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A conceptual and analytical framework for management of integrated knowledge based logistics providers

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Abstract: Driven by increasing competitive forces and the business transformation brought about by internet-based technologies, the structure and landscape of the logistics industry has changed drastically in the last few years. A new breed of logistics service providers is emerging, who has developed and adopted a new operating model which we term Integrated Knowledge Based Logistics (IKL). An IKL is characterised by its complete shift in focus, from the asset intensive operational aspects of moving goods to a variety of knowledge-based tasks such as synchronising activities between various parties in the supply chain, and ensuring supply chain continuity even in the face of disruptions. In this paper, we present the structure of such an entity, discuss its attributes and identify critical factors that impact its success. We also show how mathematical modelling tools can be employed to solve some decision problems the logistics companies face in synchronising various activities across the network.

Keywords: knowledge-based logistics; 3PL; third party logistics; supplier selection; supply chain management; MILP; mixed-integer linear programming; partner selection; information sharing.

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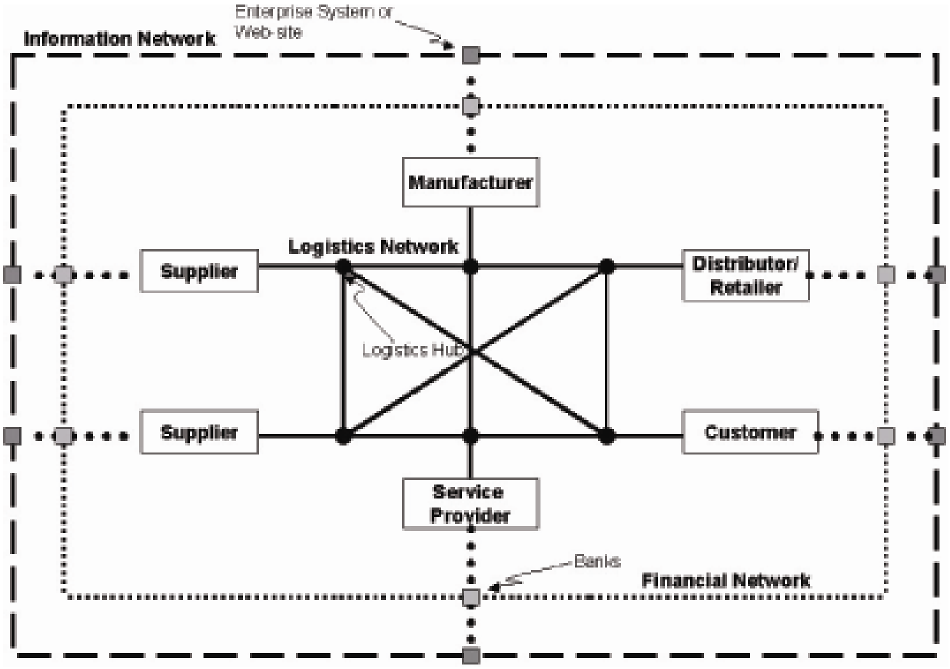
1 Introduction

Traditionally, companies operated in a vertically integrated model, resulting in supply chains that had complex management structures and were inflexible, unscalable and vulnerable. However, in the current competitive landscape, where the environment is ever changing, in order to succeed companies need to simultaneously incorporate the flexibility and the efficiency in their supply chains. To achieve this, and meet varying and diverse customer requirements at lower costs, companies are focusing on their core competencies, eliminating investments in non-core activities and increasingly relying on outsourcing. In addition, they are digitising their businesses with initiatives such as business process automation and collaborative planning leading to greater supply chain visibility, improved asset utilisation and delivery efficiency, all of these eventually leading to greater customer satisfaction. These trends asset intensive operational aspects rise to the development of 'internet-enabled supply chain networks'. The various players in such networks, namely the suppliers, customers, manufacturers and logistics providers, are all connected together through a secure integrated information, logistics and financial network as shown in Figure 1. Furthermore, these players interact with each other as members of three sub-networks, namely the supply network, the demand network and the service network to capture and serve market demand.

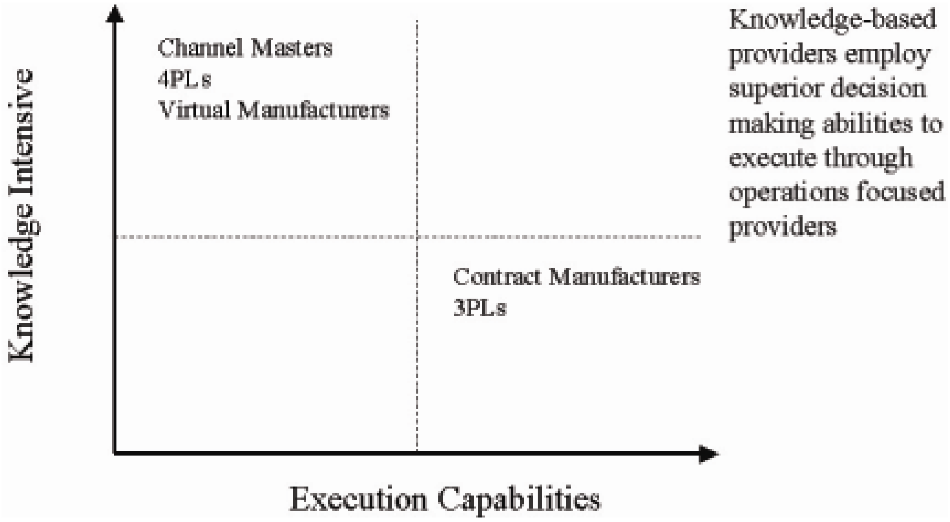
Whilst the internet promotes greater informational integration, globalisation pressures and the associated trend towards outsourcing are fomenting greater disintegration of the supply chain, wherein processes that were once wholly owned by the traditional multinational are now geographically distributed and managed offshore, outside the organisational and national boundaries. This has led to the rapid emergence of intermediaries such as Contract Equipment Manufacturers (CEMs), Third Party Logistics (3PLs) providers and B2B exchanges, to name a few. As Fortune 500 companies continue to outsource manufacturing, logistics, distribution, procurement and IT, the number of partners, such as suppliers, logistics providers, agents, financial institutions, etc., has grown, further increasing the complexity of the supply chain. In addition, efficient management of physical supply chain assets, the traditional focus of most supply chain providers, is no longer a source of competitive advantage for them. Instead, it is the data and information stream within the supply chain that has become increasingly important to control and maintain. Consequentially, these recent trends are accelerating the need to have a single, accountable firm to manage the partnerships and also to take control of the decision processes within the supply chain sub-networks of demand, supply and service. We term entities which take on this role within the supply chain as Integrated Knowledge Based Logistics (IKL) providers. IKLs are master contractors who manage an entire outsourced logistics network for a company. Thus, IKL can be defined as a company that creates value in the supply chain network or in a sub-network, through an alliance of supply chain competencies, by exploiting information flows in the supply chain to optimise customer service and reduce supply chain costs.

Figure 1 Integrated supply chain network



IKLs are, typically, dominant players within their supply chain networks, who possess deep domain knowledge and strong influence over other parties in the network. They exploit this clout to coordinate the activities across players within the sub-network and across the entire network. Due to the fact that IKLs leverage upon the complementary capabilities of other parties in the chain as and when needed, their offerings are characterised by a broad scope of multi-modal services, global reach, complex management capabilities and superior technological systems. Based on customer requirements, an IKL is able to select effective supply chain partners to team the best competencies available that optimally fulfil the requirements. Their ability to coordinate activities is to a large extent determined by their ability to transform their superior information, on the state of the network, into real-time decisions that enhance the performance of the entire network. When these dominant players achieve a high level of proficiency in coordinating the network, they no longer have to hold assets and instead rely on the physical assets of their partners in the network to fulfil market demand as shown in Figure 2, thereby substituting physical assets with dependable relationships. In this manner, new value players such as IKLs dominate the supply chain, outsource non-core capabilities to contract manufacturers and 3PLs and take control of the supply chain decision process.

Figure 2 Comparison of information-intensive IKLs and operations-focused 3PLs



1.1 Classification and examples

IKLs can emerge as intermediaries at various stages of the supply chain. Figure 3 shows a few possible classifications of IKLs based on their role within the supply chain. On the supply side the IKL can manage inbound shipments, as exemplified by VectorSCM for General Motors and Exel for Ford (in Europe) amongst others. Similarly, there are consumer-centric IKLs such as Amazon.com, UPS and others. At a slightly higher plane, there are IKLs, also known as channel masters, such as Dell and Cisco who manage the entire supply chain network inclusive of the demand, supply and service chains. Certain private and public exchanges also can be identified as performing the role of an IKL.

A generic business model diagram for a supply side (inbound logistics) IKL is shown in Figure 4. The IKL receives, on the one hand, orders from the manufacturer for materials procurement and, on the other, information on the operational status of the supply chain from its execution partners namely the suppliers and the 3PLs. It uses this information to generate plans for the movement of goods in the supply chain which are then transmitted to partners for them to execute upon. Once the goods reach the manufacturer, the manufacturer initiates payment to the IKL for the product or service delivered. In some cases, payments due to the suppliers and the 3PLs are also handed over to the IKL, who in turn is responsible to distribute the revenues and profits amongst the other parties involved in the transaction.

Similarly, examples of business models for IKLs in outbound logistics and the service logistics can be developed as well. The competencies that are common to all the IKLs are relationship management, business analytics and decision-making capabilities. We elaborate on these capabilities in the next section.

Figure 3 Classification map for IKLs

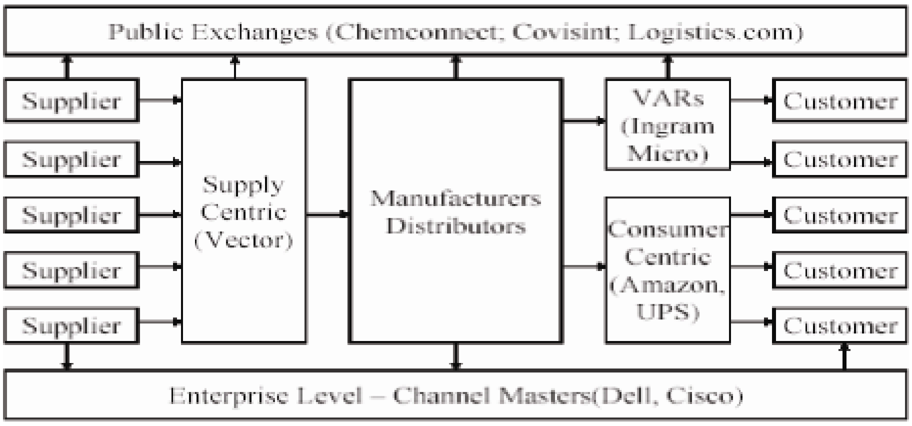
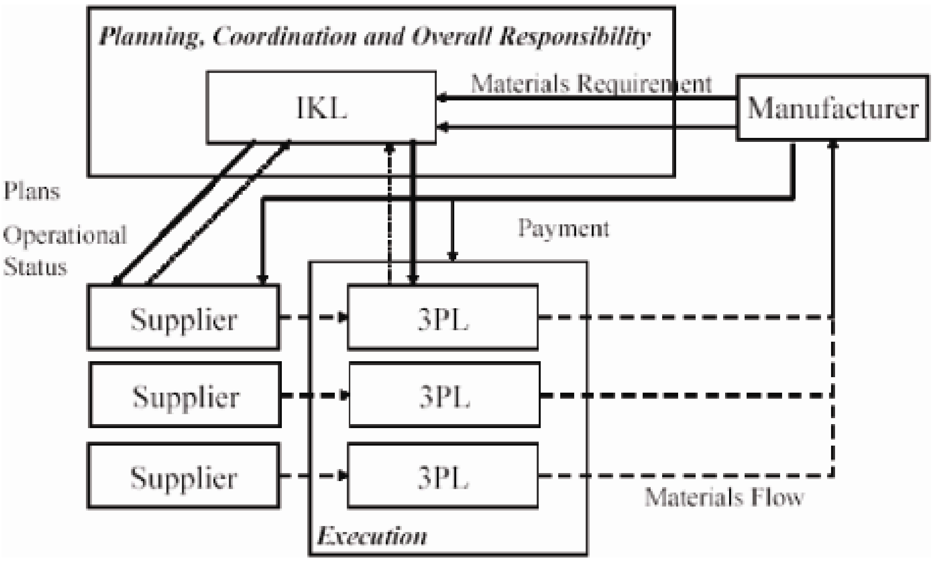


Figure 4 Supply side IKL



1.2 Who can be an IKL?

One of the questions frequently raised in the context of logistics in this knowledge-based age is: ‘Who can be an IKL?’ Can it be an Original Equipment Manufacturer (OEM), like in the case of Dell, or a CEM, as shown by Solectron, or possibly a 3PL, as exemplified by UPS? Will the 4PLs of the future evolve into IKLs providing a central data warehouse and synchronising data between relevant parties? The answer depends on the sub-network under consideration: supply network, demand network or service network. As the OEMs increase the volume of outsourced inbound manufacturing to CEMs, it is being felt that the CEMs are better placed to control the supply chain information flow. On the other hand, the outbound flow dictates that the OEMs or the dealers are better placed to take control.

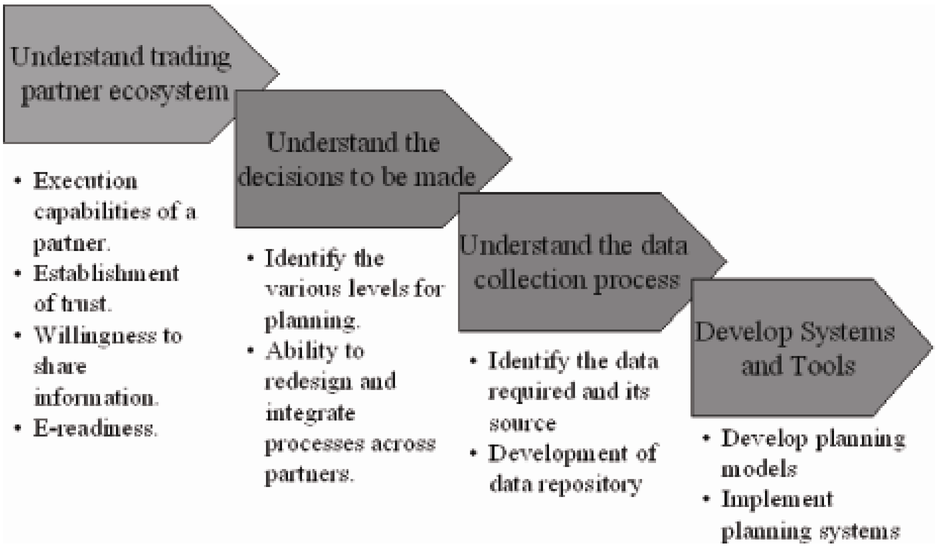
We have identified below the core competencies of successful IKLs. They include relationship management with customers and partners; deep domain knowledge of the vertical industry and the country geography, laws and practices in which the suppliers are located; detailed understanding of processes being coordinated and the ability therein to redesign and automate material and information flows amongst the partners; and the ability to integrate IT systems and packaged applications software, amongst others. Also, the IKL is the company that synchronises the planning processes across all the supply chain partners. Furthermore, the domain knowledge and access to information across the network will provide the IKLs with capabilities for cross-docking and merging in transit opportunities and also for event management in case of disruptions such as supplier failure or delays in transportation due to weather problems. Thus, IKLs can help create resilient supply networks, demand networks or service networks.

1.3 Business transformation, integration and emerging technologies

Typically, companies within the same supply chain have different processes, policies, practices, capabilities, technologies and supply chain solutions. This often creates problems for companies that need to work together. As a result, the most successful IKLs are also those that are able to reengineer business processes and employ the latest supply chain and integration technologies to enhance their offerings.

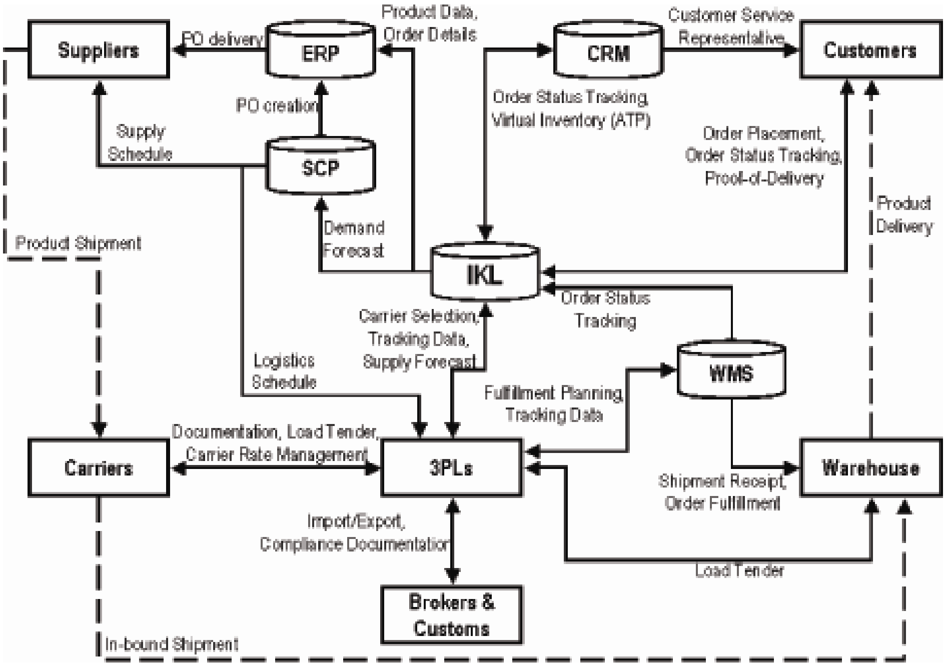
The process of business transformation involves a systematic assessment of the capabilities of the trading partner ecosystem, followed by its revamp through redesign and standardisation of intra- and inter-company processes, databases, planning and execution systems, as shown in Figure 5. Hence, attainment of competitive advantage through the ability to transform a traditional business model into one based on the IKL model is a hallmark of a successful IKL.

Figure 5 Business transformation process



Furthermore, a reengineered trading partner ecosystem will only be able to work seamlessly, if the various entities and systems within the system are well integrated. Integration is not limited to merely hooking up of computer systems. Instead, the IKL needs to ensure that companies within the network are integrated at the business process level, database level and application software level and ultimately at the organisational and cultural levels. Hence, the contracts and service-level agreements amongst the stake holders need to be in place; the routes for the orders and also the transportation of goods and information under normal and exceptional conditions need to be agreed upon. Predictably, a number of different supply chain solutions, such as Enterprise Resource Planning (ERP) (SAP, Oracle), supply chain planning (i2, Manugistics), Product Development/Collaborative Product Commerce (PTC Wind-chill, Agile) and supply chain monitoring/management solutions (Yantra, Descartes), can be seen within the same ecosystem. Whilst these solutions are very effective independently, they impede seamless supply chain execution due to their differing approaches to managing the supply chain. Hence, the IKL plays a critical role in integrating these disparate solutions together, to provide end-to-end supply chain visibility under a unified architecture, through the use of technologies such as middleware and web services as shown in Figure 6.

Figure 6 Integrated IKL planning system



In addition to emerging integration technologies such as web services, mentioned earlier, IKLs are also distinguishable by their motivation to test and implement the latest supply chain technologies. Keys amongst emerging technologies are data mining and expert systems (both at the planning level), which provide the means for the IKL to take in vast amounts of real-time data, available from the integrated network, and automatically act on it in the best interests of the IKL. At the same time, traditional supply chain planning solutions based on mathematical programming are getting more and more sophisticated and powerful. Radio-Frequency Identification (RFID)-based applications are another set of emerging technologies that will expand the granularity, depth and coverage of visibility provided by the network, on material movements and events in the supply chain. This will in turn provide more accurate and up-to-date data for better supply chain planning. Data warehousing will also be a critical technology since the IKL will have to efficiently capture, store, and distribute and manage the flood of data generated by RFID tags.

1.4 Literature survey

Our literature survey led us primarily to the substantial business literature from consultants such as Accenture on 3PLs and 4PLs. It may be noticed that Accenture's trademarked definition of a 4PL closely resembles ours. As traditionally understood, and as defined by Accenture, the 4PL is an integrator that assembles the resources, capabilities and technology of its own organisation and other organisations to design, build and run comprehensive supply chain solutions. Despite the widespread awareness of the 4PL concept, no mathematical modelling approaches have been reported in the literature for synchronising inter-enterprise processes such as synchronising the production processes of the suppliers and the OEM with the transportation schedules to minimise the total supply chain cost. In this paper, we wish to address this gap by providing an integer program based model for an IKL, specifically to manage an inbound supply chain.

The modelling approach presented in this paper draws inspiration from the existing research on supplier selection and supply chain planning, both of which have been well documented within the area of operations research and management science.

1.4.1 Supplier selection

The current literature on supplier selection extensively deals with optimal sourcing of components and raw materials by OEMs. This work on the selection of component suppliers for specific manufacturers is limited in scope to finding partners only in a two-level (manufacturer–supplier) supply chain. Weber and Current (1993) discuss a multi-criteria analysis for vendor selection. They develop a model for minimising total cost, late deliveries and supply rejection given the infrastructure constraints and constraints imposed by the company's policy. Pan (1989) presents a simple linear programming model that can be used to determine optimal order quantity amongst suppliers subject to specific quality, lead time and service requirements from the buyer. Chaudhry et al. (1993) consider the problem of vendor selection where buyers need to choose order quantities with vendors in a multi-sourcing network. Narasimhan and Stoynoff (1986) present a model for optimising aggregate procurement allocation keeping in mind contract requirements, supplier capacities and economic manufacturing quantity-related constraints. The interested reader might find Weber et al. (1991) useful for a comprehensive classification of publications on vendor selection criteria.

1.4.2 Supply chain management

In the supply chain management literature, Arntzen et al. (1995) describe a global supply chain management model that was implemented at Digital Equipment Corporation. The model incorporates capacity constraints, import taxes, fixed charges, transportation constraints, etc. and determines the locations for production and distribution, and the supplier network. D'Amours et al. (1999) discuss the impact of information sharing in networked manufacturing, by comparing the optimal supply chain design for different information sharing and bidding strategies. Some researchers have focused on the production scheduling aspects of the supply chain. Bretthauer and Cote (1996) talk about a nonlinear programming model for multi-period capacity planning. Brucker et al. (1999) discuss models for project scheduling in a resource-constrained manufacturing network. Gjerdrum et al. (2001) present a Mixed-Integer Linear Programming (MILP) model to address a key and relevant issue relating to the sharing of profits from collaboration in a supply chain. Erenguc et al. (1999) review and evaluate some of the relevant literature on production and distribution planning at each stage of the supply chain. Vidal and Goetschalckx (1997) present an extensive review of strategic production–distribution models in the literature. They compare the features of models presented by Geoffrion and Graves (1974), Geoffrion et al. (1978), Brown et al. (1987), Cohen and Lee (1989), Cohen et al. (1989), Cohen and Moon (1991), Arntzen et al. (1995) and Cole (1995).

2 Problem formulation

2.1 Problem description

We assume that there are a number of sub-assembly manufacturers who supply sub-assemblies to a large and dominant manufacturer (also known as the channel master). We also assume that the supply of these sub-assemblies to the manufacturer is coordinated by a third-party IKL who has control over or access to the resources and services of a number of logistics service providers. The logistics service providers have their own costs, capacity constraints and fixed shipping schedules. It is also possible to route some materials through transshipment hubs, where materials bound to the same destination can be packaged together for shipment, usually at a much lower overall cost. Information is also available on the ordering costs for procuring goods from the supplier and the logistics capacity from the logistics service provider. The supply requirements of the manufacturer can be fulfilled by different sets of sub-assembly manufacturers and logistics service providers at different costs and in different lead times. Importantly, they all share information on their production schedules, capacity, cost, quality, etc. with the IKL. With access to such detailed operational information on all the participants in a supply chain, the challenge for the IKL is to best meet the supply requirements of the channel master, using a combination of sellers and logistics providers, at minimal operational cost. In particular, a collaborative approach in supply chain management and coordination such as collaborative transportation management (Browning and White, 2000) is required to form an effective and efficient value web.

The challenge for the IKL is the selection of suppliers and logistics service providers who can collectively meet the deadlines of the channel master and minimise the cost of procurement and inbound logistics for the channel master. Apart from incorporating the capacity constraints in the supply chain decisions, production activities need to be synchronised with the schedules of the logistics service providers, so that items can be ready for pickup in a just-in-time manner, instead of having to wait in inventory. There can be significant cost savings through this exercise, especially in terms of synchronisation of activities leading to reduced inventory levels.

2.2 Notation

For the development of a mathematical model for the above scenario, the following notations were used.

2.2.1 Identifiers

The list of identifiers is as follows:

i: sub-assembly type identifier

I: number of sub-assembly types

j: sub-assembly supplier identifier

J: number of sub-assembly suppliers

k: manufacturer identifier

K: manufacturer facilities

l: brand identifier

L: number of brands

d: transportation mode (sea, air, etc.) identifier

D: number of transportation modes

t: time period identifier

T: total time horizon of the model.

2.2.2 Parameters

The list of parameters is as follows:

PCap_{abt}: maximum production capacity for sub-assembly of type a offered by sub-assembly supplier b in time period t. It is assumed that the offered capacity is the total available capacity with the producer, which already takes into consideration other commitments that the producer may have made on his capacity. Also the capacity is specific to the capacity of the manufacturing line for individual models and products

PC_{ab}: per unit production cost for sub-assembly of type a produced by sub-assembly supplier b

PFC_{ab}: fixed cost of production set-up or ordering for sub-assembly of type a produced at sub-assembly supplier b

TCap_{abcdt}: maximum transportation capacity for shipment of sub-assembly of type a from sub-assembly supplier b to manufacturing facility c in time period t through mode d. The transportation capacity depends on the schedules of the logistics provider. For days/time periods when the flights/shipments are scheduled the capacity is non-zero, whereas for days/time periods when the service is not available the capacity is taken to be zero

TC_{abcdt}: per unit transportation cost for shipment of sub-assembly of type a from sub-assembly supplier b to manufacturing facility c in time period t through mode d

TFC_{abcd}: fixed cost for procuring capacity for shipment of sub-assembly of type a from sub-assembly supplier b to manufacturing facility c in time period t through mode d

WC_{ab}: per unit inventory cost incurred for sub-assembly of type a in the possession of sub-assembly supplier/manufacturer b

TL_{bcd}: transportation lead time for shipment from sub-assembly contract manufacturer b to manufacturing facility c through mode d

M_{ab}: units of sub-assembly type a required in the production of one unit of model b

PS_{abt}: production scheduled for brand of type a at manufacturing facility b in time period t.

2.2.3 Variables

The list of variables used is as follows:

Q_{abt}: quantity produced of sub-assembly a by sub-assembly supplier b in time period t

I_{abt}: inventory of sub-assembly/brand a with sub-assembly supplier/manufacturer b in time period t

S_{abcdt}: quantity shipped of sub-assembly type a from sub-assembly supplier b to the manufacturing facility c through transportation mode d in time period t

S'_{abcdt} : quantity received of sub-assembly of type a from sub-assembly supplier b at manufacturing facility c in time period t through transportation mode d

F_{abt}: fixed cost of ordering/set-up applies for production of sub-assembly of type a by sub-assembly supplier b in time period t. It takes on binary values $\{0, 1\}$

F_{abcdt}: fixed cost associated with shipping sub-assembly of type a from sub-assembly supplier b to the manufacturing facility c through transportation mode d in time period t applies. It takes on binary values $\{0, 1\}$.

2.3 Mixed-integer linear programming model

We now develop a mixed-integer programming model for the inbound procurement and logistics of sub-assemblies to a manufacturer coordinated by an IKL. We assume that the IKL with access to operational information on the entire inbound supply chain employs the model to select suppliers and logistics partners, and to synchronise the material flow throughout this network. The objective of the model is to minimise the cost of procurement and inbound logistics subject to various capacity, production and logistics schedules and flow balancing constraints.

2.3.1 Objective function

The cost was calculated, as given in equation (1), as the sum of costs incurred in the procurement of sub-assemblies. The first term in the equation represents the costs for production followed by the costs for transportation and inventory holding.

$$\begin{aligned}\text{MinCOST} = {} & \left[\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(\text{PFC}_{ij}F_{ijt} + \text{PC}_{ij}Q_{ijt}\right)\right] + \left[\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{d=1}^{D}\sum_{t=1}^{T}\left(\text{TFC}_{ijkd}F_{ijkdt}TC_{ijkd}S_{ijkdt}\right)\right] \\ & + \left[\sum_{i=1}^{T}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\text{WC}_{ij}I_{ijt} + \sum_{i=1}^{I}\sum_{k=1}^{K}\text{WC}_{ik}I_{ikt}\right)\right]\end{aligned} \tag{1}$$

There are various capacity constraints on the sub-assembly suppliers, manufacturers and the logistics service providers that make the solution non-trivial.

2.3.2 Sub-assembly supplier constraints

The sub-assembly suppliers cannot produce more than their maximum production capacity. The quantity produced will be less than the maximum capacity when fixed cost of production is incurred and production is undertaken or else will be zero. Conversely, if the quantity produced is zero fixed cost of production will not apply. Hence, the maximum production of sub-assemblies is constrained by the production capacity of the sub-assembly suppliers.

$$Q_{ijt} \le \text{PCap}_{ijt}F_{ijt} \quad \text{and} \quad Q_{ijt} \ge F_{ijt} \quad \forall\, i \in I,\, j \in J \text{ and } t \in T. \tag{2}$$

The components produced are held with the sub-assembly supplier until they are shipped off to the manufacturer. The inventory of sub-assemblies at the sub-assembly supplier's end increases at the end of each period by the quantity produced and decreases by the amount of sub-assembly shipped out to the contract manufacturer and the transshipment hub, in that time period.

$$I_{ij(t-1)} + Q_{ijt} = \sum_{k=1}^{K}\sum_{d=1}^{D} S_{ijkdt} + I_{ijt} \quad \forall\, i \in I,\, j \in J \text{ and } t \in T. \tag{3}$$

However, the quantity that can be transported in a single period is constrained by the maximum capacity of the transportation infrastructure. Considering our scenario with fixed shipping schedules, in time periods when the service is available the transportation capacity is non-zero. However, for time periods where particular flights or shipments are not scheduled the transportation capacity is zero. Hence, the transportation of the sub-assembly types from the sub-assembly suppliers to the manufacturers is bound by the constraint given below. Once more, the fixed cost of shipping is modelled through a binary variable representing whether shipment is undertaken or not.

$$S_{ijkdt} \le \text{TCap}_{ijkdt}F_{ijkdt} \quad \text{and} \quad S_{ijkdt} \ge F_{ijkdt} \quad \forall\, i \in I,\, j \in J,\, k \in K,\, d \in D \text{ and } t \in T. \tag{4}$$

2.3.3 Contract manufacturer constraints

The shipped assembly parts reach the contract manufacturer after a certain amount of time, modelled by the optional constraint below:

$$S'_{ijkdt} = S_{ijkd(t-\mathrm{TL}_{jkd})} \quad \forall\, i \in I, j \in J, k \in K, d \in D \text{ and } t \in T. \tag{5}$$

The shipped assembly parts will be stored at the contract manufacturer. The contract manufacturer will produce a variety of brands, which will use up the inventory of the sub-assemblies in the process. However, only in the case of sufficient availability of all the needed sub-assemblies will production of the brands take place. Hence, the inventory of sub-assemblies required is determined by the production schedule of the manufacturer.

$$I_{ik(t-1)} \geq \sum_{l=1}^{L} M_{li} \mathrm{PS}_{lkt} \quad \forall\, i \in I, k \in K \text{ and } t \in T. \tag{6}$$

As regards the inventory levels of sub-assemblies at the contract manufacturer incoming stocks will add to the inventory and sub-assembly stocks will be used up in the production of the various brand types. The inventory status for sub-assemblies at the contract manufacturer can be determined as given below:

$$I_{ik(t-1)} + \sum_{j=1}^{J} \sum_{d=1}^{D} S'_{ijkdt} = \sum_{l=1}^{L} M_{li} Q_{lkt} + I_{ikt} \quad \forall\, i \in I, k \in K \text{ and } t \in T. \tag{7}$$

2.4 Other modelling issues: modelling a transhipment hub

A variation of the supply chain network developed above was considered by modelling transshipment hubs between the sub-assembly suppliers and the manufacturers. The role of the transshipment hubs was to provide a facility where different components bound to the same destinations could be packaged and sent together through lower cost and possibly higher volume transportation modes. Sub-assemblies from the sub-assembly suppliers arrive at the transshipment hub. They then wait at the transshipment hub to be packaged together with other items destined to the same location; or alternately if there are enough sub-assemblies to ship, or if the sub-assemblies are urgently needed, these are dispatched to the manufacturers. Holding costs are incurred for the time the sub-assemblies are warehoused in the transshipment hub.

Hence, the transshipment hub is modelled as a facility with an inventory of inbound sub-assemblies and outbound shipping packages. The set of constraints for the transshipment hub is similar to the constraints for the sub-assembly supplier and the manufacturer, with a set of constraints for inbound and outbound inventory balancing and a production constraint representing the activity of packaging different types of sub-assemblies into one shipping package. Additionally, terms need to be added to the outbound inventory flow balancing constraint for the sub-assembly suppliers, highlighting the additional shipment option to the transshipment hub. Similarly, there are additional terms in the inbound inventory flow balancing constraint for the manufacturers, representing the fact that packages from the transshipment hub add to all the inbound inventories, related to the sub-assemblies carried within the shipping package. A detailed listing of the additional constraints for a transshipment hub is given in the Appendix.

2.5 Solving the model in ILOG optimisation programming language studio

The MILP model developed herein can be solved using any of the commonly available mixed-integer solvers. For our analysis, we employed the CPLEX branch-and-bound integer solver, available in the commercial optimisation suite, Optimisation Programming Language (OPL) studio developed by ILOG.

ILOG provides a very comprehensive library of optimisation algorithms implemented in C++. These algorithms can be used for the solution of a varied number of large-scale linear, integer and constraint programming models. ILOG also incorporates a set of modelling concepts, such as activities and resources, which are very useful in the solution of scheduling and allocation problems. The OPL studio modelling environment from ILOG utilises the OPL for modelling of problems. User-defined search strategies for each model can be specified in order to reduce the computational power required for the solution.

The above MILP model was developed in OPL studio and solved for a scenario with five sub-assembly suppliers supplying two different product types to three manufacturing facilities, who manufacture two different model types. Not all manufacturing facilities manufacture all models or all suppliers supply all product types. The time horizon for the model was taken as 12 periods. The modes of transportation between the facilities were considered to be air ($d = 1$) and sea ($d = 2$). Air transportation was assumed to be twice as expensive, but four times faster than sea transportation.

3 Experimental results

Various computational experiments were performed to study the dynamic nature of the supply chain network and to analyse the performance of the supply chain under different conditions.

3.1 General observations

In the lack of any capacity constraints at the suppliers' and manufacturers' facility and the availability of transportation infrastructure, the problem leads to the trivial solution where the cheapest complete link from the supplier to the buyer is chosen.

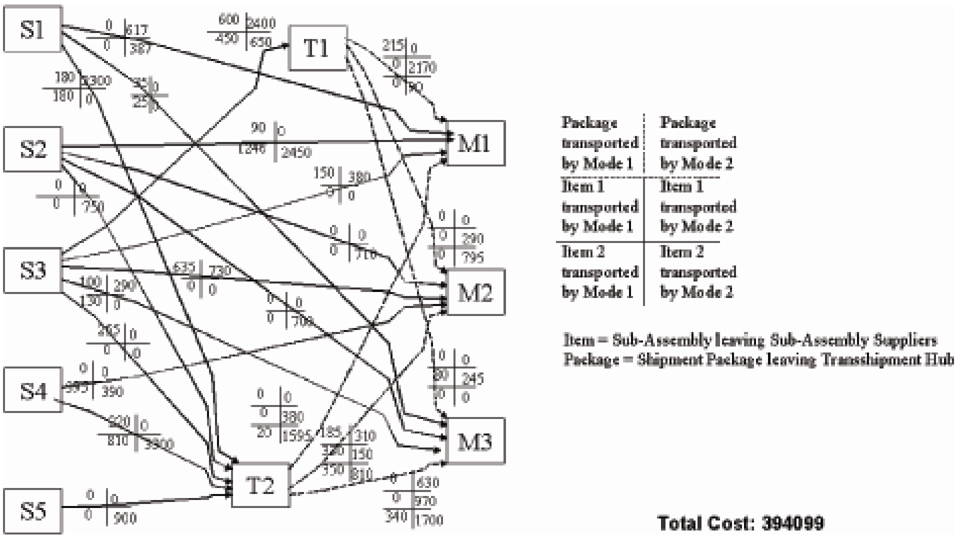
The solution of the mixed-integer programming model provides a breakdown of the optimum sub-assembly production quantity, inventory holding and manufacturing capacity utilisation for each time period at each of the sub-assembly and manufacturing locations. This information is the key to scheduling supply chain activities to perform at optimal levels. Hence, the mixed-integer programming model provides an integrated strategic-level partner-selection tool and a low-level operational synchronisation and scheduling tool as well.

3.2 Partner selection in procurement and inbound logistics

To visualise the partner selection process within the inbound supply chain, for the given manufacturer schedule, suitable suppliers were selected and their products were shipped to the manufacturing facilities through various routes and logistics service providers based on the IKL planning tool, as shown in Figure 7. In our example, we considered three manufacturing facilities supported by five sub-assembly suppliers. The supplies can be shipped directly or through a transshipment hub, via air or sea. The selection of the optimal inbound route and mode is undertaken by the IKL based on the delivery deadlines, transportation capacity constraints and the costs involved. The optimal supply chain configuration for the scenario considered is obtained as given below.

The selection of appropriate suppliers and logistics service providers is dependent on the consideration of the total landed cost of the products and the lead times involved. In some cases, shipments may be expedited through air in case of unavailability of adequate supplies at the manufacturing facility. Also, transportation takes place just-in-time so that inventory through the chain is minimised. Furthermore, transshipment hubs as considered in this paper, model cross-docking centres and also merge-in-transit processes wherein certain goods bound to the same destination are packaged together to achieve lower costs of transportation and procurement.

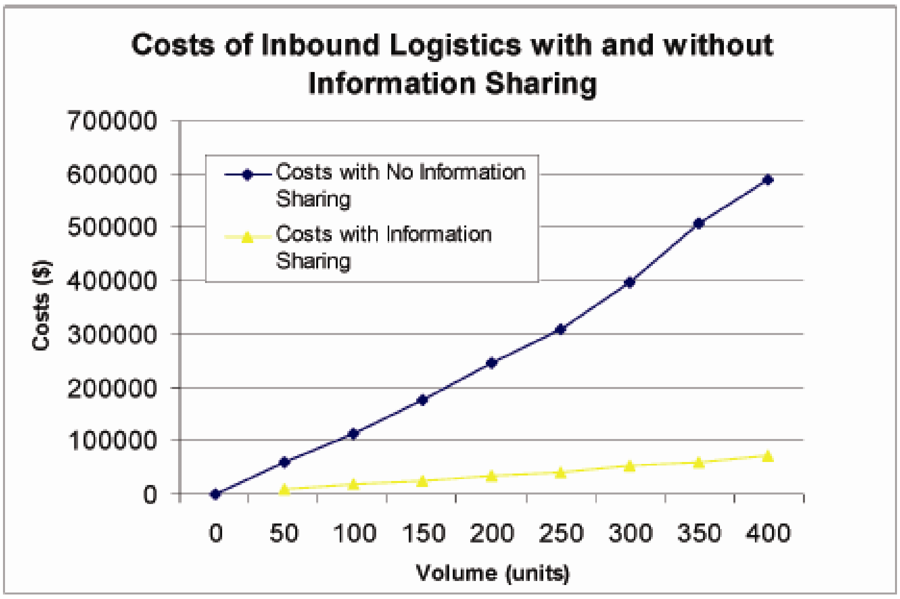
Figure 7 Supply chain configuration for the example considered



3.3 Numerical experiment 1: load analysis

We also compared the cost performance of the IKL-based inbound supply chain with a traditional inbound supply chain with no information sharing between partners. To model the traditional supply chain, we assumed that the suppliers and the manufacturer maintained certain days of inventory, based on past sales and consumption, to buffer themselves from the uncertainties in the supply pattern (Roshan and Viswanadham, 2001). The inbound supply chain network was exposed to a series of demand patterns (step inputs of varying magnitude) and the cost of operating the supply chain was observed for each case, as shown in Figure 8.

Figure 8 Costs with and without information sharing (see online version for colours)



It may be noticed from the above results that in terms of cost there is not much difference when the demand is very low. However, when the demand increases the cost of operating the supply chain without information sharing increases exponentially, whereas the cost of operating a supply chain with integrated scheduling and visibility increases only linearly. This may be explained as follows. In case of a traditional supply chain where there is limited supply chain visibility, when the loads are low the inventory that the supply chain participants need to hold is also low due to the fact that their sales are not so high. However, when the demand increases the flow through the network increases and as a result the participants need to keep a much higher level of inventory to maintain their service levels. This results in the exponential increase in costs. On the other hand, when we consider a supply chain managed by an IKL, with total visibility, the flows are synchronised for just-in-time manufacturing and hence there is no need to hold any inventory. As a result the costs only increase linearly, corresponding to the cost of production and logistics only for the goods delivered. Hence, in case of low loads the impact of information sharing may not be significant, but for higher demands it definitely is advantageous to share data between supply chain partners and adopt integrated scheduling methods.

4 Conclusions

In this paper, first we have introduced the concept of IKL and have presented an optimisation model for an IKL supervising and controlling an inbound supply network. We presented an example which illustrates the benefits of information sharing and coordinated control. There are several directions in which we are extending this work, the primary one being finding real-world applications. Others include the following:

1 There is a recent trend of outsourcing the IT functions of logistics companies to India, China and other low-cost countries. The information on the movement of goods is thus centralised and is available at one source. This can be used for monitoring and control using our models presented here.

2 The logistics infrastructure in emerging economies is not sophisticated and suppliers' timeliness as well as quality requires monitoring. The IKL model presented here is very useful in such situations for scheduling the logistical activities.

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Appendix

Additional constraints for modelling a transhipment hub

The following changes and additions were made to the model to model the transshipment hub:

h: transshipment hub identifier

H: number of transshipment hubs

g: shipment package identifier

G: number of shipment packages

X_{ab}: units of sub-assembly type a merged into one unit of shipment package b

SP_{abt}: quantity packaged of shipment package g at transshipment hub h in time period t

SPCap_{abt}: maximum quantity that can be packaged of shipment package g at transshipment hub h in time period t.

Changes to existing constraints

Constraint (2) changes to

$$I_{ij(t-1)} + Q_{ijt} = \sum_{k=1}^{K}\sum_{d=1}^{D} S_{ijkdt} + \sum_{h=1}^{H}\sum_{d=1}^{D} S_{ijhdt} + I_{ijt} \quad \forall\, i \in I,\, j \in J \text{ and } t \in T.$$

Constraint (5) changes to

$$I_{ik(t-1)} + \sum_{j=1}^{J}\sum_{d=1}^{D} S'_{ijkdt} + \sum_{h=1}^{H}\sum_{d=1}^{D} S'_{ihkdt} + \sum_{h=1}^{H}\sum_{d=1}^{D} X_{gi} S'_{ghkdt} = \sum_{l=1}^{L} M_{li} Q_{lkt} + I_{ikt} \quad \forall\, i \in I, k \in K \text{ and } t \in T.$$

Additional constraints

Additional constraints are as follows:

$$S_{ijhdt} \le \mathrm{TCap}_{ijhdt} F_{ijhdt} \quad \forall\, i \in I,\, j \in J, h \in H, d \in D \text{ and } t \in T,$$

$$S_{ijhdt} \geq F_{ijhdt} \quad \forall i \in I, j \in J, h \in H, d \in D \text{ and } t \in T,$$

$$S'_{ijhdt} = S_{ijhd(t-\mathrm{TL}_{ijh})} \quad \forall i \in I, j \in J, h \in H, d \in D \text{ and } t \in T,$$

$$I_{ih(t-1)} + \sum_{j=1}^{J}\sum_{d=1}^{D} S'_{ijhdt} = \sum_{g=1}^{G} X_{gi}\mathrm{SP}_{ght} + \sum_{k=1}^{K}\sum_{d=1}^{D} S_{ihkdt} + I_{iht} \quad \forall i \in I, h \in H \text{ and } t \in T,$$

$$\mathrm{SP}_{ght} \leq \mathrm{SPCap}_{ght} \quad \forall g \in G, h \in H \text{ and } t \in T,$$

$$I_{gh(t-1)} + \mathrm{SP}_{ght} = \sum_{k=1}^{K}\sum_{d=1}^{D} S_{ghkdt} + I_{ght} \quad \forall g \in G, h \in H \text{ and } t \in T,$$

$$S_{ihkdt} \leq \mathrm{TCap}_{ihkdt} F_{ihkdt} \quad \forall i \in I, h \in H, k \in K, d \in D \text{ and } t \in T$$

$$S_{ihkdt} \geq F_{ihkdt} \quad \forall i \in I, h \in H, k \in K, d \in D \text{ and } t \in T,$$

$$S'_{ihkdt} = S_{ihkd(t-\mathrm{TL}_{ihh})} \quad \forall i \in I, h \in H, k \in K, d \in D \text{ and } t \in T,$$

$$S_{ghkdt} \leq \mathrm{TCap}_{ghkdt} F_{ghkdt} \quad \forall g \in G, h \in H, k \in K, d \in D \text{ and } t \in T,$$

$$S_{ghkdt} \geq F_{ghkdt} \quad \forall g \in G, h \in H, k \in K, d \in D \text{ and } t \in T,$$

$$S'_{ghkdt} = S_{ghkd(t-\mathrm{TL}_{ghk})} \quad \forall g \in G, h \in H, k \in K, d \in D \text{ and } t \in T.$$