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Logistics networks: A game theory application for solving the transshipment problem

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Abstract

As competition from emerging economies such as China and India puts pressure on global supply chains and as new constraints emerge, it presents opportunities for approaches such as game theory for solving the transshipment problem. In this paper we use the well-known Shapley value concept from cooperative game theory as an approach to solve the transshipment problem for maintaining stable conditions in the logistics network. A numerical example is presented to show the usefulness of this approach.

Keywords: Logistics network; Transshipment problem; Game theory; Shapley value

1. Introduction

As competition from emerging economies such as China and India puts pressure on global supply chains and as new constraint emerge, it presents opportunities for new approaches such as the game theory approach for

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solving the transshipment problem. The International Data Corporation reports that businesses worldwide spend $19 billion annually on information technology for supply chain management. Laseter and Oliver [12] suggest that the fundamental principles of SCM, i.e., set supply chain policies strategically, analyze trade-offs holistically, and employ cross-functional support systems; have not changed despite the expanded scope of SCM that now encompasses strategic sourcing, supplier involvement in product development, and customer fulfillment processes in addition to the movement of materials.

Recent real world examples of these principles illustrate how organizations have leveraged these ideas for competitive advantage. Dell Computer Corporation was able to overcome the strategic constraints of the bullwhip effect of increasing demand variation and forecast error in the upstream supply chain faced by the other PC manufacturers (who sold through the reseller channel) by building directly to the customer order and eliminating the retailer. Procter and Gamble (P&G) found that variability in its Pampers diaper business was self-imposed through the supply chain's pricing structures, incentives, and planning and ordering processes of its retailers such as Wal-Mart to P&G and P&G's suppliers. It sought to reduce the bull-whip effect by eliminating price promotions that cause demand variations, synchronizing planning cycles, sharing forecast and demand information across the supply chain and streamlining replenishment through programs such as vendor-managed inventory [11,3,1,13].

Federated planning (where the focus is on minimizing sub-optimization in the extended supply chain by collaborating to address the trade-offs and possibly even break constraints across the extended enterprise) and collaborative planning, forecasting, and replenishment have helped retailers such as Kroger Company coordinate with suppliers such as Unilever PLC (or Ahold USA Inc. and P&G) to synchronize promotional plans, eliminate redundant regional facilities and route shipments to minimize total cost and strategically reshape their distribution networks.

Process-oriented support systems that link across functions break the functional perspective at both the strategic and tactical levels. As Table A.1 illustrates, supply chain management has also shifted business focus over the last decade from cross-functional integration to cross-enterprise. The new questions are not about best practices or current practices but about next practices that may facilitate value creation and innovation.

2. Literature review

Supply chain management (SCM), which is also known as a logistics network [19] has been extensively studied in recent years. The logistical network consists of facilities and distribution options that perform the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers. SCM encompasses the management of all these activities associated with moving goods from raw materials through to the end user. SCM coordinates and integrates all of these activities into a seamless process. It embraces and links all of the partners in the chain. In addition to the key functional areas within the organization, these partners include vendors, carriers, third-party logistics companies, and information systems providers. The emphasis on improving supply chain management has become a major objective of the corporate world because it represents an opportunity to resolve monumental problems that face corporations and create a mismatch between supply and demand throughout their supply chains. Hence, successful SCM is the process of optimizing a company's internal practices, as well as the company's interaction with suppliers and customers, in order to bring products to market more efficiently. The real challenge for companies, then, is to make the right decision about where they want to position themselves in cost, functionality and delivery performance with respect to both their customers' requirements and their competitors' strategies and gambits.

The supply chain payoff can come in many forms. It might reduce transaction costs by eliminating unnecessary steps in moving product to market. It could enhance customer service through closer coordination among vendors upstream and carriers, distributors, and customers downstream. Or may be it increases market share with better customer service or lower costs.

The issues of cost, customer service, and quality have become significant objective in the development of logistic network strategies by many firms seeking competitive advantage. Beamon [2] presented an overview and evaluation of the performance measures used in supply chain models. These performance measures are summarized as high level of efficiency, high level of customer service, and the ability to respond to a changing environment—where either of these must coincide with the firm's strategic goals. Traditionally, such network flow problems have been studied extensively for analyzing systems. Beginning with the work of Ford and Fulkerson [6], a great number of algorithms have been directed for various versions of flow problems. Urban [18] modeled and analyzed supply contracts with periodical commitment, in which the order quantities are fixed and stationary, with limited flexibility to change the order quantity at a cost to the buyer. The problem was formulated as a mixed-integer linear program and as a network flow problem and the solution methodology provided for the general, stochastic problem with consideration given to specific demand distributions.

Dynamic flow problems originate in many applications, such as production-distribution systems, communication systems, and logistic transportation scheduling. The research approach on dynamic flow problems can be modeled either as networks with discrete time steps or as networks with time continuously.

The first approach uses the time-expanded networks to produce the theoretically or practically efficient algorithms. The second approach considers networks with time-varying capacities and costs, and focuses on proving the existence of optimal solutions. Fleischer and Tardos [5] related these two approaches by extending some of the polynomial time algorithms that work in the discrete-time model to solve the analogous continuous-time dynamic flow problems. Such problems include finding maximum dynamic flows and dynamic transshipments.

Spekman et al. [15] conducted empirical research on the concept of collaborative links in supply chain management, where by openly sharing information, the supply chain partners can facilitate their abilities to jointly meet the users' needs. Collaboration resources are directly relevant in communicating with counter parties and suppliers, and forecasting can trigger automated procurement functions. This is important for developing a supply chain sourcing strategy. However, having information about inventory position for sourcing is not enough. The most important issue to the logistics decision maker is how to distribute and transport inventory on time and under stable conditions. This includes supply chain planning information about resource availability and delivery requirements so routing efficiencies and load/carrier consolidations can be realized [16].

One tactic that can be put to use by an e-business is the operation of transshipment channels in the supply chain. Hong-Minh et al. [7] examined the use of "an emergency transshipment channel"—arguing that there are times in the real-world scenarios where "emergency transshipment may arise due to rush orders from customers." However, while these types of transshipments do occur in the logistics network, it can be argued that these emergencies can lead to added costs and creates an unstable condition in the logistics network. To control the activities in the logistics network and to make the best possible use of the system's resources, stable conditions must exist.

Other issues entail defining inventory policy in support of the strategy [20,21]. One inventory policy in practice is the use of lateral stock transshipments (or simply referred as transshipment) between locations at the same echelon level. This collaboration tactic, as explained by Tagaras [17], can reduce both the logistic network's total cost and increase customer service levels simultaneously. He further points out that this collaboration could be either after the observed demand (emergency lateral transshipment) or before the realization of demand (preventive lateral transshipment). The emergency lateral transshipment (ELT) allows for inventory to be transferred between stocking points as replenishment stock within the same echelon rather than a direct delivery from the prior echelon.

In this paper we use the well-known Shapley value concept from cooperative game theory as an approach to solve the transshipment problem. We believe that this fits well with the recent SCM business scenarios found in many industries. In particular, the use of information technology (IT) as an enabler for sharing information in order to improve supply chain performance among all of the players. This is further stimulated by the devolvement of e-commerce [22]. Examples of industries that have adopted and incorporated the use of IT and e-commerce for sharing information include Efficient Consumer Response (ECR) by the grocery industry [10], Quick Response (QR) by the textile industry [4], and Wal-Mart (a giant discount retailer).

3. Flow games

A flow is a way of sending objects from one place to another in a network. The objects that travel or flows through the network are called flow units or units. For example, flow units can be a commodity, finished goods, or information. The network is presented as a graph with a set V whose elements are called vertices, and a set A of pairs of vertices called edges. The graph is denoted $G = (V, A)$. In practice, we specify a flow as a directed graph. The vertices in a directed graph are commonly called nodes, and the directed edges are often called arcs. The nodes from which units enter through a network are called source nodes, and nodes to which the flow units are routed to are called sink nodes. Source nodes offer supply, which is represented by the number of units available at the node. Sink nodes usually have demand, which is represented by the number of units that must be routed to them.

Games, which are derived from a flow situation, are called flow games. A flow game in simple terms is a way of sending objects from one place to another, but in doing this, the cooperation of players should be used. Kalai and Zemel [8] define a flow game associated to a system of vertices V (often called nodes), which are connected by arcs a_{ij} where $i \neq j$. The double subscript ij denotes the arc from node i to node j. Each arc has a capacity c_{ij}. Furthermore, a flow is a vector $X = (x_{ij})$ in which the component x_{ij} represents the flow units moving from node i to node j. There are two nodes that distinguished from the others and are called the source (s) and the sink (t), which have already been previously defined. There is also a finite and non-empty set N as the player set. The arcs are considered as owned by the players. Moreover, a coalition owns the arcs of its members. The set of coalitions is denoted C. An n-person cooperation flow game is a function v from the set of coalitions to the set of real numbers. For a coalition $S \in C$, $v(S)$ is defined as the maximum flow value for coalition S and through the network of its members if it operates on its own. Which means that $v(S)$ stands for the maximum flow that S can sustain using its own portion of the network. The function v just defined is called the characteristic function of the game.

For a game (N, v), the core of v is defined by the set of all n-vectors X satisfying $\sum x_i v(S)$ for all $S \subset N$ and $\sum x_i = v(N)$. The constraints imposed on the Core

(N, v) ensure that no coalition would have an incentive to split from the grand coalition N, and do better on its own. Meaning that an allocation of $v(N)$ belongs to the Core (N, v) and is stable during the cooperation between the players.

4. Flow games example

Consider the logistics network consisting of one supplier (s), three distributors (a, b, c), and one retailer (t) presented in Fig. 1, in which one commodity is passing instantly from one source to a sink without any loss at the other nodes (a, b, c).

The numbers shown on the arcs are the capacities of these arcs. Suppose that three persons own the arcs (P_1, P_2, P_3). Precisely P_1 (the upper arcs) owns the arcs (s, a) and (a, t) with the capacities shown. P_2 (the middle arcs) owns the arcs (s, b), (a, b), (c, b), and (b, t) with the capacities shown. P_3 (the bottom arcs) owns the arcs (s, c) and (c, t) with the capacities shown. The values are obtained on the sub-networks associated with the capacities:

$$v(1) = 19, \quad v(2) = 37, \quad v(3) = 26,$$

$$v(12) = 64, \quad v(13) = 45, \quad v(23) = 73,$$

$$v(123) = 100.$$

Now that the game is known, a good question is how much of the 100 units will be allowed to be acted by each player. Suppose that the players (owners) would agree to solve this network problem by using the Shapley Value.

5. Shapley value of the game

For a game (N, v) the Shapley Value is the function $SH_i : (N, v) \rightarrow R^n$, which is given by

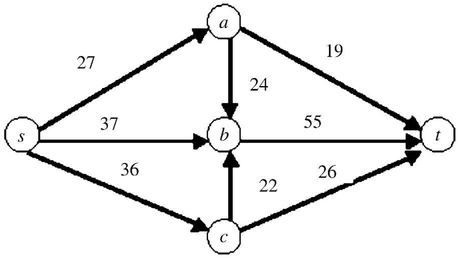

Fig. 1. Logistics Network.

$$\mathscr{S}\mathscr{H}_i : (\mathscr{N}, v) = \sum_{S \in S \subseteq N} \frac{(|S|-1)!(n-|S|)!}{n!}[v(S) - v(S - \{i\})]$$

for all $i \in N$, and V are the source.

From the example in the prior section, the Shapley Value is computed as

$$v(1) = 19, \quad v(2) = 37, \quad v(3) = 26,$$

$$v(12) = 64, \quad v(13) = 45, \quad v(23) = 73,$$

$$v(123) = 100.$$

For $i = 1$, the coalitions containing 1, are $S = \{1\}, \{12\}, \{13\}$, and $\{123\}$

$$S = \{1\};\ |S| = 1 \rightarrow (1-1)!(3-1)!/3! = 1/3,$$

$$S = \{12\}, \{13\};\ |S| = 2 \rightarrow (2-1)!(3-2)!/3! = 1/6,$$

$$S = \{123\};\ |S| = 3 \rightarrow (3-1)!(3-3)!/3! = 1/3.$$

Therefore,

$$\begin{aligned} SH_1 &: (N, v) \\ &= 1/3[v(1) - v(0)] + 1/6[v(12) - v(2)] + 1/6[v(13) - v(3)] \\ &\quad + 1/3[v(123) - v(23)] \\ &= 19/3 + 1/6[64 - 37] + 1/6[45 - 26] + 1/3[100 - 73] \\ &= 38/6 + 27/6 + 19/6 + 54/6 = 23. \end{aligned}$$

For $i = 2$, the coalitions are $S = \{2\},\{12\},\{23\}$, and $\{123\}$, and

$$\begin{aligned} SH_2 &: (N, v) \\ &= 1/3[v(2) - v(0)] + 1/6[v(12) - v(1)] + 1/6[v(23) - v(3)] \\ &\quad + 1/3[v(123) - v(13)] \\ &= 37/3 + 1/6[64 - 19] + 1/6[73 - 26] + 1/3[100 - 45] \\ &= 74/6 + 45/6 + 47/6 + 110/6 = 46. \end{aligned}$$

For $i = 3$, the coalitions are $S = \{3\},\{13\},\{23\}$, and $\{123\}$, and

$$\begin{aligned} SH_3 &: (N, v) \\ &= 1/3[v(3) - v(0)] + 1/6[v(13) - v(3)] + 1/6[v(23) - v(2)] \\ &\quad + 1/3[v(123) - v(12)] \\ &= 26/3 + 1/6[45 - 19] + 1/6[73 - 37] + 1/3[100 - 64] \\ &= 52/6 + 26/6 + 36/6 + 72/6 = 31. \end{aligned}$$

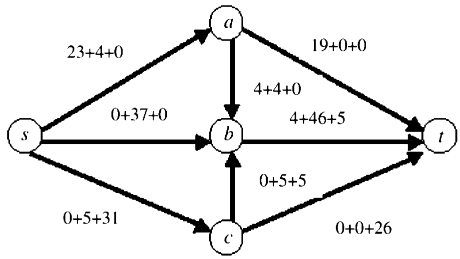

Fig. 2. Logistic Network with Shapley Value.

Hence the $x_1 + x_2 + x_3 = 23 + 46 + 31 = 100$ and the Shapley Value for the cooperative game is obtained, $SH:(N, v) = (23, 46, 31)$. The units, which belong to the three players, as they would travel through the network, are shown in Fig. 2, where on each arc the numbers written are the number of units allowable to each player.

Clearly, what happens is that the second player accepts four units from the first player on (a, b), (b, t) and five units from the third player on (c, b), (b, t). Finally, as Kalai and Zemel [8,9] point out, the core of the flow game is non-empty. We may check that the Shapley Value we computed is in the core.

We have:

$$SH_1(N, v) = 23 > 19 = v(1),$$

$$SH_2(N, v) = 46 > 37 = v(2),$$

$$SH_3(N, v) = 31 > 26 = v(3),$$

$$SH_1(N, v) + SH_2(N, v) = 69 > 64 = v(12),$$

$$SH_1(N, v) + SH_3(N, v) = 54 > 45 = v(13),$$

$$SH_2(N, v) + SH_3(N, v) = 77 > 73 = v(23),$$

$$SH_1(N, v) + SH_2(N, v) + SH_3(N, v) = 100 = v(123) = v(N).$$

Hence, we verified the appurtenance of the Shapley Value to the core, which means that this is a stable solution for the cooperation of the three players.

6. Extended application: supply chain intelligence

In the most recent years, e-commerce as been evolving from transactional to analytic, as well as from tactical to strategic. Supply Chain Intelligence (SCI) is a new category of enterprise software that promises to provide insight into strategic issues for an organization. SCI applications enable strategic decision making by collecting detailed information from every stage of the product life cycle, e.g., from material procurement to the manufacturing floor and into the hands of the end consumer where warranty periods may apply. SCI provides a broad business intelligence layer that complements enterprise resource planning (ERP) and supply chain management (SCM). It takes a very broad view of the extended supply chain utilizing atomic-level data, which is requisite to understanding total cost and long-term quality ramifications. For instance, the demand/supply chain-wide view of SCI can help an organization relate design decisions (such as which components from which suppliers are selected) with failure rates in the field (which, in turn, generate costs due to warranty obligations). SCI technologies provide answers to questions such as, "Do we need to add more distribution centers to reduce our total shipping costs for next year's projected sales by $15 million?" So, SCI applications may be run only once or a few times a year, in contrast to transaction systems, which are used all the time. Questions an enterprise seeks to answer with help from SCI systems—such as, where are we adding value to the product? What makes our customers buy our products and services? And what alternative sourcing and manufacturing options can we use to reduce our total cost of goods sold?—can have far-reaching consequences for the organization [14].

In addition, SCI can help explain production outages caused by quality or compatibility problems with specific materials from specific suppliers. These outages are well worth understanding for an organization, since increasing production yield even a small percentage through SCI can lead to millions of dollars in return, without investing in additional expensive manufacturing floor equipment in order to increase output. Table A.2 in the appendix differentiates SCM from SCI.

Supply chains, just like any other processes, must evolve, in order to reach the maximum efficiency. Enterprise Resource Planning (ERP) was the first step that industries implemented, and some are still in the process of implementing it, in order to search for this efficiency. Later, as the searches for efficiency in supply chains kept advancing, step number two was created, and called Supply Chain Management (SCM). This software complemented ERP, principally in the areas of demand and productions planning services. However, processes must evolve, and the search for efficiency turns into a search for excellence. This is how step number three has been created, and called Supply Chain Intelligence (SCI). Just as SCM complemented ERP, SCI complements both these prior steps, converting it in a much broader and specific software tool for the industry.

Many manufacturers are now implementing this new software, in the search for better performance, reduction of costs, and increment of yield. In fact, when SCI is compared with SCM, we realize that it is more strategic than tactical, and more analytical than transactional. It not only controls all the costs through efficiency, but also searches for revenue growth. It assists in the forecasting method anticipating any problems that might occur instead of just forecasting materials and productions, and it keeps and presents historic data instead of just presenting the daily information. The Shapley Value, once found, can be used to assign the dynamic flows for equilibrium. We can argue that this is critical for the transshipment problem, since this is a tactical method for maintaining stable conditions in the logistic and supply chain networks.

7. Conclusions and directions for future research

Logistics and supply chain managers in the e-commerce environment face many changes and challenges in their network environment. Performance measures such as high levels of efficiency, high levels of customer service, and the ability to respond to a changing environment are driving forces that continue to challenge these decision makers—when compared to just a decade ago. Managing these logistic and supply chain networks involve more than developing a sourcing strategy. It was presented that the primary issue that the decision maker is challenged with is how to distribute and transport inventory under stable conditions. While traditional network flow problems have been extensively studied for analyzing such systems, this paper presented a game theory application, namely the Shapley Value for the cooperation game to the transshipment network problem. Concluding that once we verify the appurtenance of the Shapley Value, then we know that we have a stable solution for the cooperation of the players. With the evolution of B2B strategies and e-commerce, we see this as opportunities in supply chain intelligence for integrating supplier-manufacturing data.

Further research could be carried out using additional players in the network. Since the diffusion level of supply chain technologies varies from one supply chain to another, traditional supply chains and electronic supply chains co-exist in markets. How do parallel, traditional and electronic supply chains differ? How can they be managed most effectively? Future research can investigate the economic and performance implications of different supply chain management choices? Are there new or different drivers for supply chains anticipating web services and other collaborative tools?

The transshipment problem is a tactical method for maintaining stable conditions in the logistic networks. In particular, a sensitivity analysis for establishing flexibilities in how the e-commerce partners cooperate in the network could be useful information to the logistics decision maker.

Appendix A. Tables A.1 and A.2 are as follows

Table A.1
The shift in SCM's business focus to create strategic advantage [12]

Old questions in SCM	New questions in SCM
How do we get the various functional areas of our company to work together to supply product to our immediate customers? ⇑ *Business focus shift from cross-functional integration to cross-enterprise*	How do we coordinate activities across companies, as well as across internal functions, to supply product to the market?
How do we minimize the costs our company incurs in production and distribution of our products? ⇑ *Business focus shift from physical efficiency to market mediation*	How do we minimize the costs of matching supply and demand while continuing to reduce the costs of production and distribution?
How do we improve the way we supply product in order to match supply and demand better, given the demand pattern? ⇑ *Business focus shift from supply focus to demand focus*	How can we get earlier demand information or affect the demand pattern to match supply and demand?
How should our company design products to minimize product cost (i.e., cost of materials, production and distribution)? ⇑ *Business focus shift from single-company product design to collaborative, concurrent product, process and supply-chain design*	How should collaborators design the product, process and supply chain to minimize costs?
How can we reduce our company's production and distribution costs? ⇑ *Business focus shift from cost reduction to breakthrough business models*	What new supply-chain and marketing approach would lead to a breakthrough in customer value?
How should we organize our company's operations to serve the mass market efficiently while offering customized products? ⇑ *Business focus shift from mass-market supply to tailored offerings*	How should we organize the supply chain to serve each customer or segment uniquely and provide a tailored customer experience?

Table A.2
The differences between SCM and SCI

Supply chain management (SCM)	Supply chain intelligence (SCI)
Largely about managing the procurement and production links of the supply chain	Provides a broad view of an entire supply chain to reveal full product and component life cycle
Transactional	Analytic
Tactical decision making	Strategic decision making
Helps reduce costs through improved operational efficiency	Revels opportunities for cost reduction, but also stimulates revenue growth

(*continued on next page*)

Table A.2 (*continued*)

Supply chain management (SCM)	Supply chain intelligence (SCI)
Usually just the SM application's data (as a vertical stovepipe)	Integrates supplier, manufacturing and product data (horizontal)
Records one state of the data representing "now"	Keeps historic record
Assists in material and production planning	What-if forecasting based on historic data
Quantifies cost of same materials	Enables an understanding of total cost
Shows today's yield but cannot explain influences on it thus provides no help for improvements	Drills into yield figures to reveal what caused the performance level so it can be improved
Simple reporting	Collaborative environment with personalizable monitoring of metrics

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