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Cost and inventory benefits of cooperation in multi-period and multi-product supply

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Abstract Cooperation among supply chain members, both horizontally and vertically, has become the norm in practice. Unlike traditional supply chains with members competing to reduce their individual costs, the overall cost of the entire supply chain is minimized in a cooperative supply chain. The savings from cooperation may be shared among the members, while a lower average cost and a lower cost variation is materialized for individual members. The problem is formulated as an integrated flow network and expanded to multi-period and multi-product, with the possibility of holding inventories in a multi-stage, multi-member cooperative supply chain. Simulation results indicate an approximately 26% reduction in total costs of the supply chain, utilizing this formulation over competitive setups. In a multi-period chain, members may hold an inventory or use an inventory policy. As the holding costs increase, the problem decomposes into a single period (just-in-time) again. The disturbing bullwhip effect disappears in cooperative supply chains.

1. Introduction

"A supply chain is a system of organizations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer", according to Wikipedia [1]. The Council of Supply Chain Management Professionals [2] defines "Supply Chain Management encompassing the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities". Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers and customers. Thus supply chain management integrates supply and demand management within and across companies, and may share information, inventories and cost savings as well.

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The coordination and integration of key business activities undertaken by an enterprise, from the procurement of raw materials to the distribution of end products to the customers, are done in the supply chain planning process [3]. E-business simplifies communication between suppliers and customers. But many suppliers still find it challenging to provide a timely delivery of goods and services to their customers due to resource limitations and geographical distances [4]. Most supply chain members act locally, as they only have local visibility and incentive. Most real-time supplier management systems lack optimization engines or dynamic capabilities for re-assigning supply allocations [5].

Supply chain literature has developed in the past two decades. Little is currently known about ways to achieve control and cooperation in supply chain networks. Much academic literature focuses on control and cooperation in simple supply chains, with conclusions frequently based on results gathered from considering one upstream and one downstream company [6]. This research presents an integrated optimization model to include all aspects of cost and capacity for multi-period, multi-stage and multi-products, and also include customer priority or product inventory and shortage. The overall optimization problem is not yet addressed in the literature for a cooperative or corporate supply chain [7]. Such optimization models have not been implemented in real cases, or used as an integrated real-time mechanism with advances in electronic procurement.

The main idea of the proposed mechanism in this paper is to formulate the cooperative supply chain as a flow network, and then solve an integrated linear programming model for the corresponding flow network. This model considers the general case of multi-member, multi-stage, multi-product and multi-period with the possibility of holding an inventory. A Cooperative Supply Optimizer System can actually be an electronic hub which gathers and processes necessary information on capacities and operation costs from supply chain members. It guides chain members in ordering decisions and providing a minimum overall cost for the entire supply chain. Without such a concept and mechanism, members make decisions on their order quantities based on their local and accessible information, resulting in the non-optimal performance of the entire supply chain and higher cost variances for individual members.

Information about member behaviour may be used to punish selfish members (i.e. members that tend to act based on their locally-optimum preference rather than the solution provided) with a reduction of their order fulfilment priority factor for future periods. The paper extends previous studies with limited scope to multiple-period, multiple-stage and multiple-product cooperative supply chains. Obviously, most real-world scenarios involve more intricate and complicated characteristics, such as the stochastic nature of demand or different inventory management systems. The proposed preliminary mechanism may be broadened and studied with the potential for more complex situations.

Organization of the paper is as follows. The next two sections review the literature on cooperative supply chains, limited to publications relevant to this research. Section four is devoted to the problem definition, including flow networks and the assumptions associated with the problem definition. The next section covers evaluation of the model, including assessment of its performance, bullwhip and just-in-time effects. The last section is the conclusion and an extensive reference section. Appendices provide formulation models. A simplified case example with numerical analysis is provided.

2. Cooperative supply chains

Two opposite models of supplier chains, cooperative and non-cooperative, have emerged from both practice and academic research [8]. The traditional, ''more common arm's length'', approach to supplier management is characterized by the buying firm's efforts to avoid dependence on the suppliers and to maximize bargaining power'' [9]. The metaphor of the firm as an ''island in a sea of market relationships'' [10] captures fully the distinctive feature of this standpoint. In contrast to the competitive/non-cooperative approach, many firms work closely with their suppliers as partners, developing and integrating them for the long-term. Various studies showed that such a strategy leads to better information sharing and, as a result, constantly improving quality, a product development cycle and a highly efficient governance mechanism that minimizes transaction costs [5,8,11].

With the spread of a cooperative perspective, the business world's view changed thoroughly, giving rise to a strategic network of interdependence firms pursuing convergent interests and deriving mutual benefits [12]. This alternative perspective, as a reaction to the competitive approach, partly spread out initially from Japanese JIT purchasing [13]. It emphasizes the empowerment of a collaborative network. Economic interest, keeping with current relationships rather than entering new ones, creates reputational concerns [14]. It keeps partners aligned to the norms of trustworthy behavior [15,16]. Zipkin [17] compared the competitive and cooperative inventory policies in a two-stage supply chain [18] to show that competition reduces overall efficiency.

Outsourcing has become a hot topic for many companies recently. Although each supplier is a distinct business, the clients persist in complete or high control over the timing and mix of their required supply. Many suppliers enter into partnership or alliance agreements, so that they can share the benefits of serving customers better in a particular market [19]. Such cooperation can result in lower overall costs shared by all business units [20]. Cooperation among members at various stages or, in other words among a network of buyers and sellers, is a major challenge in cooperative supply chains [21]. As the number of businesses related to the supply, manufacturing and distribution of products increases in practice, the cooperation issue becomes immensely complicated [6]. In real-world situations, most firms pay attention to optimizing separately their production and distribution planning decisions. But these local decisions limit possible improvement in overall decision effectiveness and efficiency.

Supply networks are known and widely publicized phenomena, especially in high-tech sectors, such as Microsoft or Genentech, which pursue their network strategies through strategic alliances or research and development joint ventures [22]. Multinational companies in steel, paper and automotive industries interact tightly with their suppliers, sub-suppliers, distributors and customers to develop new technologies or increase efficiency [23]. There are many examples of large firms from several sectors that rely strongly on networks for their rapid growth, such as Apple Computers, Benetton, Toyota, Corning and McDonald's [24]. Effective supplier management is regarded in Brazil, for example, as crucial to differentiate oneself from competitors in the long run [25].

Supply chain management includes contract management, information and revenue sharing, quantity-discounts, cooperative advertising, promotional rebate and franchising, quantity-price-discounts, and buy-back contracts [6,26–28]. Li and Wang [21] provided a survey of traditional cooperation mechanisms for supply networks taking an inventory control approach. Cachon [29] provided a study of coordination contracts to show the increase in the number of members in supply networks; transforming traditional contracts into inefficient cooperation mechanisms. Lee and Whang [30] described sales, inventory, demand forecast, order status and production schedules as different types of information sharing. They, as well as Cachon and Fisher [31], clearly show the significance of information sharing in a two-level supply chain. However, lack of information sharing aggravates the incurred costs in a supply chain with multiple members at several stages [32–34]. Managing and sharing business information includes Customer Relationship Management (CRM), Supplier Relationship Management (SRM), e-marketplaces and e-chains [4,35–38].

Dudek and Stadtler [39] studied a two-member supply chain. By defining members' mathematical operational model, they proposed a negotiation mechanism to reduce total costs. Chen et al. [40] proposed a flexible, negotiation-based, multi-agent system where new members can join in the supply chain or its current members may leave. Fox et al. [41] developed a high-level framework for supply chain functions, with the idea of encapsulating these functions in corresponding software agents. Consequently, Fox et al. [42] presented a general approach to supply chain management operations covering the planning and execution of actions with different types of software agent.

A significant question is that; if supply chain members do not trust each other completely, why should they accept sharing their own strategically important information? Sahin and Robinson [43] used a literature review in product flow and information sharing in supply chains, showing an advantage based on the degree of information sharing. Li [44] investigated the incentives for members in a two-level supply chain, with one manufacturer and several retailers sharing information horizontally. He concluded that voluntary information sharing is not rationally preferable, and examined conditions under which information can be traded, restricting unplanned shared information as much as possible.

Zarandi et al. [45] attempted to provide an agent-based architecture based on fuzzy logic to create a responsive and cooperative supply chain. Ding and Chen [46] considered using negotiations in the return policy to coordinate a three-stage supply chain, with a single member at each stage. Fink [47] proposed using a mediator software agent to conduct a bilateral negotiation process until both firms accept a contract. Lee et al. [32,33] developed a stochastic, periodic, order-up-to inventory model to manage a procedure for process localization in the supply chain. They proposed an approach to operation and delivery processes target market structures. Cachon and Lariviere [6] considered a two-stage supply chain, including a supplier and a retailer in which time is divided into an infinite number of discrete periods. Consumer demand at the retailer is stochastic, independent across periods, and stationary. The system's optimal solution minimizes the total average cost per period.

Cohen and Lee [48] developed an aggregate model integrating material control, production and distribution sub-models for establishing a requirement policy for materials in every factory in the supply chain production system. Barbarsoglu and Ozgur [49] developed a mixed-integer mathematical model with a centralized planning to address production and two-echelon distribution decisions simultaneously. A Lagrangean relaxation approach was used to decouple imbedded distribution and production sub-problems in solving the resultant large-scale problem.

Lee and Kim [50] extended the concept of Byrne and Bakir [51] to propose a hybrid approach combining analytical and simulation models to solve manufacturing-distribution planning problems involving multi-products and multi-periods in supply chains. Ozdamar and Yazgac [52] developed an integrated production–distribution model for operation of a multinational company in a central factory where products are distributed to geographically distant warehouses. A hierarchical planning approach was adopted to make use of medium range aggregate information with an optimal fleet size.

Gunnarsson and Rönnqvist [53] considered the integrated planning of production and distribution for a pulp company. Their solution is based on heuristics, with a one year planning period and several time periods. The work presented by Almansoori and Shah [54] was an attempt to design and operate a deterministic, steady-state hydrogen supply chain network, using a mathematical modelling approach. The model was developed to consider the availability of energy sources and their logistics and the variation of hydrogen demand over a long planning horizon leading to phased infrastructure development. The proposed model was formulated as mixed-integer linear programming.

Using linear programming techniques to formulate and analyze the various supply chain management problems has a long record in the literature. Inventory management and production–distribution planning problems use linear programming extensively [17,55–60]. Designing distribution networks [61–63], facility location allocation [64–66], the facility capacity allocation problem [67] and aggregate planning [4,68] may also use Linear Programming. Mixed Integer programming provides a more accurate description of different supply chain problems. But reaching fast and exact solutions to the problem might be a challenge [69].

3. Problem definition

A multiple period, multiple product, cooperative supply chain is considered, with multiple members, at four stages which are suppliers, manufacturers, distributors and retailers. Each product is manufactured from a number of basic components or raw materials ordered from the suppliers. A supplier has a limited capacity for providing each basic component. Each manufacturer may produce any product limited by its production and delivery capacity or decided by its strategy for each product. The distributors, within their capacities too, may provide products from the manufacturers to the retailers who represent a number of end customers. Forecast demand is available for the next several periods, depending on accessibility of information from the retailers for the next T periods.

The above definition removes three simplifying assumptions in the current supply chain literature, i.e. the limited number of members in supply chain stages, the limited number of planning periods and a single-product. The model assumes the prices for the components, and the products are constantly independent of the chain performance. They are derived from the overall competitive supply and demand and are not controlled significantly by individual members. The problem is thus concerned with minimizing total costs of providing products to customers, including any lost sales or excess capacity costs. The proposed formulation therefore aims to minimize total operational costs for the entire supply chain, including production, transportation, lost sales, inventory holding and excess capacity components. Such a supply chain is thus more competitive, by considering the overall cost to end-customers.

It is further assumed that the supplies received by the manufacturers are entirely used to produce the final products, without any waste. Initially, the retailers are provided with demand information for various product types at different periods. Members conversely decide on the quantities and sources of their orders. In practice, the distributors examine how to provide products from the manufacturers to the retailers to place orders. Therefore, distributors are considered as unpreventable intermediate nodes, and no excess inventory may remain with distributors at the end of planning periods. Contrary to distributors, holding of inventory by retailers and manufacturers is commonplace.

3.1. Flow networks

The fundamental concept used in the proposed mechanism is the flow network. A flow network is a directed graph in which each node can produce, consume or pass a flow. 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 node. A source node has outgoing arc(s) to produce the flow, and a sink node has only incoming arc(s) to consume the flow. Furthermore, a flow network may have several sources and sinks, rather than just one of each. Several studies [70,71] provide comprehensive surveys of algorithms for solving flow network problems.

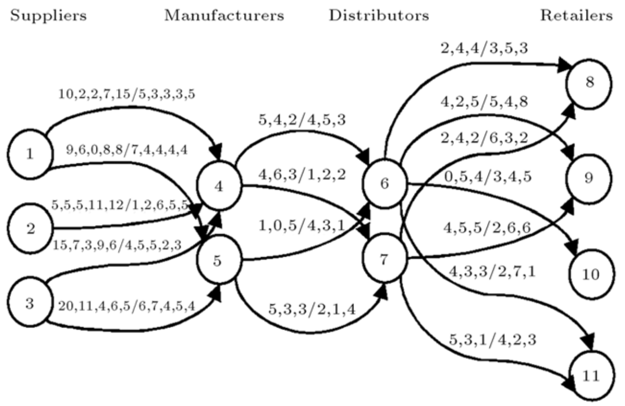

Figure 1: Example of a supply chain with 3-commodities.

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 $(u, v) \notin E$, and it is assumed that $c(u, v) = 0$. Two nodes are distinguished in a typical flow network: source node, s, and sink node, t. Every arc lies on some path from the source to the sink. $f(u, v)$, which can be positive, zero or negative is the flow from node, u, to node, v. A flow is a real-valued function, $f : V \times V \to \mathbf{R}$, that satisfies the following properties:

(a) Capacity constraint: for all $u, v \in V$, require $f(u, v) \leq c(u, v)$;
(b) Skew symmetry: for all $u, v \in V$, require $f(u, v) = -f(v, u)$;
(c) Flow conservation: for all $u \in V - \{s, t\}$, require $\sum_{v \in V} f(u, v) = 0$.

For multiple source or sink nodes, the source node or sink node may be replaced with a set of source nodes or a set of sink nodes in the definition [71]. Associated with each commodity is a demand, shipped through the network. The multi-commodity flow problem covers the distribution of different commodities from their respective sources to their sinks through a common network, so that total flow going through each edge does not exceed its capacity. The mechanism searches for a feasible multi-commodity flow solution, i.e. a way of shipping the commodities that satisfies the demands within the capacity constraints. This problem is solved using either existing exact algorithms or approximation heuristics [72,73].

3.2. A simple illustration

A numerical example for a simple single period case is provided below to illustrate the proposed mechanism. Consider a supply chain consisting of 3 suppliers, 2 manufacturers, 2 distributors and 4 retailers as shown in Figure 1. The supply chain provides 3 types of product to the customers. It is assumed that Distributor 7, for example, does not supply to Retailer 10. The products are made of 5 basic components. The bills of materials for the products are:

$$A_1 = \{1, 0, 1, 0, 2\},$$
$$A_2 = \{0, 1, 0, 0, 1\},$$
$$A_3 = \{3, 1, 0, 2, 0\}.$$

In Figure 1, capacities and costs are shown on the arcs. Numbers before/on the arcs are capacities. Numbers after/are costs for different types of product or basic components. Demand information for Retailers 8, 9, 10 and 11 is, as follows:

Table 1: Optimal flows of products.

(u, v)	$f_1(u, v)$	$f_2(u, v)$	$f_3(u, v)$
(4, 6)	3	0	2
(4, 7)	4	3	3
(5, 6)	1	0	5
(5, 7)	0	3	1
(6, 8)	2	0	1
(6, 9)	0	0	0
(6, 10)	0	0	4
(6, 11)	2	0	2
(7, 8)	1	1	1
(7, 9)	2	5	3
(7, 11)	1	0	0

Table 2: Optimal flows of basic components.

(u, v)	$f_1(u, v)$	$f_2(u, v)$	$f_3(u, v)$	$f_4(u, v)$	$f_5(u, v)$
(1, 4)	2	2	2	1	4
(1, 5)	0	6	0	8	6
(2, 4)	5	5	2	0	12
(3, 4)	15	1	3	9	6
(3, 5)	19	3	1	4	5

$$d_{18} = 3, \quad d_{28} = 1, \quad d_{38} = 2,$$
$$d_{19} = 2, \quad d_{29} = 5, \quad d_{39} = 3,$$
$$d_{110} = 0, \quad d_{210} = 0, \quad d_{310} = 4,$$
$$d_{111} = 3, \quad d_{211} = 0, \quad d_{311} = 2.$$

d_{311} demand for Product 3 at Retailer 11. A unit of lost sales, due to shortage of inventory, is assumed to impose 25 units of cost on the supply chain.

Using the proposed coordination mechanism, Network I consisting of 66 decision variables and 87 constraints, and Network II with 25 decision variables and 40 constraints are formed. Note that these are relatively small Linear Programming models. Optimal values of decision variables are shown in Tables 1 and 2. The total cost of the model, with member cooperation, is obtained at 659. This is compared to a cooperative case where each retailer tries to obtain the least costly shipment at 782, which yields 27.2% reduction in overall supply chain cost for this small example.

3.3. General formulation

The cooperative, multi-period, multi-product, supply chain problem is formulated with four stages, as a flow network with a linear program format (a detailed formulation is shown in Appendix A). The model is described by Expressions (A.1)–(A.13). Appendix A shows the objective function, showing the total operation costs of the supply chain. It 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 3rd term represents the cost of lost sales. The 4th and 5th parentheses represent the holding cost for the remaining inventory from the previous period. Costs incurred in the supply chain from the excess capacity in Network I and Network II are shown by the two subsequent terms. Finally, the 8th term stands for the production costs.

There are 12 constraint sets denoted by numbers (2) to (13) in the model. First, three constraint sets (2, 3, 4) are equivalent to the capacity constraint, skew symmetry and flow conservation properties of flow networks (for Network I), respectively. Constraint 5 guarantees satisfying demand for the retailers. Constraint 6 is equivalent to the capacity constraint of flow networks (for Network II). Constraint 7 guarantees satisfying demand from the manufacturers for basic components to produce sufficient products. Constraint 8 assures sufficient production by the manufacturers. Constraint 9 assures the non-negativity of lost sales. Finally, Constraints 10, 11, 12 and 13 are non-negativity constraints on the values of outflow and quantities of product.

Specific elements used in the model are described as follows: Inventory is allowed to be carried from one period to the next, incurring a holding cost for each particular item, depending on the combination of demands, capacities and costs. In a later section, analyzing the bullwhip effects of inventory at various stages, an inventory policy is set to include carrying the current month's consumption to the next period. The rationale for such a policy may be to deal with possible changes in future demand. The holding cost may include the usual interest and opportunity costs, storage and insurance expenses, in addition to any possible damage or obsolescence cost, which are product and location specific.

As this model formulates the cost function, assuming that income and price are constant and given, any incremental costs resulting from deviations from maximum fixed values should be considered and added to the model. Excess capacity costs are therefore considered, as expenses are incurred to insure maximum capacity, regardless of its actual usage. The cost of the capacity used is built into production costs, while excess capacity counts for expenses incurred anyway from the unutilized capacity. Lost sales costs similarly count for any unmet demand due to capacity or cost limitations. Again, lost sales costs are product and stage dependent. They may cover the value of expected opportunity or net profit.

Another coefficient is introduced in the model as the "order fulfilment priority" assigned to the rth retailer and the ith type of product in period t ($0 < PR_{ir} \leq 1$). This is defined as the portion of a retailer's demand to be met for a product type. It is set proportional to the level of cooperation by the retailer. Originally, it is set to 1.0 for all retailers, unless using total capacities would not produce a feasible solution to meet total demands. If that is the case, the order fulfilment priorities are reduced proportionally or by some priority rules, and the model is solved again. In the general model, this urges the retailers to avoid selfish behaviour in pursuing their local individual solutions and abide by the global supply chain. This allows the manufacturers to forgo profit temporarily to urge cooperation in the long term.

If supply chain members choose order quantities according to the timed 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 keep safety stock due to cost or capacity considerations. Therefore, Inv I_{irt} and Inv I_{imt} are not necessarily zero at the beginning of the planning periods. Please note that for the sake of presentation simplicity, the order and production lead-times are not considered or set to zero. However, with small changes in the general formulation, a positive but deterministic lead-time may be considered at each stage for each basic component or product type.

Additional constraints may specify the inventory policy, which are not all included in the paper but are used in the analysis. The assumption for the deterministic nature of demand may seem a limitation in real cases. However, the solution may be used as a base, and some safety inventory may make up for the variation in demand. The model is a linear programming model, although its number of variables and constraints may be large. Existing polynomial-time algorithms, such as Karmarkar's algorithm [74], can be used to solve it efficiently. Upon solving the model and informing the supply chain members of their respective flow values, they are able to place orders accordingly for an optimal situation for the entire supply chain.

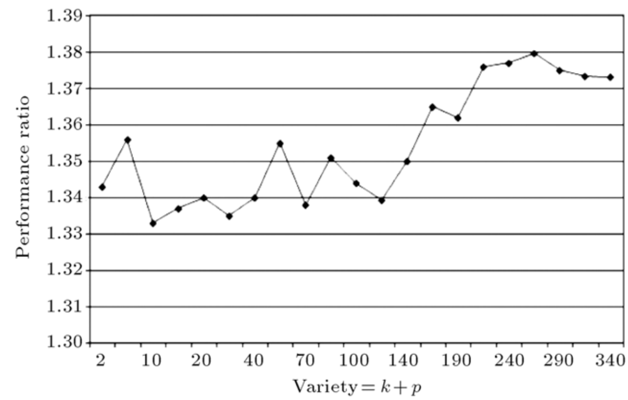

Figure 2: Performance ratio as a function of variety.

4. Evaluation

A simulation program is developed and used where results show how the proposed solution would perform and be useful in different situations. To evaluate the performance of the solution, locally optimum behavior by individual members is considered, as a benchmark comparison, to determine the usefulness of the proposed mechanism (Appendix A). Consider performance ratio I as an indicator for this purpose:

$$\text{performance ratio I} = \frac{\text{total cost without CSO}}{\text{total cost with CSO}}. \tag{1}$$

It is also determined how the performance ratio is dependent on the variety of flows in the supply chain. $k + p$ is a metric to represent the variety of flows in the supply chain. A sample 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. A planning period of one year, or twelve monthly periods, is considered during the simulation. Figure 2 depicts simulation results from the ILOG CPLEX 11.0 standard mathematical programming solver.

The average value for the performance ratio is 1.354, or 26.14% reduction in total costs. Its performance ratio is always higher than 1.332, and its increase is the variety in supply chain increases. Therefore, the proposed model performs better and is more valuable in cases of high variety supply chains.

In order to determine the 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.

$$\text{Network Size} = S + M + D + R. \tag{2}$$

During the simulation, random values for the number of members are set, such that $D \geq M$, $R \geq D$ and $S \geq M$. Figure 3 illustrates how performance ratio varies with 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.

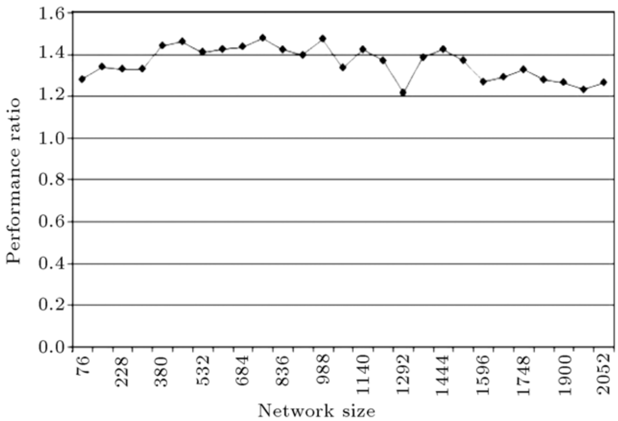

Figure 3: Performance ratio as a function of network size.

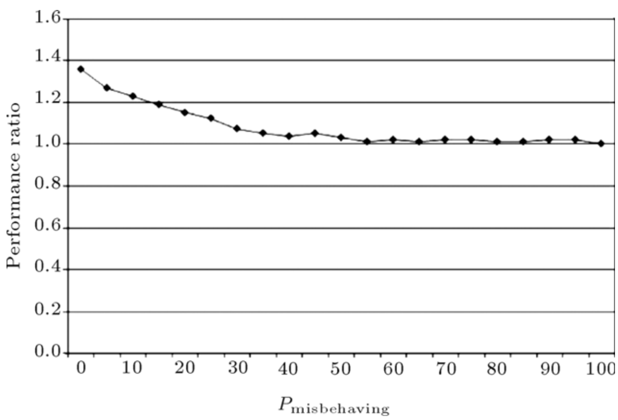

Figure 4: Performance ratio as a function of percentage misbehaving members.

Further, we investigate how the ratio (percentage) of misbehaving members (those that do not behave in a locally optimum style) affects the performance ratio. Consider a supply chain with 70 suppliers, 10 manufacturers, 20 distributors and 50 retailers in which 20 different products from 150 various components flow.

Note that the number of misbehaving members at each stage of the supply chain is appropriate to the relative number of stage members, compared with the whole number of supply chain members. Figure 4 depicts the effect of the percentage of misbehaving members, i.e. $P_{\text{Misbehaving}}$, on the performance ratio.

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

4.1. Just-in-time supply chain

The concept of just-in-time purchasing, originally publicized by the success of the Toyota Corporation in Japan, and later accepted by corporations universally, requires that requirements are ordered and delivered each period to match the exact utilization of materials and products [13]. In fact, inventory is considered evil and wasteful in the just-in-time philosophy, due to the large sum of all holding costs. Under such a system, only current requirements are produced and no inventory is held. At this point, it would be insightful to evaluate the significance of the number of planning periods used in finding the supply chain solution. Obviously, a global multi-period optimization is better in total costs than the sum of sub-optimum single-period solutions. For an example here, a small sample with three periods is used. Hence, consider performance ratio II, based on the following definition:

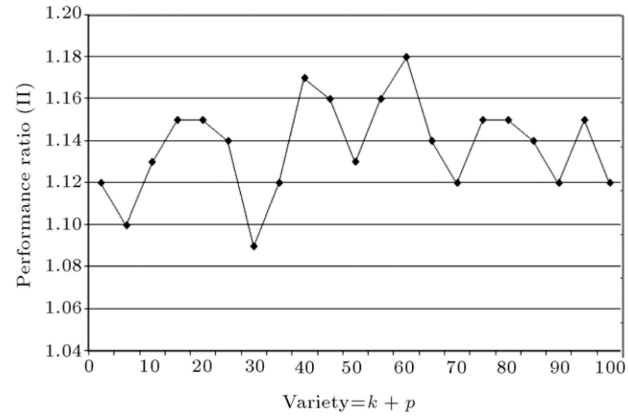

Figure 5: Impact of number of planning periods.

$$\text{performance ratio II} = \frac{\text{total cost with CSO when } T = 1}{\text{total cost with CSO } T = 3}. \quad (3)$$

In this example, the same parameters and supply chain setup as above are used in the simulation. As expected and also depicted by the graph in Figure 5, a three-month planning horizon is more cost effective in comparison to a single-month. It varies again as the variety in the supply chain increases. In this example, the average value of the performance ratio is 1.138, or 12.13% reduction in total costs.

As the number of periods in the planning horizon increases, the performance ratio also increases. However, the rate of increase diminishes rapidly. For the above example, if the number of periods increases from 3 to 6, the average performance ratio in the simulation increases from 1.138 to 1.174. Therefore, periods beyond the first few are insignificant, even though the inventory is to be held.

The Just-In-Time (JIT) approach implies a lack of necessity to hold inventory. It however requires accurate planning and supply mechanisms [13]. In the proposed model, supply chain members may hold inventory as available information about future costs of the supply chain may indicate buying and holding some items, which is more cost effective than buying the items at a future period when they are needed. However, a higher holding cost may cancel out the preference to hold inventory.

To determine the impact of holding costs, the supply chain is simulated at different levels of total inventory costs, while all other parameters of the model are fixed. To demonstrate the JIT concept, the holding cost parameters of the supply chain are set, so that no inventory is held. In other words, supply chain members exclusively purchase components/products that they need in the current period. It can be concluded from simulation results illustrated in Figure 6 that increasing holding costs results in a lower performance ratio II due to the impact of higher inventory costs, as supply chain members would opt to purchase their current needs and hold fewer inventories. In fact, the point of no inventory (JIT) is reached quickly, when the multiple components of holding costs commonly add up.

Table 3: Fluctuations of production levels along supply chain for small changes in demand [75].

Period	Supplier		Manufacturer		Distributor		Retailer		Demand
	Flow	Stock	Flow	Stock	Flow	Stock	Flow	Stock	
1	100	100 100	100	100 100	100	100 100	100	100 100	100
2	20	100 60	60	100 80	80	100 90	90	100 95	95
3	180	60 120	120	80 100	100	90 95	95	95 95	95
4	60	120 90	90	100 95	95	95 95	95	95 95	95
5	100	90 95	95	95 95	95	95 95	95	95 95	95
6	95	95 95	95	95 95	95	95 95	95	95 95	95

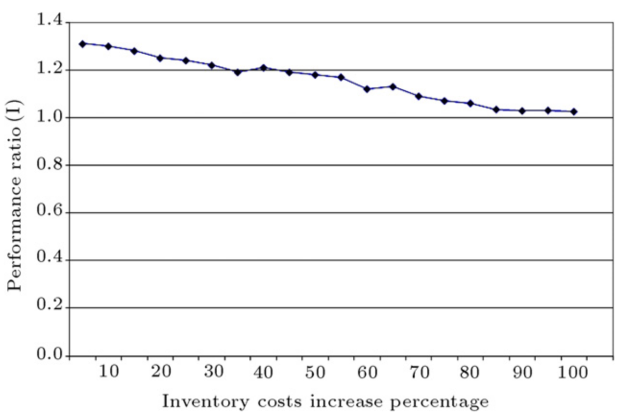

Figure 6: Performance ratio II as a function of increase in the inventory costs.

However, from examining the detailed results, further increase in holding costs will actually change the problem back into independent single period problems, as members opt to secure only what they need for the current period. It will in fact occur when the cost of holding inventory exceeds the difference of purchasing another cooperative member at that same stage. This is another indication that lengthy forecasts are not needed in cooperative supply chains, and the just-in-time system will prevail.

4.2. Bullwhip effect

Supply chains are often referred to as a pipeline of products, which is somewhat misleading. Pipelines are supposed to carry liquid at a reasonably ordered and constant rate, while supply chains have their own dynamic behaviour patterns that tend to distort the smooth flow of information up the chain and the product moving down the chain [75]. The flow at lower levels of the supply chain may be turbulent, even when demand at the end of the chain is relatively stable. Small changes in one part of the chain can cause seemingly erratic behaviour in other parts. A phenomenon that is now well known as "supply chain amplification" or "the bullwhip effect" suggests that the variability of orders increases as they move up the supply chain from retailer to wholesaler to manufacturer to supplier [32,33,76]. The first academic description of the bullwhip phenomenon is usually ascribed to Forrester [77] who explained it as a lack of information looping between the supply chain components, which are difficult to deal with using managerial intuition.

In a supply chain, although consumer sales do not seem to vary much, there is pronounced variability in the retailer orders to the wholesaler. Furthermore, the wholesaler order quantities to the manufacturer, as well as the manufacturer orders to the supplier, vary even more in time [76]. This effect is a problem of cooperation, consisting of an amplification of demand variability in the supply chain. Thus suppliers receive more variable and unpredictable orders than retailers [78]. The semiconductor equipment industry is, for example, more volatile than the personal computer industry [79]. Multi-echelon supply chains do have an "uncoupling" effect on the operations they connect, with some advantages for each individual operation's efficiency. Unfortunately, they introduce some "elasticity" into the chain as well, which often dramatically limits the effectiveness of the chain as a whole [75].

To demonstrate the bullwhip effect, a simple supply chain example with one product in four stages is used in Table 3. Demand for the final product starts at 100, but reduces by a small amount in period 2. All prior stages in the supply chain work on the principle of keeping in stock one period's demand. The column "stock" shows the starting inventory and the ending inventory for each period. A change of 5 in retailer demand has produced a change of 10 in distributor demand. Carrying the logic to the supplier's column, the flow has fluctuated by at least four times, as did the inventory levels.

The bullwhip effect may have a number of negative effects in a supply chain, causing significant inefficiencies. The bullwhip effect typically leads to excessive inventory investments throughout the supply chain, as the parties involved need to protect themselves against demand variations [80]. This problem leads to unnecessary inventory and decreased customer service levels due to backorders or to inventory shortages/lost sales [32,33]. By eliminating or controlling the bullwhip effect, it is possible to increase supply chain profitability [81]. Techniques to reduce the bullwhip effect, based on considering the supply chain as a dynamic system and the application of control techniques, have been summarized by Sarimveis et al. [82].

To quantify the bullwhip effect in a supply chain, a simple measure is used as the standard deviation of flow across multiple periods for a product at each stage. For the simple example in Table 1, the standard deviation for retailer demand in 6 periods comes to 2.04. The standard deviation for supplier flow in 6 periods is amplified to 53.08. The bullwhip effect has grown more than 26 times. Simulation results for non-cooperative supply chains, using the formulation in Appendix B, also shows that the average standard deviation for the supplier is more than 20 times that of the retailer for 6 periods.

In evaluating the deviations from the members of the optimum allocation, it was shown earlier that the deviation in competitive behaviour actually disappears in cooperative supply chains. A more critical criterion for evaluating the solution here is the effect of bullwhip phenomenon. For the integrated production–distribution solution, with cooperative information sharing among supply chain members, simulation results verified that the average standard deviation of retailer demand is closely reflected in supplier demand with only 4% error, using the formulation in Appendix A. It may, therefore, be argued that there is no bullwhip effect in the cooperative supply chains.

5. Conclusion

Traditionally, the members in a supply chain compete selfishly to minimize their own local costs. But the trend has changed towards cooperative supply chains where the members collaborate to minimize the overall cost for the entire supply chain. This paper studies cooperative supply chains versus competitive ones, to show that members gain a lower cost average and a lower cost and inventory variance over time. This is to assume that customer demand is known and the price is fixed for all suppliers in a general case of multi-member, multi-stage, multi-product and multi-period. Lost sales and inventory are allowed for manufacturers or retailers to lower the overall multi-period cost.

A flow network is developed and solved for an integrated supply chain framework, by using a set of linear programming models. Considering operation capacities and costs for all members in the supply chain, each type of product is produced from a set of basic components and sent to the distributors who in turn, ship to retailers to satisfy customer demands. Using the solution from this model, the members are able to make decisions that result in overall minimum cost for the entire supply chain. From simulation results, the proposed solution responds efficiently. It is also shown that only a small number of periods are practically effective in the multi-period solution. The problem becomes a single period (JIT), if inventory holding costs increase. The bullwhip effect of competitive supply chains, it is argued and exhibited, disappears, as members act in an integrated competitive fashion.

Appendix A. Problem formulation

Consider a directed network graph, $G = (V, E)$ where 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 or transportation from an organization to another for each period, depending on the nature of a relationship. A cost factor is then assigned to each arc, representing the costs of supply, production, distribution and transportation, for each unit of a product or a component. These costs are assigned to the first member in a relationship (i.e. organization u). The notation used in the model is described below:

- i: index indicating type of product, where $i = 1, 2, \ldots, k$;
- j: index indicating type of component (or raw material), where $j = 1, 2, \ldots, p$;
- t: index indicating time period, where $t = 1, 2, \ldots, T$;
- p: index for number of different types of components/materials;
- k: index for number of different of types of products;
- a_{ij}: quantity of component/raw material type j necessary to produce a unit of product type i.

$A_i = \{a_{i1}, a_{i2}, \ldots, a_{ip}\}$: set of components/raw materials to compose one unit of a product type i (for example $A_4 = \{0, 2, 1\}$ shows a unit of 4th type of products contains 2 units of component type 2 and 1 unit of component type 3. Component type 1 is not needed for this product).
$\text{Sset} = \{sp_s, \forall s = 1, 2, \ldots, S\}$: set of suppliers;
$\text{Mset} = \{\text{manu}_m, \forall m = 1, 2, \ldots, M\}$: set of manufacturers;
$\text{Dset} = \{\text{dist}_d, \forall d = 1, 2, \ldots, D\}$: set of distributors;
$\text{Rset} = \{\text{ret}_r, \forall r = 1, 2, \ldots, R\}$: set of retailers.

The original directed graph, G, representing the supply chain, may be 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, where are considered as sources and sinks of flow, while in Network II, components/raw materials flow where suppliers and manufacturers are to take these roles. However, a single integrated mathematical model which involves both the Network I and Network II is solved.

- Network I: a flow network with nodes consisting of Mset, Dset, Rset and arcs, which connect these;
- Network II: a flow network with nodes consisting of Sset, Mset and arcs, which connect these;
- V_1: set of vertices of Network I ($V_1 = \text{Mset} \cup \text{Dset} \cup \text{Rset}$);
- V_2: set of vertices of Network II ($V_2 = \text{Sset} \cup \text{Mset}$);
- V: set of vertices of directed graph G;
- d_{irt}: quantity of customer demand for product type i from retailer r in period t ($r = 1, 2, \ldots, R$);
- $c_{it}(u, v)$: capacity of arc (u, v) for flow of product i in period t (in Network I);
- $o_{it}(u, v)$: cost of flow of each unit of product i through arc (u, v) in period t (in Network I);
- $f_{it}(u, v)$: value of flow of product type i in arc (u, v) in period t (in Network I);
- $c_{jt}(u, v)$: capacity of arc (u, v) for flow of component/material type j in period t (in Network II);
- $o_{jt}(u, v)$: cost of flow of component/material type j via arc (u, v) in period t (in Network II);
- $f_{jt}(u, v)$: amount of flow of component/material type j via arc (u, v) in period t (in Network II);
- QP_{imt}: quantity of production of ith type of products in mth manufacturer in period t;
- $\text{Inv}\ I_{irt}$: inventory level for ith type of product at rth retailer at the beginning of the planning period t;

Inv I_{imt}: inventory level for ith type of product at mth manufacturer at beginning of planning period t;
H_{irt}: holding cost for rth retailer for a unit of ith type of product inventory at end of planning period t;
H_{imt}: holding cost for mth manufacturer for a unit of ith product inventory at end of planning period t;
LS_{irt}: lost sale cost for rth retailer and every unit of ith type of products in period t;
$\mathrm{ECC}_{it}(u, v)$: excess capacity cost corresponding to arc (u, v) in period $t (u, v \in V_1)$;
$\mathrm{ECC}_{jt}(u, v)$: excess capacity cost corresponding to arc (u, v) in period $t (u, v \in V_2)$;
UC_{imt}: production cost for each unit of ith type of product by mth manufacturer in period t;
PR_{irt}: order fulfilment priority assigned to rth retailer and ith type of product in period $t (0 < PR_{ir} \leq 1)$;
z: objective function representing the total cost incurred by the supply chain.

Parameters $c_{it}(u, v)$, $c_{jt}(u, v)$, $o_{it}(u, v)$ and $o_{jt}(u, v)$, are given as input data for the planning horizon. $c_{it}(u, v)$ is interpreted as the maximum feasible capacity of organization u (i.e. distributing and transporting) for providing product i and delivering it to organization v with cost $o_{it}(u, v)$; $o_{it}(u, v)$ is the distribution/transportation cost. $c_{jt}(u, v)$ and $o_{jt}(u, v)$ have similar interpretations, replacing products with basic components/materials. d_{irt} is an input parameter to the model. LS_{irt}, H_{irt}, Inv I_{irt}, Inv I_{imt}, $\mathrm{ECC}_{it}(u, v)$, $\mathrm{ECC}_{jt}(u, v)$ and UC_{imt} are also predefined parameters as inputs to the model. These parameters may be available from previous period data.

Parameters PR_{irt} are initially assigned value one. If there is no feasible solution for the model, it is reduced for some retailers with less cooperative backgrounds and it solves the model again. Application of PR_{irt} and other parameters are clarified further in the next section. Finally, $f_{it}(u, v)$, $f_{jt}(u, v)$ and QP_{imt} are decision variables. The proposed model for the whole supply chain is as follows:

$$\begin{aligned}\min z = & \left(\sum_{u,v\in V_1}\sum_{i=1}^{k}\sum_{t=1}^{T} o_{it}(u, v) f_{it}(u, v)\right) \\ & + \left(\sum_{u,v\in V_2}\sum_{j=1}^{p}\sum_{t=1}^{T} o_{jt}(u, v) f_{jt}(u, v)\right) \\ & + \left(\sum_{r=1}^{R}\sum_{i=1}^{k}\sum_{t=1}^{T}\left(\left(d_{irt} - \mathrm{Inv}\, I_{irt} \right.\right.\right. \\ & \left.\left.\left. - \left(\sum_{u\in V_1} f_{it}(u, \mathrm{ret}_r)\right)\right) LS_{irt}\right)\right) \\ & + \left(\left(\sum_{r=1}^{R}\sum_{i=1}^{k}\sum_{t=1}^{T}(\mathrm{Inv}\, I_{irt} H_{irt})\right)\right) \\ & + \left(\sum_{m=1}^{M}\sum_{i=1}^{k}\sum_{t=1}^{T}(\mathrm{Inv}\, I_{imt} H_{imt})\right) \\ & + \left(\sum_{u,v\in V_1}\sum_{t=1}^{T}\left(\sum_{i=1}^{k}(c_{it}(u, v) \right.\right. \\ & \left.\left. - f_{it}(u, v)) ECC_{it}(u, v)\right)\right) \\ & + \left(\sum_{u,v\in V_2}\sum_{t=1}^{T}\left(\sum_{j=1}^{p}(c_{jt}(u, v) \right.\right. \\ & \left.\left. - f_{jt}(u, v)) ECC_{jt}(u, v)\right)\right) \\ & + \left(\sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{k} QP_{imt} UC_{imt}\right), \end{aligned} \tag{A.1}$$

subject to:

$$f_{it}(u, v) \leq c_{it}(u, v), \quad \forall i = 1, 2, \ldots, k, \quad \forall u, v \in V_1,\ \forall t = 1, 2, \ldots, T; \tag{A.2}$$

$$f_{it}(u, v) = -f_{it}(v, u), \quad \forall i = 1, 2, \ldots, k, \quad \forall u, v \in V_1,\ \forall t = 1, 2, \ldots, T; \tag{A.3}$$

$$\sum_{v\in V_1} f_{it}(u, v) = 0, \quad \forall i = 1, 2, \ldots, k, \quad \forall u \in \mathrm{Dset},\ \forall t = 1, 2, \ldots, T; \tag{A.4}$$

$$\sum_{u\in V_1} f_{it}(u, \mathrm{ret}_r) \geq (d_{irt} - \mathrm{Inv}\, I_{irt}) PR_{irt}, \quad \forall i = 1, 2, \ldots, k, \quad \forall r = 1, 2, \ldots, R,\ \forall t = 1, 2, \ldots, T; \tag{A.5}$$

$$f_{jt}(u, v) \leq c_{jt}(u, v), \quad \forall j = 1, 2, \ldots, p, \quad \forall u, v \in V_2,\ \forall t = 1, 2, \ldots, T; \tag{A.6}$$

$$\sum_{u\in V_2} f_{jt}(u, \mathrm{manu}_m) \geq \sum_{i=1}^{k}\left(a_{ij}\sum_{v\in V_1} f_{it}(\mathrm{manu}_m, v)\right), \quad \forall j = 1, 2, \ldots, p, \forall m = 1, 2, \ldots, M, \quad \forall t = 1, 2, \ldots, T; \tag{A.7}$$

$$QP_{imt} + \mathrm{Inv}\, I_{imt} \geq \sum_{v\in V_1} f_{it}(\mathrm{manu}_m, v), \quad \forall j = 1, 2, \ldots, p, \forall m = 1, 2, \ldots, M, \quad \forall t = 1, 2, \ldots, T; \tag{A.8}$$

$$\left(d_{irt} - \mathrm{Inv}\, I_{irt} - \sum_{d=1}^{D} f_{it}(\mathrm{dist}_d, \mathrm{ret}_r)\right) \geq 0, \quad \forall hi = 1, 2, \ldots, k, \forall r = 1, 2, \ldots, R, \quad \forall\, t = 1, 2, \ldots, T; \tag{A.9}$$

$$f_{jt}(sp_s, \mathrm{manu}_m) \geq 0, \quad \forall s = 1, 2, \ldots, S, \quad \forall m = 1, 2, \ldots, M, \forall\, j = 1, 2, \ldots, p, \quad \forall t = 1, 2, \ldots, T; \tag{A.10}$$

$$f_{it}(\mathrm{manu}_m, \mathrm{dist}_d) \geq 0, \quad \forall m = 1, 2, \ldots, M, \quad \forall d = 1, 2, \ldots, D, \forall i = 1, 2, \ldots, k, \quad \forall t = 1, 2, \ldots, T; \tag{A.11}$$

$$f_{it}(\mathrm{dist}_d, \mathrm{ret}_r) \geq 0, \quad \forall d = 1, 2, \ldots, D, \quad \forall r = 1, 2, \ldots, R, \forall i = 1, 2, k, \quad \forall t = 1, 2, \ldots, T; \tag{A.12}$$

$$QP_{imt} \geq 0, \quad m = 1, 2, \ldots, M, \quad \forall i = 1, 2, \ldots, k,\ \forall t = 1, 2, \ldots, T. \tag{A.13}$$

Appendix B. Description of locally optimum behavior

As described above, selfish members in a traditional supply chain place orders based on their locally optimum utility, rather than complying with the globally optimum solution. Competitive supply chain members place orders based on their locally optimum utility, rather than complying with the globally optimum solution. If this is the case, each competitive member tries to find available sources with the lowest cost until their demand is fulfilled.

Consider the modeling of a supply chain utilizing 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 the 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 competitive 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 sources
with the lowest cost)
}.
```

Based on the pseudo-code above, each member of supply chain wanting to source its demands simply searches for available sources with the lowest costs. It is assumed that members of each stage do their respective sourcing sequentially, with a random order. For example, if there are three members, $R1$, $R2$ and $R3$, at the retailer stage, a random sequence can imply that first $R1$ do its sourcing, followed by $R2$, and finally $R3$ tries to find its sources based on what is available. Finally, the cost of the supply chain will be sum of the costs of all members of the supply chain.

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