(m3, d3)$	13	8	26	12	4	1
$(d1, r1)$	17	15	37	11	2	5
$(d1, r2)$	15	19	46	14	1	3
$(d1, r3)$	14	27	14	10	5	2
$(d2, r1)$	16	22	18	10	1	4
$(d2, r2)$	15	7	33	9	4	1
$(d3, r2)$	16	13	36	17	3	5
$(d3, r3)$	14	21	27	9	2	1
$(d3, r4)$	17	22	46	23	2	3

Table 2. Network (II) specifications.

Network (II)									
Arc	$c_1(u,v)$	$c_2(u,v)$	$c_3(u,v)$	$o_1(u,v)$	$o_2(u,v)$	$o_3(u,v)$	$\mathrm{ECC}_1(u,v)$	$\mathrm{ECC}_2(u,v)$	$\mathrm{ECC}_3(u,v)$
$(s1, m1)$	193	190	420	10	7	15	2	1	1
$(s1, m2)$	257	210	530	11	5	11	3	2	3
$(s2, m1)$	264	348	370	10	9	10	1	1	4
$(s2, m2)$	339	144	445	8	8	14	2	2	1
$(s2, m3)$	490	370	465	7	9	10	2	4	3

Table 3. Retailers' parameters.

d_{11}	12	LS_{11}	22	$\text{In}\nu(I)_{11}$	5	H_{11}	7
d_{12}	18	LS_{12}	9	$\text{In}\nu(I)_{12}$	0	H_{12}	8
d_{13}	22	LS_{13}	15	$\text{In}\nu(I)_{13}$	3	H_{13}	8
d_{14}	17	LS_{14}	17	$\text{In}\nu(I)_{14}$	2	H_{14}	10
d_{21}	14	LS_{21}	14	$\text{In}\nu(I)_{21}$	0	H_{21}	15
d_{22}	15	LS_{22}	11	$\text{In}\nu(I)_{22}$	0	H_{22}	12
d_{23}	26	LS_{23}	16	$\text{In}\nu(I)_{23}$	6	H_{23}	13
d_{24}	19	LS_{24}	13	$\text{In}\nu(I)_{24}$	0	H_{24}	17

Table 4. Manufacturers' parameters.

$\text{In}\nu(I)_{11}$	0	H_{11}	10	UC_{11}	10
$\text{In}\nu(I)_{12}$	2	H_{12}	12	UC_{12}	12
$\text{In}\nu(I)_{13}$	1	H_{13}	8	UC_{13}	8
$\text{In}\nu(I)_{21}$	1	H_{21}	13	UC_{21}	13
$\text{In}\nu(I)_{22}$	3	H_{22}	16	UC_{22}	16
$\text{In}\nu(I)_{23}$	0	H_{23}	17	UC_{23}	17

Table 5. Network (I) flow values.

Arc	$f_1(u,v)$	$f_2(u,v)$
$(m1,d1)$	13	18
$(m1,d3)$	0.4	5.4
$(m2,d2)$	16	15
$(m2,d3)$	17.6	13
$(m3,d1)$	1	16
$(m3,d3)$	13	0.6
$(d1,r1)$	0	6
$(d1,r2)$	0	8
$(d1,r3)$	14	20
$(d2,r1)$	7	8
$(d2,r2)$	9	7
$(d3,r2)$	9	0
$(d3,r3)$	6	0
$(d3,r4)$	16	19

Table 6. Network (II) flow values

Arc	$f_1(u,v)$	$f_2(u,v)$	$f_3(u,v)$
$(s1,m1)$	193	190	165
$(s1,m2)$	171	210	530
$(s2,m1)$	71.1	4	370
$(s2,m2)$	339	92.5	445
$(s2,m3)$	236.9	155.5	465

Table 7. Quantity of products.

QP_{11}	13.7
QP_{12}	31.6
QP_{13}	13
QP_{21}	22.4
QP_{22}	25
QP_{23}	16.9

makes sense because the networks' capacities are set such that the supply chain is capable of fulfilling all the customer demands. Moreover, there is no remained inventory after the planning period (i.e. $\text{Inv}(II)_{ir}$ and $\text{Inv}(II)_{im}$ have become zero).

In the lack of sufficient capacity, lost sale plays a role in total costs. In the aforementioned example if $c_3(s2, m2) = 0$, solution of the model results in 78.2 lost sale cost.

RESULTS

To evaluate the solution the locally optimum behavior by the members is considered as a comparison benchmark to determine usefulness of the proposed mechanism (see Appendix). Consider performance ratio as an indicator for this purpose:

$$\text{Performance Ratio} = \frac{\text{Total Cost without SCO}}{\text{Total Cost with SCO}}. \quad (21)$$

First we want to determine how performance ratio is dependant to variety of flows in the supply chain. $k + p$ is a metric to represent variety of flows in the supply chain. Simulated supply chain contains 70 suppliers, 10 manufacturers, 20 distributors and 50 retailers. Values for k and p are set randomly such that $k < p$ and their summation equals the intended value. during simulation. Figure 1 depicts simulation results from ILOG CPLEX 11.0 standard mathematical programming solver.

The average value for performance ratio is 1.354 or 26.14% reduction in total costs.

In order to determine effectiveness of the mechanism in different sizes of the supply chain, the problem is simulated considering a supply chain providing 20 different products from 150 various components. Network size can be expressed as the total number of supply chain members:

$$\text{Network Size} = S + M + D + R. \quad (22)$$

During the simulation random values for number of members are set such that $D \geq M$, $R \geq D$ and $S \geq M$. Figure 2 illustrates how performance ratio varies with network size.

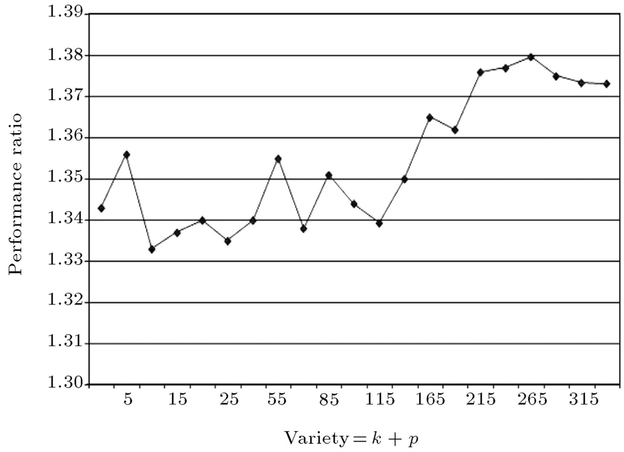

Figure 1. Dependency of performance ratio to the variety of flows.

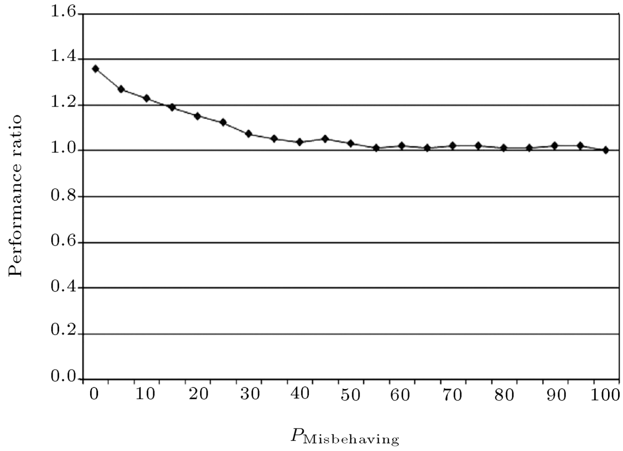

Figure 3. Dependency of performance ratio to the percentage of misbehaving members.

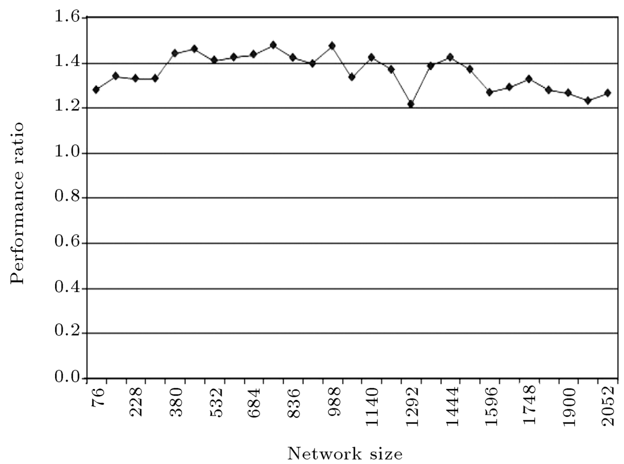

Figure 2. Dependency of performance ratio to the network size.

Considering the average value for performance ratio is 1.358, it can be concluded that network size does not affect the performance ratio.

Finally, we want to investigate how the ratio (percentage) of misbehaving members which do not behave in a locally optimum style affect the performance ratio. Consider a supply chain with 70 suppliers, 10 manufacturers, 20 distributers and 50 retailers in which 20 different products from 150 various components flow. Note that the number of misbehaving members in each stage of the supply chain is appropriate to relative number of the stage's members comparing with the whole number of supply chain members. Figure 3 depicts the effect of the percentage of misbehaving members, i.e. $P_{\text{Misbehaving}}$, on the performance ratio.

According to simulation results, performance ratio deteriorates when the percentage of misbehaving members increase. With $P_{\text{Misbehaving}} = 10\%$ the performance ratio is 1.23. When $P_{\text{Misbehaving}} = 30\%$ the performance ratio falls to 1.07. A stable performance ratio about 1.03 is observed when $P_{\text{Misbehaving}} \geq 40\%$. Thus, higher percentage of misbehaving members leads to lower effectiveness of the proposed solution.

According to the aforementioned simulation results, the proposed solution responds efficiently in different situations. The CSO could be implemented using practical IT-based architectures to be exploited in real circumstances.

CONCLUSION

This paper proposes a software-based coordination mechanism for a multi-stage and multi-product supply chain. Each type of product is produced from a set of basic components or raw materials. The supply chain is modeled as a flow network considering operation capacities and costs for all members of the supply chain. By developing and solving a set of linear programming models, members are able to make decisions which result in overall minimum cost for the entire supply chain. Existing literature, assuming a limited number of members in the supply chain and only a single product, did not reflect the real world supply chains.

To achieve the above goal, a central entity named Corporate Supply Optimizer (CSO) receives information about relationships, capacities, costs and some operational parameters from members of the supply chain at the beginning of the planning period. The CSO then forms and solves a linear programming model and sends optimal order quantities to the members.

It is possible that supply chain members may place orders and get products (or components) more than specified optimum flow values determined by the CSO so that they hold inventory at the end of the planning period. Maintaining safety stock or forecasting capacity deterioration can explain such behavior. At all events, the CSO gets the information about the behavior of the members (directly from themselves or indirectly inferred from the whole supply chain received information) and might punish selfish members (i.e. members that tend to act based on their locally-optimum preference rather than the solution provided by the CSO), with reduction of their order fulfillment priority factor in the upcoming periods.

Further research can focus on several issues. Developing an exact reputation mechanism to detect non-cooperative members and consequently exact determination of priority factor in the model, exploration of multi-period problem, extending the functionality of the CSO in areas such that strategic planning, investigating stochastic models are proposed as future works.

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APPENDIX

Description of Locally Optimum Behavior

As mentioned before, selfish supply chain members place orders based on their locally optimum utility rather than complying with the CSO's globally optimum solution. If this is the case, each selfish member tries to find available sources with the lowest cost until its demand is fulfilled. As mentioned before, the case of locally optimum behavior is used as a benchmark for comparison and evaluating improvements using the CSO.

Consider modeling of supply chain using the concept of flow networks. Assume v is a destination member which wants to receive flow (product, component or raw materials) from a source node t where an arc (t, v) exists in the corresponding graph. Consider S as an array of information about all potential sources for v to fulfill its demand, such that S_t (tth element of the array) is an ordered pair $(o(t, v), c(t, v))$. Remember from previous sections that $o(t, v)$ indicates cost of flow in the arc (t, v), and $c(t, v)$ shows capacity of this arc. In fact, the member v forms array S using the information received from its potential source nodes. The following pseudo-code describes the selfish behavior of the destination member v:

UnfulfilledDemand = Demand

Sort array S ascendingly based on$o(t, v)$

While (UnfulfilledDemand> 0)

$\{f(t, v) = \min$ (UnfulfilledDemand, $c(t, v)$)

UnfulfilledDemand=UnfulfilledDemand $- f(t, v)$

$t = t + 1$ (i.e. going to the next potential source with the lowest $\cos t$)}.

Note that since the selfish behavior described in the pseudo code does not depend on the supply chain stage at which the selfish member is located, i or j indices can be associated with $c(t, v)$, $o(t, v)$, and $f(t, v)$ based on the type of corresponding flow (i.e. i index for flows in Network (I) and j index for flows in Network (II)).

BIOGRAPHIES

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