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Object oriented modeling and decision support for supply chains

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Abstract

Numerous algorithms and tools have been deployed in supply chain modeling and problem solving. These are based on stochastic models, mathematical programming models, heuristic techniques, and simulation. Since different decision problems in supply chains entail different approaches to be used for modeling and problem solving, there is a need for a unified approach to modeling supply chains so that any required representation can be created in a rapid and flexible way. In this paper, we develop a decision support system DESSCOM (decision support for supply chains through object modeling) which enables strategic, tactical, and operational decision making in supply chains. DESSCOM has two major components: (1) DESSCOM-MODEL, a modeling infrastructure comprising a library of carefully designed generic objects for modeling supply chain elements and dynamic interactions among these elements, and (2) DESSCOM-WORKBENCH, a decision workbench that can potentially include powerful algorithmic and simulation-based solution methods for supply chain decision-making. Through DESSCOM-MODEL, faithful models of any given supply chain can be created rapidly at any desired level of abstraction. Given a supply chain decision problem to be solved, the object oriented models created at the right level of detail can be transformed into problem formulations that can then be solved using an appropriate strategy from DESSCOM-WORKBENCH. We have designed and implemented a prototype of DESSCOM. We provide a real-world case study of a liquid petroleum gas supply chain to demonstrate the use of DESSCOM to model supply chains and enable decision-making at various levels.

Keywords: Modeling; Simulation; Optimization; Supply chain management; Decision support system; Object oriented modeling

1. Introduction

Supply chains are now at the centrestage of business performance of manufacturing and service enterprises. Because of the inherent complexity of decision making in supply chains, there is a growing need for modeling methodologies that can help identify and innovate strategies for designing high performance supply chain networks. A large number of manufacturing and service organizations are therefore seeking modeling systems that can help identify and implement strategies for designing and improving their supply chain networks.

Supply chain decision making is a complex process. Some of the important reasons for the complexity of the decision making process are:

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- large scale nature of the supply chain networks,
- hierarchical structure of decisions,
- randomness of various inputs and operations,
- dynamic nature of interactions among supply chain elements.

Modeling and analysis to gain a better understanding of the system complexity and to predict system performance are critical in the system design stage, and often valuable for system management. Thus there is an ever increasing need for modeling supply chains.

1.1. Contributions

The principal contribution of this paper is in architecting a decision making tool for supply chains, based on sound modeling and problem solving approaches. Our work has led to a prototype of a supply chain decision support system which we call decision support for supply chains through object modeling (DESCOM). DESSCOM includes two major subsystems in it: (1) DESSCOM-MODEL provides object oriented modeling support for supply chains, and (2) DESSCOM-WORKBENCH provides a suite of problem solving methods that can be used for decision making using the models.

Our approach to modeling of supply chains extends and unifies earlier approaches to object oriented modeling of supply chains. We have conceptualized and built a comprehensive library of supply-chain specific objects with which faithful models of given supply chains can be rapidly configured. The models can be built at any desired level of detail. This is accomplished by DESSCOM-MODEL. From the models so created, DESSCOM-MODEL can generate problem formulations for supply chain problems at strategic, tactical, and operational levels. The problems can be solved using a suite of tools provided in DESSCOM-WORKBENCH, providing decision-making support. The prototype of DESSCOM built as part of this work has been tested on a variety of supply chain problems, including real-world case studies. DESSCOM has two distinguishing features:

1. From the supply chain objects provided, one can conveniently generate problem formulations for supply chain problems. For example, a linear program or a mixed integer linear program (MILP) is automatically generated when we configure the supply chain objects from the perspective of a particular problem.
2. DESSCOM-MODEL enables formulation of model and problem at any desired level of abstraction (strategic, tactical, and operational). Since a wide variety of OR tools are and can be made available in DESSCOM-WORKBENCH, a wide variety of supply chain problems can be solved.

In addition, the design of DESSCOM has been carried out using best practices in object oriented design such as UML modeling and design patterns. This makes DESSCOM's design amenable for future extensions such as incorporation of new decision-making algorithms and inclusion of new objects.

1.2. Paper outline

In Section 2, we discuss different aspects of supply chain decision making. We classify supply chain decisions according to the time horizon of decisions and also according to the functional area. We also discuss important performance measures of supply chain networks. We provide an overview of tools and techniques available for supply chain decision making. Finally we review the relevant literature.

In Section 3, we present an object oriented modeling approach for supply chain networks. We first describe various objects of our object library. The objects belong to two categories: Structural objects and policy objects. We have used unified modeling language (UML) [5]) for creating generic object models of supply chain elements. We provide an example of a LPG (liquid Petroleum gas) supply chain to illustrate our object modeling approach. This object library forms the core of DESSCOM-MODEL.

In Section 4, we discuss the architecture of DESSCOM. We discuss DESSCOM-WORKBENCH, which provides the tools and techniques deployed in decision making. Following this, we explain various steps involved in using DESSCOM. We also provide an overview of implementation aspects of a prototype of DESSCOM.

In Section 5, we present a real-world case study, that of the LPG supply chain of Section 3, to demonstrate the use of DESSCOM. We then explore the use of DESSCOM in facilitating decision making at three levels: Strategic, tactical, and operational. The specific problems that we explore in this case study are

- location of bottling plants (a strategic decision),
- aggregate level inventory optimization (a tactical decision),
- detailed level inventory optimization based on simulation (an operational decision).

We discuss the future evolution of DESSCOM in Section 6, after presenting the conclusions of this study.

2. Supply chain decisions and models: A review

2.1. Supply chain decisions

Supply chain decisions have been classified based on their temporal and functional consideration. Supply chain decisions can be broadly classified into three categories: Strategic (long-term), tactical (medium-term), and operational (short-term and real-time) according to the time horizon of the decisions.

Functionally, there are four major decision areas in supply chain management: Procurement, manufacturing, distribution, and logistics. In addition, there are also certain global decisions whose scope extends over multiple functions. There are strategic, tactical, and operational questions in each of these areas. These are described in detail by Shapiro [42].

2.2. Supply chain performance measures

Supply chain performance measures can be classified broadly into two categories [46]: Qualitative measures (such as customer satisfaction and product quality) and quantitative measures (such as order-to-delivery lead time, supply chain response time, flexibility, resource utilization, delivery performance, etc.). In our study we consider only the quantitative performance measures.

Quantitative metrics of supply chain performance can be classified into two broad categories: Non-financial and financial.

2.2.1. Non-financial performance measures

Important metrics include: Cycle time, customer service level, inventory levels, resource utilization, performability, flexibility, and quality. There is a detailed discussion of these in [46]. We will focus here on the first four measures.

Cycle time: Cycle time or lead time is the end-to-end delay in a business process. For supply chains, the business processes of interest are the supply chain process and the order-to-delivery process. Correspondingly, we need to consider two types of lead times: *Supply chain lead time* and *order-to-delivery lead time*. The order-to-delivery lead time is the time elapsed between the placement of order by a customer and the delivery of products to the customer. The supply chain process lead time is the time spent by the supply chain to convert the raw materials into final products plus the time needed to deliver the products to the customer.

Customer Service Level: Customer service level in a supply chain is a function of several different performance indices. The first one is the *order fill rate*, which is the fraction of customer demands that are met from stock. For this fraction of customer orders, there is no need to consider the supplier lead times and the manufacturing lead times. Another measure is the *backorder level*, which is the number of orders waiting to be filled. To maximize customer service level, one needs to maximize order fill rate, and minimize backorder levels. Another measure is the *probability of on-time delivery*, which is the fraction of customer orders that are fulfilled on-time, i.e. within the agreed-upon due date.

Resource utilization: A supply chain network uses resources of various kinds: Manufacturing resources (machines, material handlers, tools, etc.); storage resources (warehouses, automated storage and retrieval systems); logistics resources (trucks, rail transport, air-cargo carriers, etc.); human resources (labor, scientific and technical personnel); and financial (working capital, stocks, etc.). The objective is to utilize these assets or resources efficiently so as to maximize customer service levels, minimize lead times, and optimize inventory levels.

2.2.2. Financial measures

There are several fixed and operational costs associated with a supply chain. Ultimately, the aim is to maximize the revenue by keeping the supply chain costs low. Costs arise due to inventories, transportation, facilities, operations, technology, materials, and labor [2].

2.3. Review of relevant work

An insightful survey of common pitfalls in supply chain management practices is provided by Lee and Billington [29]. This paper deals with quantitative models for supply chain management. A research summary of various quantitative models for supply chains is provided in [45]. These models can be broadly classified into optimization models, analytical performance models, and simulation models. The tools and techniques used for optimization in industry for solving supply chain problems are discussed by Hicks [22,23].

2.3.1. Optimization models

A major portion of the supply chain literature consists of multi-echelon inventory control models. A comprehensive review of these models can be found in Vollman et al. [49]. These methods generally deal with operational or tactical/operational levels. Multi-echelon inventory models have been successfully implemented in industry. Cohen et al. [8] describe OPTIMIZER: IBM's multi-echelon inventory system for managing service logistics. They develop efficient algorithms and data structures to achieve large scale systems integration. Ettl et al. [14] consider a supply network model to generate base stock levels at each store so as to minimize the overall inventory capital and guarantee the customer service requirements.

The other major focus area of supply chain optimization models is to determine the location of production, warehousing, and sourcing facilities, and the paths the products take through them. These methods provide models mostly for strategic and strategic/tactical levels. One of the earliest works in this area is by Geoffrion and Graves [21]. They describe a mixed integer programming model for determining the location of distribution facilities. Cohen and Lee [9,10] consider global manufacturing and distribution networks and formulate mixed integer optimization programs. Lee and Billington [31] validate these models by applying it to analyze the global manufacturing strategies of Hewlett-Packard. Arntzen et al. [1] provide a comprehensive deterministic model for supply chain management called global supply chain model (GSCM), to determine optimal manufacturing and distribution strategies. A successful implementation of this model was done at the Digital Equipment Corporation.

2.3.2. Analytical performance models

Models of supply chains in a dynamic and stochastic environment consider the network as a discrete event dynamic system. Such systems can be studied as Markov chains, stochastic Petri nets and queueing network models [38,47]. Malone and Smith [32], in their study, have looked at organizational and coordination structures, which constitute a key element of any business process. Raghavan and Viswanadham [37] discuss performance modeling and dynamic scheduling of make-to-order supply chains using fork-join queueing networks. Viswanadham and Raghavan compare make-to-stock and assemble-to-order systems using generalized stochastic Petri net models [48]. They also use integrated queueing and Petri net models for solving the decoupling point location problem, i.e. the point (facility) in the supply chain from where all finished goods are assembled to confirmed customer orders [38].

2.3.3. Simulation and information models

Models discussed above are high abstraction models for business processes under simplifying assumptions such as Markovian dynamics. To obtain very accurate and detailed models, one has to represent many realistic features, which is possible in simulation models. Development of simulation models for understanding issues of supply chain decision making has gained importance in recent years. Some of the studies are Malone [33], Connors et al. [11], and Feigin et al. [15]. Bhaskaran and Leung [3] describe re-engineering of supply chains using queueing network models and simulation.

Feigin et al. have looked into enterprise modeling and simulation in an object oriented environment [15]. Similar work has been done by Mujtaba et al. [35] and Chu [7]. But typically developing and implementing object models for a given supply chain takes a long time. A set of generic objects representing various entities of supply chain can greatly shorten this period. Swaminathan et al. [44] have taken this approach.They have built a generic object-based agent framework with which they can build simulation models for a variety of supply chain networks.

The Integrated Supply Chain Management (ISCM) Project [17,18,27] has led to the development of a unified testbed used by the agents built for supply chain functions: Logistics, transportation management, order acquisition, resource management, scheduling and dispatching. These agents rely on ontologies for activity, state, time, resources, cost, quality and organization as a common vocabulary for communication and use the services of Information Agents that automatically distribute information and manage information consistency and evolution.

Huang et al. [25] have proposed mobile objects as a natural framework for structuring a supply chain information system. Much of the recent work on web-enabled supply chain information systems [36] also uses the object model as the conceptual framework.

2.3.4. *Software tools*

A variety of commercial software packages for supply chains indicate the growing importance of this area.

- IBM Supply Chain Simulator (IBM-SCS): The IBM supply chain simulator is a software tool that can help a company or a group of companies make strategic business decisions about the design and operation of its supply chain [6]. IBM-SCS deploys a mix of simulation and optimization functions to model and analyze supply chain issues such as facilities location, replenishment policies, manufacturing policies, logistics strategies, stocking levels, lead times, process costs, and customer service. SCS is built upon SIMPROCESS, a general purpose business process simulator.
- i2 Technologies (Rhythm) Rhythm or Trade Matrix family of supply chain management products have emerged as leading supply chain products in recent times [39]. The Rhythm suite of products includes: Supply Chain Planner, Supply Chain strategist, Scheduler, Global Logistics Manager, and Demand Planner.
- SAP (APO): Advanced Planner and Optimizer of SAP corporation [12] is now being extensively marketed and deployed. APO consists of the following software modules: Enterprise Planning, Demand Planning, Production Scheduling, and Distribution Planning.
- Manugistics (Manugistics6): Manugistics6 [34] is a broad supply-chain planning and management suite, consisting of the following: Configuration, constraint-based master planning, demand management, manufacturing planning and scheduling, material planning, network design and optimization, purchase planning, replenishment planning, supply chain analytics, transportation management, vendor managed inventory (VMI)/continuous replenishment planning (CRP).

2.3.5. *DESSCOM relevance*

Commercial ERP tools such as SAP R/3 [12] etc. have detailed objects for supply chain elements but do not use any sophisticated decision-making algorithms since the emphasis is on automating transaction processing. Commercial supply chain tools such as Rhythm and Trade Matrix [39] focus mostly on very specific supply chain problems and sophisticated algorithms for chosen few problems. Use of general purpose simulation packages entails extensive work in creating a supply chain model and typically support only simulation. Special purpose tools such as the

IBM-SCS [6] enable rapid creation of supply chain models, but support only simulation and a small set of other OR techniques. The ISCM project [27] provides autonomous agents for operational and tactical level planning. The above tools are focused on building models to support very specific decision making and commit to addressing problems at a specific level of detail only. The tool proposed in this paper, DESSCOM, provides capabilities to model supply chains at different levels of detail by providing different levels of abstraction of objects comprehensively and consistently. This provides DESSCOM with the power to enable solution of a hierarchy of decision making problems.

3. Object models of supply chains

In this section, we first discuss the need for and the advantages of object oriented modeling approach. Following this, we present our object library for supply chains. We provide a detailed description and classification of various objects in our library. Finally we bring out the utility of the object library using an illustrative example.

3.1. Rationale for object models

One reason for the widespread appeal of object oriented modeling [4,26,40] is the *natural mapping* paradigm. This is made possible by the object construct, which allows a one-to-one mapping between objects in the system being modeled (e.g. distributor, supplier, plant, vehicle, etc.) and their abstractions in the object model. Object oriented modeling also has a major effect on implementation through its facilitation of modular design and software reusability. When exploited, object oriented programming features such as encapsulation, inheritance, and polymorphism facilitate code reuse and programming efficiency. The feature of encapsulation enforces structured development. Object oriented modeling also offers potential advantages in the incremental development and verification of large-scale systems. Thus object oriented modeling applied to supply chain modeling and analysis can be potentially very beneficial.

Supply chain decision making requires rapid and flexible modeling approach at various levels of detail. Object oriented modeling can be used to design and implement reusable classes for building models of supply chains and create a supply chain object library. The concept of an object library facilitates rapid model development of any given supply chain and aids in application of the modeling architecture to specific scenarios at various levels of abstraction.

3.2. Major objects in the supply chain library

We present an object library with reusability and extensibility features for modeling and analysis of supply chain networks. We classify the elements of our object library into two categories: Structural objects and policy objects.

The structural objects are the physical entities of supply chain networks. The physical structure of the supply chain networks is modeled using these classes. Physically the supply chain network is composed of plants, warehouses, distributors, retailers, suppliers, customers, orders, vehicles, etc. The policy objects embed business logic which is used for controlling the flow of products and information through the network. The policy elements provided in our library are inventory policy, order management policy, demand planning policy, supply planning policy, distribution policy.

The set of structural objects is used in conjunction with the policy objects to build the object models of a supply chain. These models are used to provide customized inputs for various decision problems to be studied.

3.2.1. Structural objects

The classes representing the structural objects are described below. We provide a taxonomy of the objects in Fig. 1. The objects like suppliers, distributors, etc. are considered to be external entities. Therefore their subclasses have not been shown in the taxonomy of the supply chain. The supply chain consists of the following entities:

Customer: A customer can be either an internal customer or an external customer. The internal customers are the various entities of the network like the plants and the distributors. The external

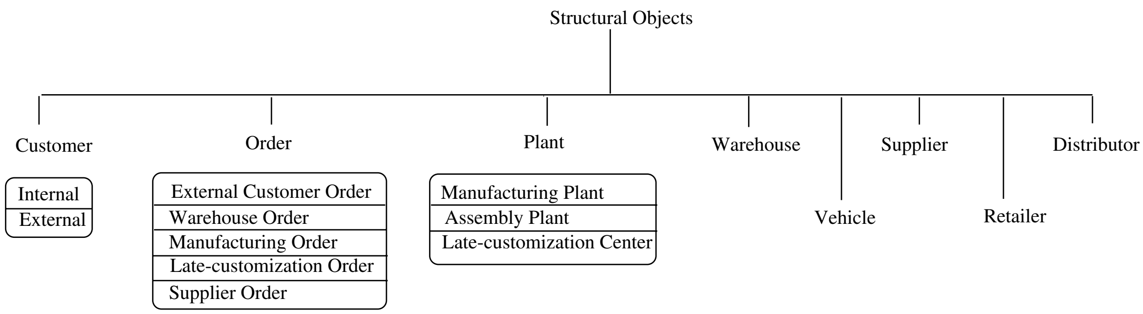

Fig. 1. A taxonomy of structural objects.

customers are the consumers of the products (finished or semifinished) of the supply chain. The customer class may also contain information on the desired service level and priority of the customer.

Order: An order contains the name and the quantities of the desired products, the name of the customer, and the name of the entity to which the order is placed. An order can belong to any of the following categories: external customer order, warehouse order, manufacturing order, late-customization order, and supplier order. External customer orders are generated either from forecasts (demand planning policies) or by the customer objects in a deterministic manner.

Plant: A plant manufactures or assembles finished or semifinished products from raw materials, and/or sub-assemblies. A plant may have its associated raw material warehouse, in-process inventory warehouse, and finished goods warehouse. We have the following derived classes from the base class plant: Manufacturing plant and late-customization center. Manufacturing process requires specified cycle time to convert input parts into output products. Several factors are responsible for the performance of a plant, for example the capacity, availability of input parts, and the fluctuations in the cycle time.

Supplier: A supplier provides a plant with raw materials or sub-assemblies. A supplier could be a manufacturing plant, or a late-customization center, or a full fledged supply chain. Since the supplier is outside the purview of the supply chain under study, it is modeled as a class which can supply the required products under specified constraints. We have considered only lead-time and capacity constraints, but other specific constraints can be easily added to the supplier class.

Retailer: An external customer generally buys the products from the retailer. A retailer has an associated warehouse, where the inventories of the products are stored. A retailer can receive deliveries from distributor, or manufacturing plant, or late-customization center, or from some other retailer. The product is delivered to customer if it is available in the retailer's warehouse. Otherwise the order is added to a queue for the particular product, according to a pre-assigned priority. The order is delivered when the product is received (from distributor, or plant, or late-customization center as the case may be).

Distributor: A distributor receives deliveries from manufacturing plant, or late-customization center, or from other distributors. The distributor may have an associated warehouse. It supplies to the retailers, or sometimes to other distributors. It may also supply to the late-customization center with information on customer specified requirements.

Vehicle: Transportation vehicles move products from one node of the network to another. Each vehicle has characteristics in terms of products it can carry, capacity (in volume or weight), costs, and speed.

Warehouse: A warehouse is a storage facility which is characterized by the nature and capacity of the products it can store. A warehouse can be attached to the plant, the distributor, and the retailer. A warehouse can be used for storage of raw-material inventories, in-process inventories, and finished product inventories.

3.2.2. Policy objects

The policy objects model strategies which describe the protocols used in procurement, manufacturing, transportation, and distribution of material within the supply chain. Policy objects have an identity and behaviour of their own and it is therefore appropriate to model them as full-fledged objects. Moreover, separating the policy objects from the structural objects enables composing them in very flexible and powerful ways to obtain comprehensive modeling power. Policy objects enable a society of structural objects to have varying behaviours. For example, a structural object such as "Warehouse" can be composed with a policy object such as "Inventory Policy" to describe different types of warehouse management and replenishment schemes. We have identified and defined the following policy objects. A taxonomy of the policy objects is shown in Fig. 2.

Inventory policy: Inventory policies guide the flow of materials in the supply chain networks. Different inventory policies include multi-echelon inventory policies, and EOQ policies [14,24,49].

Manufacturing policy: The manufacturing policy can be make-to-stock, or make-to-order, or assemble-to-order, or a combination of these policies [9,11,30,38].

- *Make-to-stock policy:* The plant builds products according to advance plans, and pushes the finished products into the warehouses.
- *Make-to-order policy:* The plant produces a product from its input parts only when an order for that product is received.
- *Assemble-to-order policy:* The manufacturing plant produces components which can be assembled by the late customization center according to customer specification.

Order management policy: The order management policy models the order processing and scheduling at any node of the supply chain. The delay incurred in the process is also considered. For simplicity we do not allow any partial shipment of an order.

Demand planning policy: The demand planning policy generates forecasts of expected demands for future periods. Various forecasting policies like time series, and regression analysis (based on factors like competition, economic condition, promotional efforts, etc.) are considered [16].

Supply planning policy: Supply planning is a critical process in determination of company's service and inventory levels. This models the allocation of production and distribution resources to meet the actual and forecasted demand under capacity and supply constraints [10,13,16].

Distribution policy: The product distribution is the process of delivering a product from the supplier site to the end customer. The scheduling policies include routing and scheduling of vehicles to optimize delivery schedules [19].

3.3. Design patterns

Design patterns [20] have emerged as an important best practice in object oriented design. The use of design patterns enables robust and highly reusable objects to be created. This is a critical requirement for DESSCOM's object library. Several design patterns have been used as part of

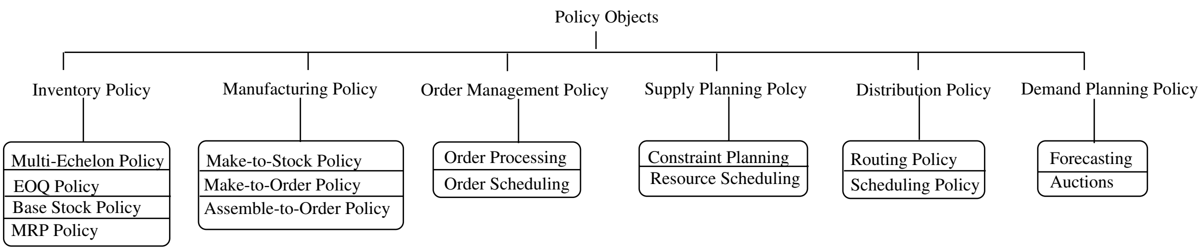

Fig. 2. A taxonomy of policy objects.

DESSCOM's object library. These include abstract factory, strategy, mediator, composite, and chain of responsibility. We will discuss two of the design patterns [20] we have used in building DESSCOM.

- *The strategy pattern:* The Strategy pattern consists of a number of related algorithms encapsulated in the form of classes. A class which requires a particular service or function and which has several ways of carrying out that function is a candidate for the Strategy pattern. Objects choose between these algorithms based on computational efficiency or user choice. There can be any number of strategies and more can be added and any of them can be changed at any time. There are a number of cases in programs where we would like to do the same thing in several different ways. For example, we may have different distribution strategies (Fig. 3). Strategy pattern allows us to choose from several algorithms dynamically.
- *The mediator pattern:* When a program is made up of a number of classes, the logic and computation is divided logically among these classes. However, as more of these isolated classes are developed in a program, the problem of communication between these classes becomes more complex. The more each class needs to know about the methods of another class, the more tangled the class structure can become. Further, it can become difficult to change the program, since any change may affect code in several other classes. The Mediator pattern addresses this problem by promoting looser coupling between these classes. Mediators accomplish this by being the only class that has detailed knowledge of the methods of other classes. Classes inform the mediator when changes occur and the Mediator passes them on to any other classes that need to be informed. The various supply chain objects in our system communicate with the help of mediator class objects. For example we have created mediator objects to communicate between various suppliers, vehicles, and plants; plants, warehouses, distributors, retailers, and vehicles. The advantage is that the mediator is the only class that needs to be changed if some classes change or new classes are added. Thus reuse of the various objects become easier.

3.4. An illustrative example

To illustrate creation of object models by DESSCOM, we discuss a real-world supply chain network and present a first level object model that will be created by DESSCOM-MODEL. The system (see Fig. 4) [41] can be described as follows. Shri Shakti (SS) LPG Limited imports and markets liquid petroleum gas (LPG) in South India. SS has its import facilities located at Kakinada and Mangalore ports. It has two storage facilities, one for each port. The storage facilities are located in the vicinity of these ports. The LPG is transported from the port to the storage facilities through pipelines. The quantity of LPG that SS can import at either of the ports is practically unlimited. SS

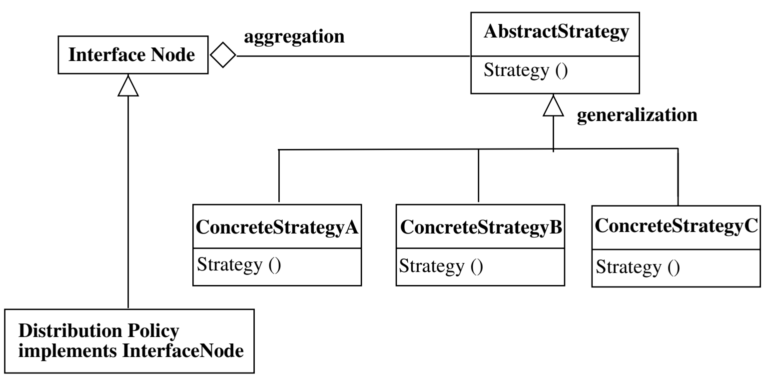

Fig. 3. An example of a strategy pattern.

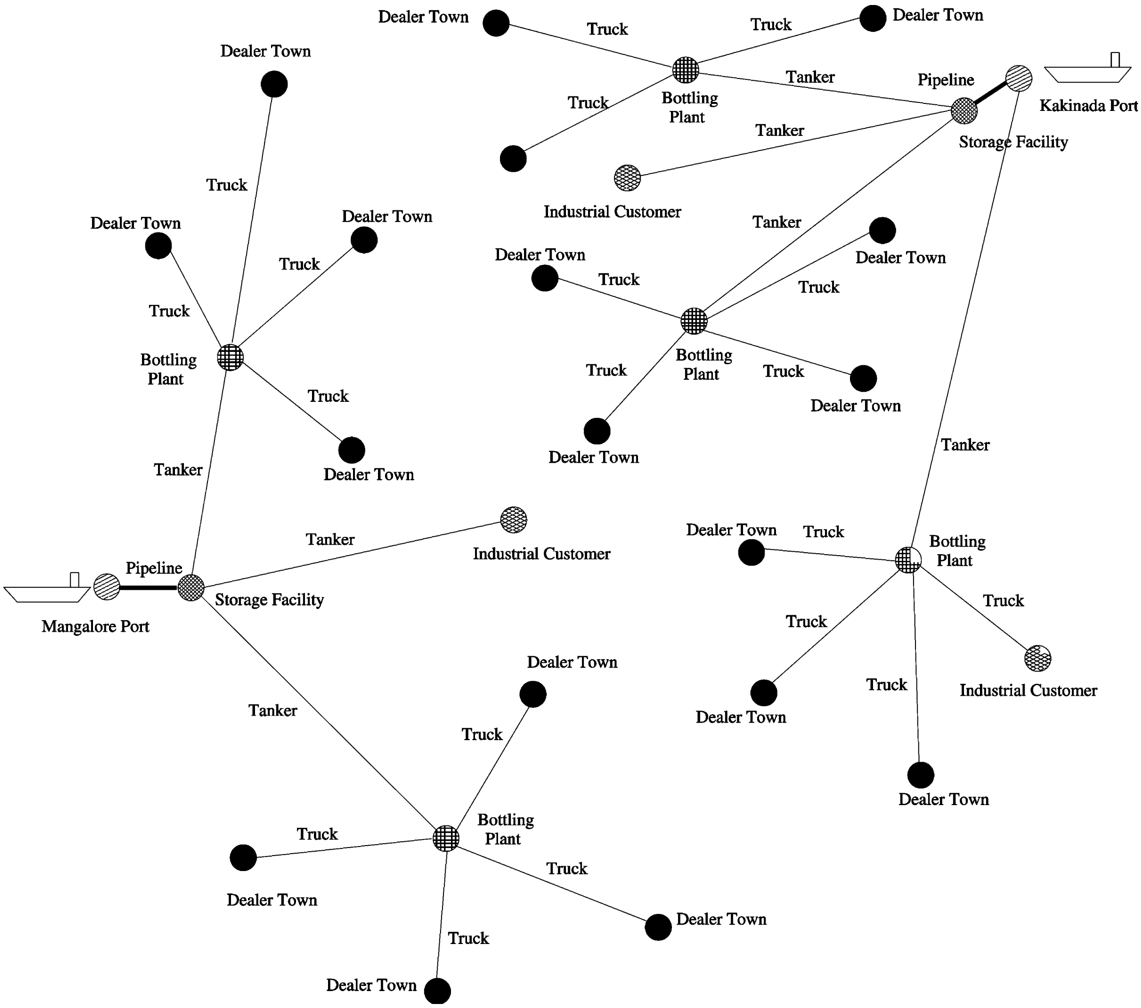

Fig. 4. Diagram representing the SS LPG supply chain.

sells LPG in bulk to industrial customers directly from the two storage facilities. It markets LPG in packed form to domestic and commercial establishments through its dealers. When a customer's cylinder runs out of LPG, the dealer replaces the empty cylinder with a filled cylinder at the customer's location (dealer and customers are typically at most five miles apart). The dealer recovers the cost of transporting cylinders from commission on a per-refill basis from SS.

Each dealer town (town in which SS has one or more dealers) gets its supplies from a designated bottling plant. Each bottling plant typically services a set of dealer towns. Each dealer sends the empty cylinders in full truck loads to its associated bottling plant. Since the plant maintains an inventory of filled cylinders, the trucks are fully loaded with filled cylinders on their return trips to the dealer. Each bottling plant receives LPG in tankers from the cheaper of the two ports and storage facilities (those at Kakinada and Mangalore), cheaper in terms of per unit cost of procurement and transportation. The tankers are dedicated to transporting LPG, and hence, SS pays the transporters for both delivery and return trips to the storage facilities.

An object model for this system can be built using the object library of DESSCOM. SS supply chain follows make-to-stock manufacturing policy. This system consists of the following entities: Port, pipeline, LPG storage facility, tanker, industrial customer, bottling plant, truck, dealer, domestic customer, and commercial customer. The make-to-stock policy and the above objects are derived from our object library. The object model built using DESSCOM's object library for this system is shown in Fig. 5. This object model becomes the basis for formulating and studying various strategic, tactical, and operational decision issues. We shall discuss the use of DESSCOM in modeling and solving some of these problems in Section 5.

Note that this object model includes only structural objects. By including policy objects appropriately, the model will be able to describe the supply chain structure and behaviour completely. For example, a policy object "Inventory Policy" suitably subclassed into classes such as "EOQ Policy", "Multi-echelon Policy", etc can be composed with a structural object such as "Warehouse" to describe inventory control dynamics in the supply chain. Similarly, a policy object such as "Distribution Policy" can be composed with a structural object such as "Distributor" to represent a wide variety of distribution mechanisms.

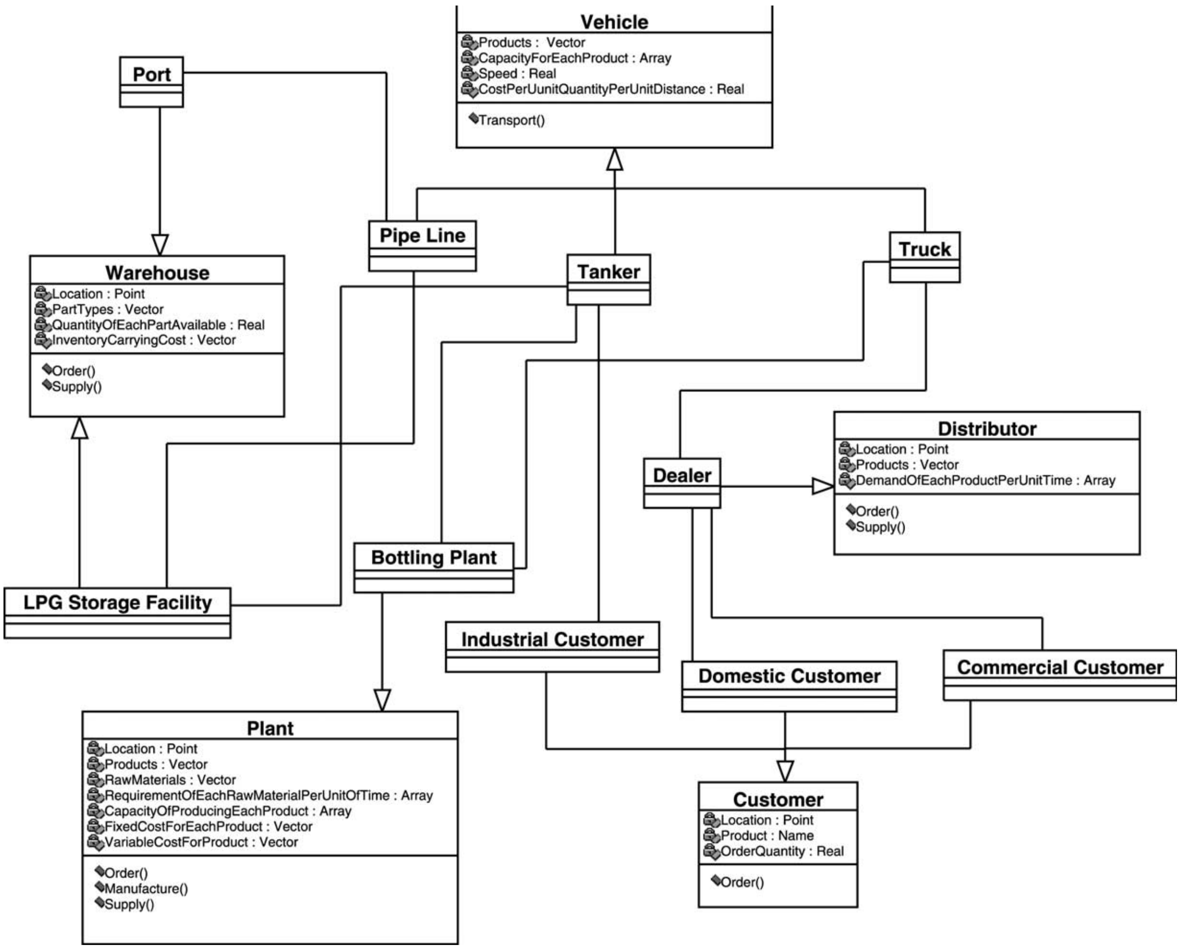

Fig. 5. An Object model of SS LPG supply chain.

4. Architecture of DESSCOM

Fig. 6 shows the architecture of DESSCOM. The arrows in the diagram indicate either "sequence" information or "data dependency" information. The system has two major subsystems.

- DESSCOM-MODEL, a modeling system that facilitates rapid creation of supply chain models at a desired level of abstraction using a library of generic objects
- DESSCOM-WORKBENCH, a decision workbench that can support a wide variety of tools and techniques which could be deployed in supply chain problem solving.

4.1. DESSCOM-MODEL

The modeling system provides a library of generic supply chain objects. One can construct hierarchical models of any supply chain under consideration using these objects. These constructs

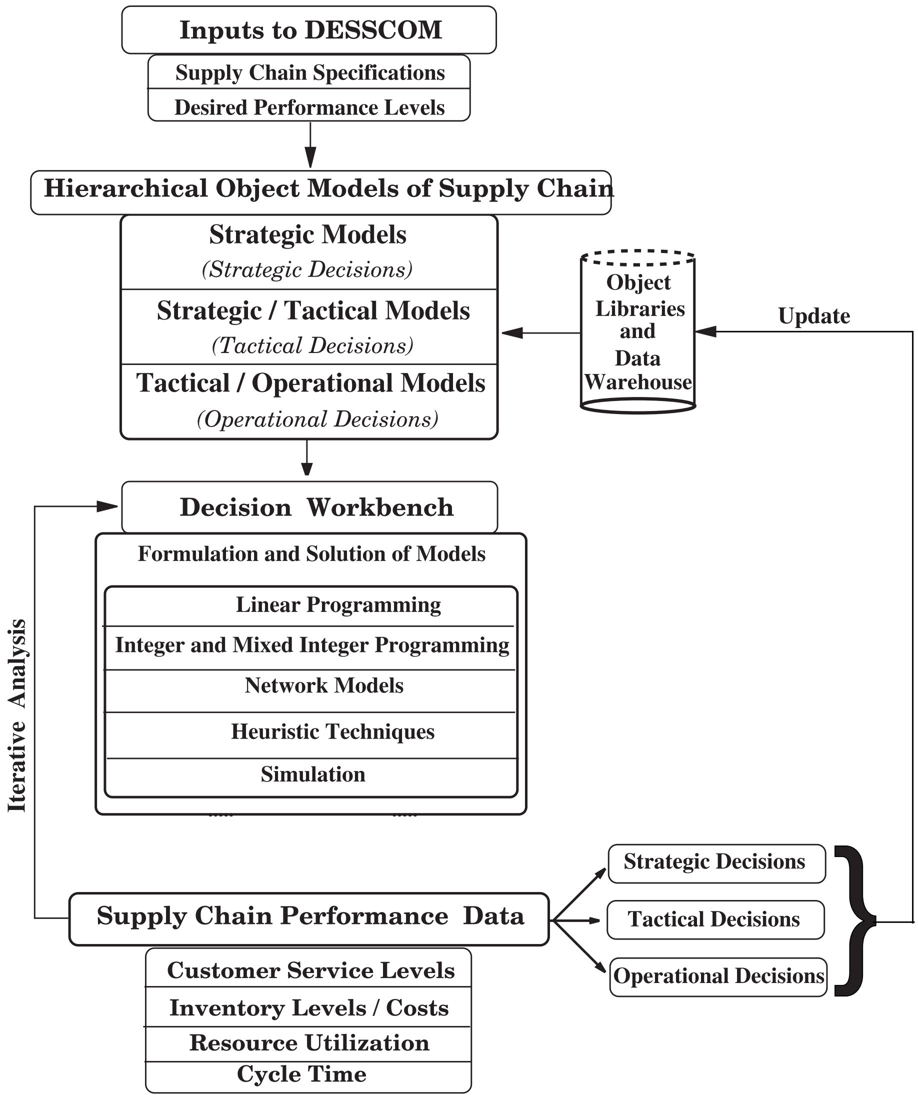

Fig. 6. The architecture of DESSCOM.

can be modeled at required granularity to aid in strategic, tactical, and operational decisions. The modeling process starts with identification of structural objects and policy objects in the network. The network configuration can be updated at any point of time by adding or altering various objects of the supply chain without having to take recourse to cumbersome programming efforts. The models thus created can be used in analysis of the system under various scenarios. DESSCOM can therefore be used to optimize the system and evaluate performance measures under different scenarios. The development time for various models is considerably reduced. These models are used to provide inputs for various tools of the decision workbench. The object library has been described in Section 3.2 and an object model for an illustrative supply chain has been presented in Section 3.4.

4.2. DESSCOM-WORKBENCH

Different problems require different modeling approaches. Some problems may require detailed simulation models to evaluate various alternatives available. For example, the problem of deciding the best manufacturing control strategy among make-to-stock, make-to-order, and assemble-to-order does not admit any easy or tractable analytical models. On the other hand, there are various problems such as selection of new suppliers and scheduling which can possibly be modeled accurately analytically. There are certain cases where the iterative use of a modeling approach may provide the best solution. For example, consider the problem of controlling inventory at various locations while maintaining service levels for customers. This problem can be solved analytically only at an aggregate level of detail. Therefore after getting an initial solution through an analytical approach the system can be simulated under various scenarios to evaluate the system by capturing the dynamics in more detailed way. Thus simulation along with analytical modeling can often be deployed in the decision making process.

As already reviewed in Section 2, there are a wide gamut of tools and techniques deployed in supply chain problem solving at the strategic, tactical, and operational levels. We have elaborated on this topic in Section 2. DESSCOM-WORKBENCH includes commonly deployed approaches such as linear programming, mixed integer programming, and simulation, and can also easily support customized solutions.

Different tools in the workbench need the supply chain details to be presented in different ways and at different levels of abstraction. Object models can support this in a natural way. Such models once built can be used to provide customized viewpoints required for specific supply chain issues.

Thus DESSCOM could be used by the users who are responsible for implementing supply chain decisions. The decision workbench can be used to compute various optimal decisions or to evaluate different alternatives available.

4.3. Use of DESSCOM

The usage of DESSCOM can essentially be organized into the following four steps: Specify supply chain, generate problem formulation, solve problem, and iterate if necessary.

4.3.1. Specify supply chain

The construction of object models require proper identification of the following:

- structural objects,
- policy objects,
- connections between various objects.

Structural features of a supply chain may include some or all of the following:

Suppliers: Number of vendors, capacity allocated to each of them, their locations, etc.

Logistics: Number, location, size, and capacity of warehouses, modes of transportation, in-house fleet, contract carriers, etc.

Manufacturing: Plant location(s), flexible or dedicated manufacturing plants, capacities, etc.

Distribution: Location size, and capacity of distribution centers and architecture, retailer locations, etc.

The policies adopted at the various objects need to be specified. Examples include: whether the supply chain follows a make-to-order manufacturing policy, or what are the inventory policies practiced by the distributors and the retailers, or what customer service levels are required to be attained, etc. The various modes of transport and possible routes available between the various entities have to be defined.

Once the identification of various objects of the supply chain is complete, the mapping of the actual entities to the objects of our library is to be done. The scope of the objects can be suitably enhanced or constrained by inheriting and instantiating various classes from the object library.

When we create an object model of a given supply chain the following variables are instantiated amongst others:

- SupplyChain.NoOfPlants
- SupplyChain.NoOfDistributor
- SupplyChain.P[i]: ith plant
- SupplyChain.P[i].XCoord: X-coordinate of the ith plant
- SupplyChain.P[i].YCoord: Y-coordinate of the ith plant
- SupplyChain.P[i].Capacity[p]: Capacity for producing product p
- SupplyChain.P[i].FixedCost[p]: Fixed cost associated with p
- SupplyChain.P[i].VariableCost[p]: Variable cost associated with p
- SupplyChain.D[j]: jth distributor
- SupplyChain.D[j].XCoord: X-coordinate of the jth distributor
- SupplyChain.D[j].YCoord: Y-coordinate of the jth distributor
- SupplyChain.D[j].AnnualDemand[p]: Annual demand at j.

4.3.2. Generate problem formulation

The object model created in the previous step is then used to generate the data for an analysis or an optimization model of the supply chain. For example, it may be required to compute the supply chain process lead time using a queueing network model, in which case, the data required for the queueing network model is picked up from the object model at the required level of detail. As another example, let us say, we wish to find optimal locations for the supply chain facilities, in which case, the data required for a MILP capturing this problem is picked up from the object model. Automatically generating the problem formulation becomes possible for some standard, well known problems in supply chains. For such problems, DESSCOM precisely knows what are the inputs, decision variables, and what is the exact problem to be solved. DESSCOM also knows the object structure to expect for this problem and also knows how to pick up the input parameters from these objects. Manual intervention is required only to direct DESSCOM to the relevant problem and an appropriate problem solving tool.

We have created an interface which allows the use of these variables to create a model for well defined problems. Often, other inputs like new plant capacities, fixed costs, and variable costs etc. are needed as input to build the MILP model. We have provided standard equations used in facility location problems. The user has to specify the constraints which does not appear in our list using Java constructs. We have provided some examples to help the user build the same.

4.3.3. Solve problem

The problem formulation generated above is then solved using an appropriate methodology. For example, a queueing network model formulated in the above step can be solved by a queueing network solver provided in DESSCOM-WORKBENCH. Or a MILP formulated in the above step can be solved by a standard package available in the workbench. Often, a model formulated in the previous step may be solvable by a variety of methods provided in the workbench. In such cases, the user of DESSCOM will need to deploy the most appropriate tool to employ. A knowledge-based system that can select the most appropriate tool to use, based on the nature of the input problem will be very useful here.

4.3.4. Iterate

When the problem is solved, we either get some analysis results or we get optimal values for certain decision variables. If we wish to use the analysis results to decide new settings for some decision variables, then we need to conduct the analysis again to see if the new settings result in performance improvement. Typically, when a descriptive model is analyzed repeatedly each time with new settings to improve performance and ultimately optimize the system performance, we will need to use the DESSCOM-WORKBENCH iteratively. Also, often, we may use an analytical model to obtain optimal parameters at an aggregate level and subsequently use a more detailed model such as simulation to fine-tune these parameters to take into account details.

4.4. Implementation of DESSCOM

The development of DESSCOM was done on Sun Solaris™ platform. The object library and the workbench have been encoded in Java™ programming language [28]. Hence our system is platform independent.

The object modeling for supply chain networks was done using UML [5]. We prepared the various UML models of supply chain networks using Rational Rose™ [43]. Most of the code of the various classes of the object library was automatically generated from these UML models by Rational Rose. The main classes of the object library have already been described in Section 3.

DESSCOM-WORKBENCH uses the object models of a given supply chain to provide customized input for various tools and techniques. As a first step, we have integrated the following different tools with our workbench to support decision making.

- a linear programming package,
- a Mixed integer linear programming package,
- standard inventory control policies,
- a discrete event system simulator.

5. Case study of a liquid petroleum gas supply chain

We now consider the LPG supply chain presented in Section 3.4 and demonstrate the efficacy of DESSCOM in modeling and decision making. For this problem, we discuss:

- location of bottling plants (an example of a strategic decision),
- aggregate level inventory optimization (an example of a tactical decision),
- detailed level inventory optimization (an example of an operational decision).

The object model developed in Section 3.4 can be used for studying various decision problems. First, we discuss the use of DESSCOM in modeling and solving the location problem investigated by Sankaran and Raghavan [41].

5.1. Location of bottling plants

Plant location is a strategic decision that management takes prior to other decisions like marketing strategies, or production planning decisions. For the LPG supply chain under discussion, Sankaran and Raghavan [41] have developed a MILP for solving the plant location problem. The inputs required for the above MILP are shown in Table 1. Given these inputs, it is required to determine the optimal number of LPG plants and optimal locations for these LPG plants.

Table 1
Inputs required for the location problem

m	The number of potential plant sites
n	The number of dealer towns
i	An index for plant sites
j	An index for dealer towns
k	An index for plant sizes
D_j	The annual sales potential for LPG (in MTPA) in town j
f_k	The fixed cost of an LPG bottling plant of size k
C_k	The capacity (in MTPA) of a bottling plant of size k
c_{ijk}	The annual cost of transportation of assigning town j to site i of capacity k

DESSCOM helps generate inputs for various linear programming and integer linear programming models in the well known mathematical programming system (MPS) format and linear programming (LP) format. The inputs for the MILP model for the location problem are generated by DESSCOM. This is discussed below for some sample cases.

- The capacity and costs associated with a plant are parameters of the plant class. Thus for generating the inputs for an ILP these values are taken from each instance of plant class.
- Location is a parameter for the classes: plant, warehouse, dealer, and customer. Therefore generating Euclidean distances between any pair of instances of these classes is straightforward.

Thus, once we have constructed the object model of a system, deriving the inputs for any well defined optimization algorithm can be carried out. The activity diagram for the plant location problem is given in Fig. 7. The corresponding MILP generated in LP format was given as input to the well known optimization solver lp-solve.

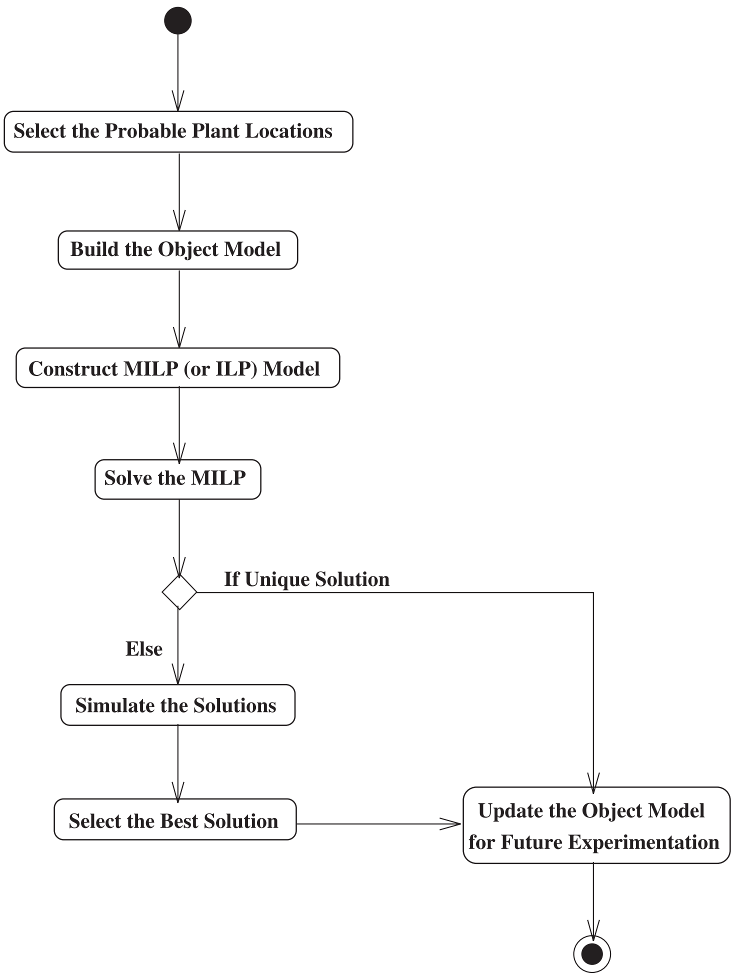

Fig. 7. Activity diagram for the location problem.

We now discuss a specific instance of the location problem that we solved using DESSCOM using some synthetic data. Suppose SS has two bottling plants P_1 and P_2 of capacity 5000 tonnes per annum. The marketing division has identified a potential additional demand for about 6500 metric tonnes per annum (MTPA). This requires setting up additional LPG plants. Assume that SS has identified two new plants (P_3 and P_4) say in addition to the already existing ones and the management of SS is debating over the alternatives available.

The costs associated with setting up (fixed costs) and running (variable costs) new plants of various capacities are given in Table 2. Considering the Kakinada port as the origin, we have provided each plant and dealer towns with X- and Y-coordinates. The coordinates of the plants and the dealer towns are given in Tables 3 and 4. The unit of measurement is kilometers. The transportation cost is considered as a constant multiple of the distances between the plants and the dealer towns. Using the available data we generated a MILP for the location problem under consideration. Using lp-solve provided in DESSCOM-WORKBENCH, a new plant P_3 of 7000 MTPA capacity was found to offer the optimal solution to the MILP. The costs and and the dealer towns assigned to the plants P_1, P_2, and P_3 corresponding to the optimal solution are provided in Tables 4 and 5.

Table 2
The fixed and variable costs associated with LPG plants of various capacities

Plant capacity (1000 MTPA)	Fixed cost (Rs. millions)	Variable cost (Rs. millions/tonne)
1.0	21.5	0.62
3.0	22.7	0.54
5.0	23.5	0.48
7.0	24.6	0.45
9.0	25.4	0.43

Table 3
Coordinates of plant locations

Plant	X-coordinate	Y-coordinate
1	200.0	300.0
2	1800.0	1700.0
3	600.0	1400.0
4	1300.0	700.0

Table 4
Coordinates of dealer towns and the associated annual demands and plants

Dealer town	X-coordinate	Y-coordinate	Associated plant	Annual demand (in cylinders)
1	100.0	100.0	1	21 000
2	400.0	300.0	1	40 000
3	300.0	500.0	1	15 000
4	400.0	800.0	1	28 000
5	600.0	1600.0	3	56 000
6	700.0	1000.0	3	18 000
7	700.0	200.0	1	61 000
8	900.0	1500.0	3	49 000
9	1500.0	1600.0	2	36 000
10	1400.0	2000.0	2	75 000
11	100.0	1900.0	3	44 000
12	1400.0	1500.0	2	67 000
13	1900.0	2100.0	2	40 000
14	400.0	1700.0	3	58 000
15	2100.0	1300.0	2	12 000
16	800.0	1900.0	3	18 000
17	2100.0	1700.0	2	51 000
18	1100.0	200.0	1	35 000
19	1200.0	500.0	1	27 000
20	300.0	1400.0	3	76 000
21	100.0	1200.0	3	46 000
22	0.0	700.0	1	39 000
23	400.0	2100.0	3	72 000
24	800.0	600.0	1	65 000
25	1100.0	1500.0	2	31 000

Table 5
Optimal plant locations and associated annual demands

Plant	No. of associated dealer towns	Associated port	Annual demand (in cylinders)
1	9	1	331 000
2	7	2	312 000
3	9	2	437 000

5.2. Aggregate level inventory optimization: An analytical approach

The object model developed above can be used in many other ways. We shall now describe its applicability to a tactical decision problem, namely a multi-echelon inventory problem arising in the SS supply chain.

Assume that dealers of SS replenish their stock of filled cylinders from a fixed bottling plant. Each bottling plant in turn gets its supply of LPG from a fixed storage facility located at a port. This is a two echelon inventory system. We assume the (Q, r) policy [24] is followed at both the bottling plant and at the dealer's store. The object model is now required to be updated to capture the inventory policy which is derived from our object library. Note that inventory policy is a policy object. By composing structural object instances with policy objects instances in very flexible ways, one can create all possible supply chain scenarios.

We now discuss how the object model built above can be used to generate the two echelon model discussed in [24], by considering the case of one bottling plant and the associated dealers. The inputs required by the model are given in Table 6.

The decision variables for the problem are: Q_i is the order quantity for product i at the plant, r_i the reorder point for product i at the plant, Q_{im} order quantity for product i at dealer m, r_{im} reorder point for product i at dealer m.

The above decision variables are computed in the following way (see [24] for details). The expected number of outstanding backorders for product i at the plant at any point of time is

$$B(Q_i, r_i) = \frac{1}{Q_i}[\beta(r_i) - \beta(r_i + Q_i)] \approx \frac{\beta(r_i)}{Q_i}$$

where

$$\beta(r_i) = \frac{\theta_i^2}{2}[1 - G_i(r_i - 2)] - \theta_i r_i[1 - G_i(r_i)] + \frac{r_i(1 - r_i)}{2}[1 - G_i(r_i)] \quad \text{and}$$

$$G_i(x) = 0 \quad \text{for } x < 0$$

$$W_i = \frac{B(Q_i, r_i)}{D_i}, \quad Q_i = \frac{D_i}{F}$$

$n(r)$ is the expected no. of backorders during a cycle $= \theta p(r) + (\theta - r)(1 - G(r))$.

To satisfy a service level of S percent, we have to choose the smallest value of r satisfying

$$n(r) \leqslant (1 - S)Q$$

The per unit demands, unit costs, lead times, service levels, order frequencies, and other parameters for solving the above model can be computed from the instances of the various classes of the object model shown in Fig. 5.

We have solved an example case for this problem. The input data are provided in Tables 5 and 7. Table 8 shows the results (that is, reorder points for plants and dealer towns) of the aggregate level optimization.

These results provide good approximate solutions which can be improved upon using simulation. The required data for driving the model was generated from the object model of the

Table 6
Inputs for the multi-echelon inventory problem

N	Total number of distinct product types in the system
M	Total number of dealers served by the plant
D_{im}	Daily demand (units/day) for product i at dealer m
D_i	Daily demand (units/day) for product i at the plant $D_i = \sum_{m-1}^{M} D_{im}$
c_i	Unit cost of part i
l_i	Replenishment lead time (days) for product i to the plant
l_{im}	Lead time (days) for dealer m to receive product i from the plant
θ_i	Expected demand (units) during replenishment lead time for product i ($\theta_i = D_i l_i$)
$p_i(k)$	Probability of exactly k demands during replenishment lead time for product i (assuming Poisson demand) $p_i(k) = \theta_i^k e^{\theta_i}/k!$
$G_i(x)$	Cumulative distribution function of demand for product i during replenishment lead time $G_i(x) = \sum_{k=0}^{x} p_i(k)$
W_i	Expected time (days) an order for product i waits at the plant due to backordering
L_{im}	Approximate effective lead time (years) for an order of $L_{im} = l_{im} + W_i$ product i from from dealer m to be filled by the plant
S	Desired average service level at the plant
F	Desired average order frequency at the plant

Table 7
Inputs for the two echelon inventory system

1 cylinder (cyl) $\equiv$ 15 kg
1 truck $\equiv$ 100 cylinder
c = unit cost of one cylinder = Rs. 150
S_i = desired average service level at plant $i = 95\%$
F_i = desired average order frequency at plant $i = 12$
s_i = desired average service level at dealer $i = 95\%$
F_i = desired average order frequency at the dealer $i = 26$
$\mathrm{EOQ} = \frac{\text{annual demand}}{\text{order frequency}}$

Table 8
Comparison of the reorder points obtained from the analytical model and simulation model

Plant/dealer town	Reorder points from analytical model (truck loads)	Reorder points from simulation model (truck loads)
P_1	4900	5400
P_2	4800	5200
P_3	6700	7000
D_1	1	1
D_2	1	3
D_3	1	1
D_4	1	2
D_5	1	3
D_6	1	1
D_7	1	3
D_8	1	3
D_9	1	1
D_{10}	1	2
D_{11}	1	2
D_{12}	1	3
D_{13}	1	3
D_{14}	1	3
D_{15}	1	1
D_{16}	1	1
D_{17}	1	3
D_{18}	1	3
D_{19}	1	2
D_{20}	1	2
D_{21}	1	3
D_{22}	1	3
D_{23}	1	3
D_{24}	1	3
D_{25}	1	2

supply chain. We use the results (i.e. the reorder points) of this analytical model as an initial input for the simulation model that is discussed next.

5.3. Detailed level inventory optimization: Simulation approach

Here, we show that the LPG object model can also be used to support operational decisions. The multi-echelon inventory problem discussed in the earlier section is considered for modeling by simulation here. We capture the following realistic assumptions while building the simulation model.

- A customer can order for more than one unit at any given time. Therefore we consider the order quantities to be varying between one and a maximum possible order quantity. (This value is one of the parameters to be specified while building the object model. Default value is unity.)
- Actual demands, order frequencies, lead times, service times, and transportation times, can be different from the average values considered for analytical modeling. For the simulation model we have considered all of these parameters to be exponentially distributed.
- The assumption of economic order quantity (EOQ) may not hold in real life. For example due to bulk arrival of orders one may have to order more than the optimal EOQ.

To show the level of detail modeled in the simulation here, we have presented in Fig. 8, an activity diagram for a dealer object in the simulation model.

All the inputs for the earlier analytical approach hold for the simulation model also. The additional inputs required for running the simulation are total simulation time, average service times and transportation times, initial inventory levels, and the reorder levels. We have taken the total simulation time as 90 days or 3 months. The initial inventory levels are assumed to be equal to the expected demand for a fortnight or 15 days. A comparison of the reorder levels obtained through analytical and simulation approaches is provided in Table 8. The results point out that the results from simulation models, which are closer to real life scenarios, tend to differ from the aggregate level analytical solutions. The results highlight the fact that the aggregate analytical results give good approximate solutions. These approximate solutions provide

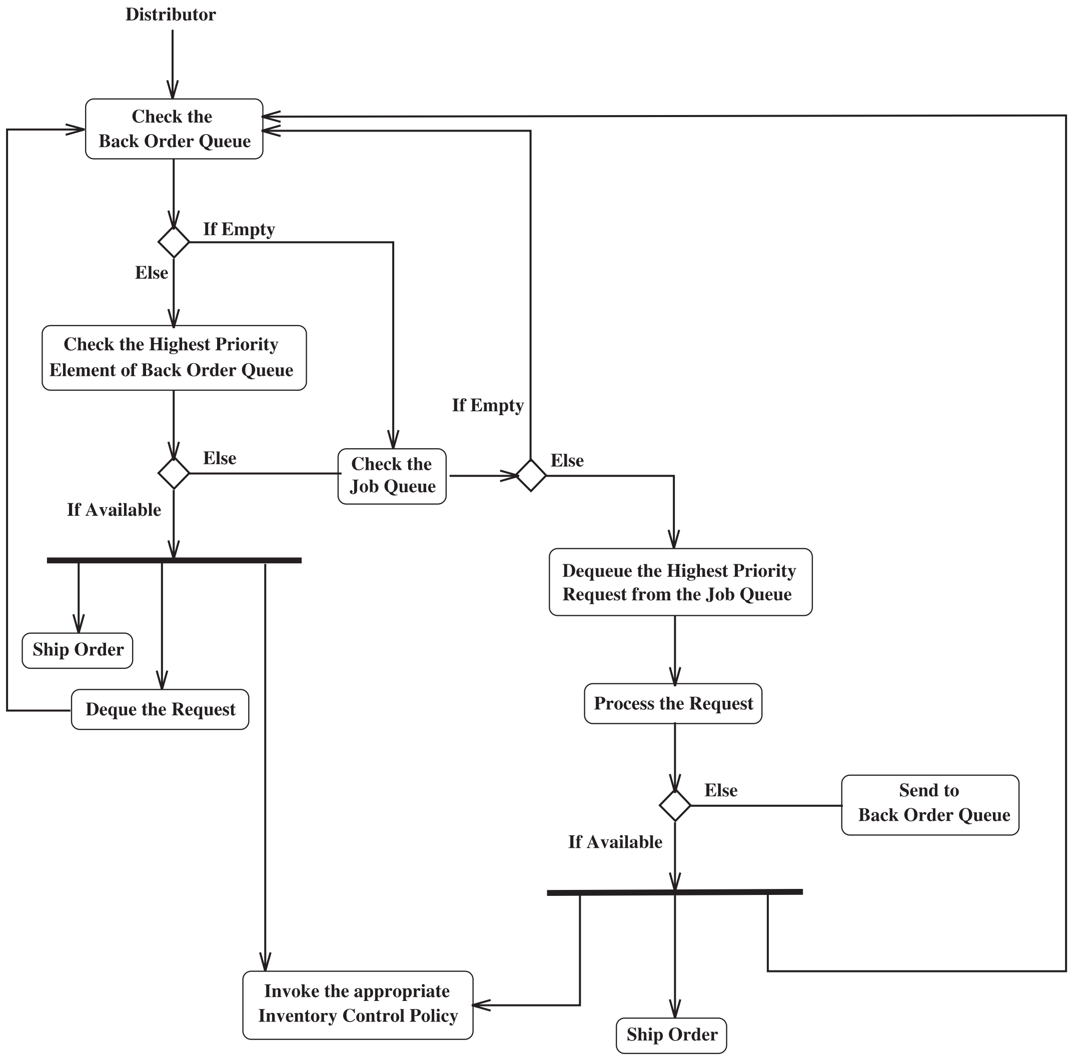

Fig. 8. Activity diagram for the dealer object.

good initial solutions, which can be fine tuned in iterative steps using simulation. It is important to note that significantly greater effort and computational time will be required to obtain a solution from simulation model without the initial starting points obtained from the analytical model.

6. Summary and future work

In this paper we have described DESSCOM, a decision support workbench to support the decision making process in supply chain networks. DESSCOM supports supply chain decision making at the strategic, tactical, and operational levels and comprises two major subsystems:

(a) DESSCOM-MODEL, that facilitates rapid creation of supply chain models at a desired level of abstraction, and
(b) DESSCOM-WORKBENCH, that enables the use of a wide gamut of tools and techniques that can be deployed in supply chain problem solving.

Our approach to modeling of supply chains extends and unifies the earlier approaches to object oriented modeling of supply chains. We have conceptualized and built a comprehensive library of supply-chain specific objects using which faithful and accurate models of given supply chains can be configured. These object models of the network are used to build customized models for various decision problems arising in supply chains at various levels.

We have illustrated the efficacy of DESSCOM using a real life case study of a liquid petroleum gas supply chain in Section 5. The problems studied were:

- location of bottling plants (an example of a strategic decision),
- aggregate level inventory optimization (an example of a tactical decision),
- detailed level inventory optimization (an example of an operational decision).

We have built a prototype of DESSCOM as described in Section 4. We have created the object library using Java programming language. Several further enhancements to DESSCOM are possible. These include

- *Improving the object library:* We have tried to make the object library as comprehensive as possible. But there still is a lot of scope of improving the library. More objects can be added to cover a wider spectrum of supply chains. More attributes and functionalities can be added to the existing classes of our library to reduce the effort involved in adding more functionalities by inheriting from the various classes.
- *Enhancing the workbench:* In the prototype of DESSCOM that we have built we have provided some useful tools for decision making such as mixed integer linear programming package, mathematical modeling tool for multi-echelon inventory optimization, and discrete event simulator. In view of the wide gamut of tools and techniques available, the possibilities of enhancing the workbench are several.
- *Assisting the choice of tool to be employed:* A typical user may not be aware of the various tools available for solving a particular decision problem. A knowledge-based approach to help the user in selecting the proper tools will greatly increase the benefits of DESSCOM.
- *Provide a visual interface to the user for modeling the supply chains:* At present we are using text inputs for specifying the supply chains. A visual user interface for DESSCOM will enhance the ease of modeling. Since DESSCOM is built using Java programming language, minimum effort will be required for providing such an interface.
- *Distributed deployment:* As a further work DESSCOM may be implemented in a distributed environment. It should be provided with the capability for run-time modifications of the objects. This will greatly enhance its modeling capabilities. Real time data from the actual entities of the supply chain can be used for modeling and analysis. The actual impact of various decisions can then be studied and analyzed on line.

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