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An object-oriented framework for simulating supply systems

MD Rossetti*, M Miman and V Varghese
University of Arkansas, Fayetteville, AR, USA

A framework is a set of reusable classes that work together to facilitate the construction of software within a particular domain. In this paper, we present an object-oriented framework for developing simulation models involving supply chain networks. The key object-oriented artefacts for modelling inventory-based supply chain networks are presented including the classes, their attributes, relationships, and behaviours. The framework's implementation within Java is also presented through a number of examples. The examples illustrate the capabilities of the framework to build large-scale multi-echelon, multi-item inventory networks with time-based transport between locations.
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1. Introduction

We conceptualize a supply chain as a network of facilities and distribution options that allow products to flow from suppliers to customers. We present a general-purpose object-oriented framework for developing simulation models of supply chains. While other more general network structures can be easily modelled with our framework, we concentrate on illustrating the framework on supply networks that have an arborescent tree of inventory holding points (IHPs) as illustrated in Figure 1. In an arborescent network, each IHP can have one and only one supplier; however, our framework is not limited in this respect. We will discuss how to handle the case of many to many relationships between IHPs later in this document.

Each IHP is a location within the network that can stock inventory item types (ie stock keeping units or SKUs). At the top of the network is a supplier that can supply any item type with a possible lead-time. The top-level supplier essentially acts as an external supplier for the top level of the tree. An IHP at any level can supply one or more customers (eg other IHPs). The bottom most level of the hierarchy receives requests for demand for inventory from external customers. This type of structure forms the general class of inventory systems called multi-echelon inventory systems. From a supply chain perspective, looking up from the bottom of the tree back to the external supplier, we have the customer's supply chain. In such situations, it is useful to understand the effect of inventory stocking location, demand, transport delay, control policy, etc on the performance of the system.

While analytical models do exist for specific multi-echelon inventory system configurations, the wide variety of conditions under which such systems operate is often better suited to a simulation-based approach to evaluating system performance. In this paper, we describe an object-oriented framework that allows the easy development and simulation of systems like that shown in Figure 1 and can serve as a foundation for developing much more complicated models. For example, the spare parts network that we illustrate in a later section was easily developed by simply sub-classing from or using the available components within the basic framework. Besides the implementation of relatively standard multi-echelon situations, the framework can also model more dynamic supply situations. For example, in an emergency planning context, we can have suppliers lose their ability to support certain items or locations and to dynamically gain the ability to support other items and locations based on events or other control logic.

In our framework there are no physical limitations (except for memory) that limit the size of the model (eg number of echelons, retailers, inventory items, allocation of inventory to each IHP, etc). The framework is based on the Java programming language and thus assumes that the modeller can program in a general-purpose object-oriented language such as Java. As we will see in our illustrative examples, even non-programmers could build relatively complex models by following the outline presented in our examples. In addition, because the software is open-source it could easily be embedded in a more sophisticated graphical user interface package that takes advantage of the full features of the Java language (eg dialog boxes, databases, etc). From that perspective, we expect a variety of potential users from researchers in academia to practitioners in industry and the military. Note that class diagrams provided in this paper as

*Correspondence: MD Rossetti, Industrial Engineering Department, 4207 Bell Engineering Center, University of Arkansas, Fayetteville, AR 72701, USA.
E-mail: rossetti@uark.edu

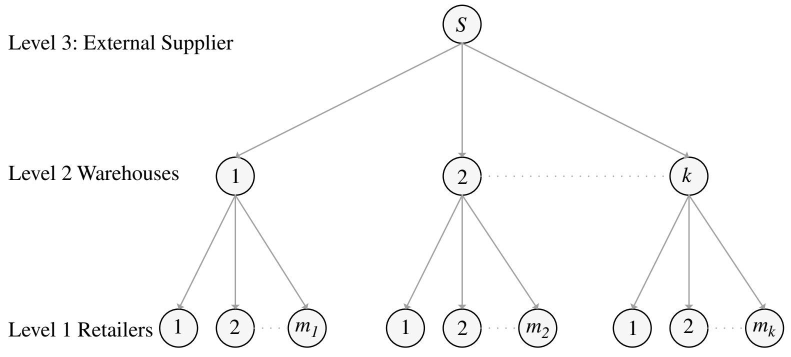

Figure 1 An arborescent supply chain structure.

well as Figure 3 can help potential users to conceptualize the abilities of the framework.

This paper represents an expansion of the work in Rossetti *et al* (2006) and also presents new modelling concepts/examples in an expository fashion. Our intention is not to analyse or optimize a particular supply chain situation. Rather, our purpose is to describe the modelling foundation and capabilities of our supply chain simulation framework through discussion and examples. This should serve as a basis for researchers and practitioners who might be interested in using the framework and it should provide a better understanding of general methods to model logistic systems.

The rest of this paper is structured as follows. In the next section, we present a brief overview of the literature in this area to give context for how our framework fits into this modelling area. Then, we introduce the framework by discussing the elements for modelling inventory stocked at a single location. This will cover the modelling of classic inventory situations such as reorder point and order up to systems. Then, we describe how the framework can use the basic inventory modelling components to build models with multiple locations, stocking multiple item types with transport between locations. Finally, we summarize and discuss future research.

2. Literature review

Previous research in supply chain simulation modelling can be roughly classified into two main areas: applications of simulation modelling to supply chain analysis and development of modelling approaches or tools to better facilitate the simulation of supply chains. For example, the paper by Schunk and Plott (2000) describes the application of simulation to the optimization of supply chain management activities through modelling. Moreover, Li and Zhao (2006) apply an adaptive multi-agent modelling method to agile supply chain simulation, and illustrate the concrete modelling process within the context of a task allocation problem. In addition, interested readers can find an extensive study that surveys different types of simulation for supply chain management and discusses several methodological issues in this area provided by Kleijnen (2005). Overall, these many applications of simulation to supply chain analysis have led researchers to conclude that simulation is one of (if not the best way) to truly analyse dynamic supply chain performance. For example, Dong (2001) considered simulation as a better technology for designing supply chain systems due to the system variation and interdependencies. In addition, Ingalls (1998) concluded that simulation is the best method to analyse supply chain systems where the key driver is variance. Unfortunately, while simulation facilitates the analysis of complex supply chains it has the disadvantage of requiring large amounts of data and taking a long time to develop. Q1

Because of the challenges of applying simulation to supply chain modelling, researchers (and commercial entities) have taken an interest in developing better modelling tools. Early attempts at developing tools in this area date back to the late 1960s and early 1970s. For example, Bowersox *et al* (1972) describe a complete FORTRAN-based supply chain simulator that also incorporated optimization procedures to simulate and design physical distribution systems. More recently, a common approach is to develop a tool to analyse a company's supply chain. For example, the paper by Ingalls and Kasales (1999) combines both the analysis of a supply chain (for Compaq computer) and the development of a tool that can more easily allow such an analysis over time. These tools often take the form of supply chain simulators. In this line, there are many commercial off the shelf simulators such as SCOPE, SIMLOX, and LogSAM, which have been applied in military supply chains.

The Supply Chain Operations Reference (SCOR) model is widely accepted as the cross-industry standard for supply chain management. Several supply chain simulators were developed in the past of which IBM Supply Chain Simulator (SCS) is an important one based on ideas in SCOR. Bagchi *et al* (1998) gives a brief outline on the components in SCS and describes how it was used in the modelling of two diverse industries (Food Industry and Computer Industry). The SCS allows detailed costing and financial analysis to be made based on the simulation of a supply chain. Smart-SCOR is a new addition to IBM's arrays of tools for supply chain management and it conforms to the SCOR standards. It facilitates supply chain transformations. A supply chain transformation initiative consists in changing the ways in which an enterprise forms and operates its supply chain, concerning the decisions from supply chain network rationalization to business process re-engineering. Smart-SCOR sees transformation in two different levels, from supply chain strategy design/redesign to supply chain process improvement (Dong *et al*, 2006). In addition, Pundoor and Herrmann (2006) developed a supply chain simulation framework based on the SCOR model. This framework has been used for building simulation models that integrate discrete event simulation and spreadsheets. The simulation models are hierarchical and use sub-models that capture activities specific to supply chains. The SCOR framework provides a basis for defining the level of detail in such a way that it includes as many features as possible, while not being industry specific. Their approach enables the reuse of sub-models, which reduces the model development time. They describe the implementation of the simulation models and detail how the sub-models interact with each other. A similar framework based on SCOR and through identification of standard applications, the right level of abstraction, and associated requirements for data has been developed by Jain (2007). Finally, Chatfiled *et al* (2006) Q2 presents the software (SISCO) for the storage, modelling, and generation of supply chains where the user specifies the structure and policies of a supply chain with a GUI-based application and then saves the supply chain description in the open, XML-based Supply Chain Modelling Language (SCML) format. SISCO automatically generates the simulation model when needed by mapping the contents of the SCML file to a library of supply-chain-oriented simulation classes. Their methodology is an object-oriented, agent-style system architecture.

A reader interested in understanding our other research in this area should refer to Rossetti *et al* (2006), Rossetti and Chan (2003), Rossetti and Thomas (2006). In particular, Rossetti *et al* (2006) overviews other software architectures (eg Swaminathan, 1998) and approaches for simulating supply chains. In the following section, we discuss the basic building block for our framework based on the inventory layer of the supply chain.

3. Inventory modelling

In our modelling, we have identified a key abstraction for the modelling of supply chains, which we term the *inventory layer*. The other layers in our overall framework include a *facility layer* and a *transport layer*. In this paper, we primarily discuss the inventory layer. We do this by describing the object-oriented constructs within the layer and by illustrating their use.

Our object-oriented framework is built upon a Java Simulation Library (JSL), which is described in Rossetti (2007). The JSL is an open source simulation library for Java. The JSL has packages that support random number generation, statistical collection, basic reporting, and discrete-event simulation modelling. The development of a simulation model is based on sub-classing the ModelElement class that provides the primary recurring actions within a simulation and event scheduling/handling. The user develops and instantiates instance of subclasses of ModelElement. The model elements are added to an instance of the Model class or to other ModelElements. This facilitates the modelling of a hierarchy of systems. Then, the user instantiates an instance of the Experiment class so that the simulation model can be executed. The JSL is divided into Java packages (calendar, examples, modelling, spatial, observers, and utilities) where each package is further organized through sub-packages. The modelling package is further divided into packages (processes, resources, queues, transporters, etc) that facilitate more detailed modelling. In this section, we will discuss a package developed to represent the inventory layer within our framework.

3.1. Overview of key classes

The framework is predicated on the general notion of modelling things that can fill demand and things that can send demand. The DemandFillerIfc and the DemandSenderIfc interfaces represent these two concepts. In addition, we have the concept of transporting demand between senders and fillers represented by the DemandCarrierIfc interface. These three concepts as well as a rigorous state transition pattern for instances of Demand allow the very flexible modelling of general-purpose supply networks.

To make these general concepts concrete, the user must implement the appropriate interfaces or abstract base classes. The inventory package currently has 35 interfaces, seven abstract base classes, and 56 classes that facilitate inventory system modelling. Obviously, we cannot discuss all of these classes in this paper. For basic modelling with the inventory package, there are six key (concrete) classes that must be well understood: ItemType, Demand, DemandGenerator, Inventory, BackLogPolicyAbstract, and InventoryPolicyAbstract. For simplicity in our discussion, we will refer to instances of these classes by the lower case nouns related to the class names whenever the context is clear. For example, item type and demand refer to instances of ItemType and Demand, respectively.

The class ItemType represents or describes the items or products in the inventory system. The Demand class represents a request for inventory and provides the status of the request. A demand knows (has attributes for) the item type associated with the request, the sender of the request, the filler of the inventory items, the carrier of the items, the amount of the request, and other customer requirements associated with the request, such as whether backlogging or partial filling is permitted. The DemandGenerator class creates demands and acts as a customer that sends the demand by providing details of the customer requirements. The Inventory class represents units of a particular item type that can be requested and keeps track of the amount of inventory on-hand, backlogged, on order, etc. An instance of the Inventory class represents the state of the inventory at any given time. In addition, it provides methods for requesting units of an item type and for filling demands for a given item type. Every Inventory class is associated with an inventory policy. The class, InventoryPolicyAbstract, is an abstract base class that allows for the encapsulation of rules to control the associated inventory; it is a rule, policy, or strategy that governs the re-ordering behaviour for inventory. An inventory policy determines when to order and how much to order. Currently, a variety of different inventory policies, such as continuous and periodic review policies, have been implemented. In addition, a backlog policy can be associated with the Inventory class. An abstract base class, BackLogPolicyAbstract, represents the different rules or behaviours that can be used to backlog demands for inventory and to fill backlogs associated with inventory. Figure 2 illustrates the behaviours and attributes of these six classes as well as their relationships. For example, within Figure 2, the class Inventory has a reference to a back log policy as well as an inventory policy. Within the diagram, instances of a DemandGenerator will know its demand filler via an instance of Inventory.

The interactions between these classes are facilitated by four key interfaces: DemandFillerIfc, DemandSenderIfc, DemandCarrierIfc, and DemandStateChangeListenerIfc. Again, where the context is clear, we will refer to instances that implement these interfaces by the appropriate nouns based on the name of the interface. For example, something that implements the DemandFillerIfc interface will be called a demand filler. The interface, DemandFillerIfc, represents

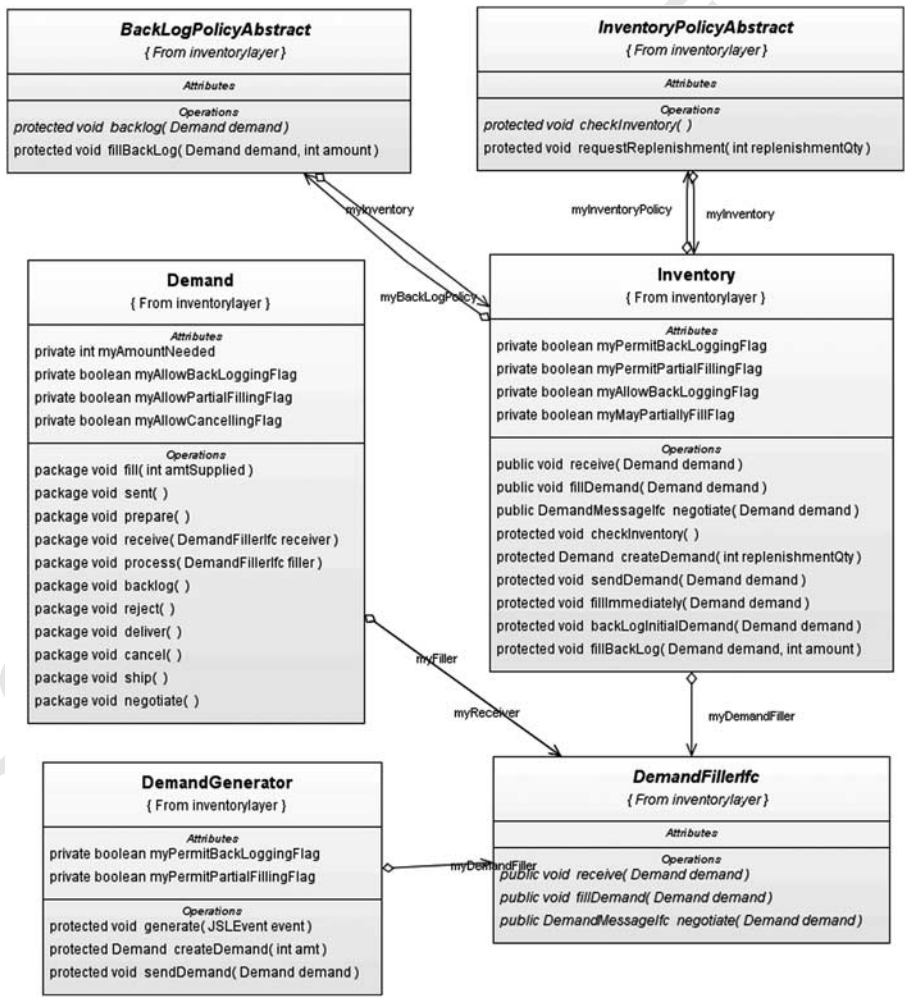
BackLogPolicyAbstract
{ From inventorylayer }
Attributes
Operations
protected void backlog(Demand demand)
protected void fillBackLog(Demand demand, int amount)
InventoryPolicyAbstract
{ From inventorylayer }
Attributes
Operations
protected void checkInventory( )
protected void requestReplenishment(int replenishmentQty)
myInventory
myInventoryPolicy
myInventory
myBackLogPolicy
Demand
{ From inventorylayer }
Attributes
private int myAmountNeeded
private boolean myAllowBackLoggingFlag
private boolean myAllowPartialFillingFlag
private boolean myAllowCancellingFlag
Operations
package void fill(int amtSupplied)
package void sent( )
package void prepare( )
package void receive(DemandFillerIfc receiver)
package void process(DemandFillerIfc filler)
package void backlog( )
package void reject( )
package void deliver( )
package void cancel( )
package void ship( )
package void negotiate( )
Inventory
{ From inventorylayer }
Attributes
private boolean myPermitBackLoggingFlag
private boolean myPermitPartialFillingFlag
private boolean myAllowBackLoggingFlag
private boolean myMayPartiallyFillFlag
Operations
public void receive(Demand demand)
public void fillDemand(Demand demand)
public DemandMessageIfc negotiate(Demand demand)
protected void checkInventory( )
protected Demand createDemand(int replenishmentQty)
protected void sendDemand(Demand demand)
protected void fillImmediately(Demand demand)
protected void backLogInitialDemand(Demand demand)
protected void fillBackLog(Demand demand, int amount)
myFiller
myReceiver
myDemandFiller
DemandGenerator
{ From inventorylayer }
Attributes
private boolean myPermitBackLoggingFlag
private boolean myPermitPartialFillingFlag
Operations
protected void generate(JSLEvent event)
protected Demand createDemand(int amt)
protected void sendDemand(Demand demand)
myDemandFiller
DemandFillerIfc
{ From inventorylayer }
Attributes
Operations
public void receive(Demand demand)
public void fillDemand(Demand demand)
public DemandMessageIfc negotiate(Demand demand)

Figure 2 Relationships between key classes in inventory package.

something that can receive demand to be filled. The class Inventory implements this interface and thus promises to act like a demand filler. A class, like DemandGenerator, that implements the interface DemandSenderIfc specifies how it will send demand while the interface, DemandCarrierIfc, knows how to ensure that a filled demand is delivered. For example, classes that allow time-based transport between locations have been implemented based on the Demand-CarrierIfc interface. Finally, the interface, DemandState-ChangeListenerIfc, allows listeners to be attached to instances of Demand so that they get notified when the demand changes state.

3.2. Representation of demand state

The interaction between these classes and interfaces depends upon a rigorous state specification for instances of Demand as shown in Figure 3. While complex, the state representation for demand enforces the proper use of demands within a simulation model, as well as providing greater flexibility for modellers to plug in their own logic. The state diagram was implemented using the state and flyweight patterns described in Gamma *et al* (1995) to enforce the appropriate state transitions within the Java programming language.

When a demand is created, it is placed in the 'in preparation' state. While in this state the requirements associated with the request for inventory can be changed (eg amount requested, item type, partial filling option, back logging option, etc). While in the preparation state, a demand can transition to either the negotiating state or the sent state. The negotiating state represents the situation in which the demand is being negotiated between a potential demand filler and the creator of the demand. This is intended for models involving negotiation such as auctions and is not discussed further in this paper. The sent state indicates that the demand has been sent to a demand filler to be received.

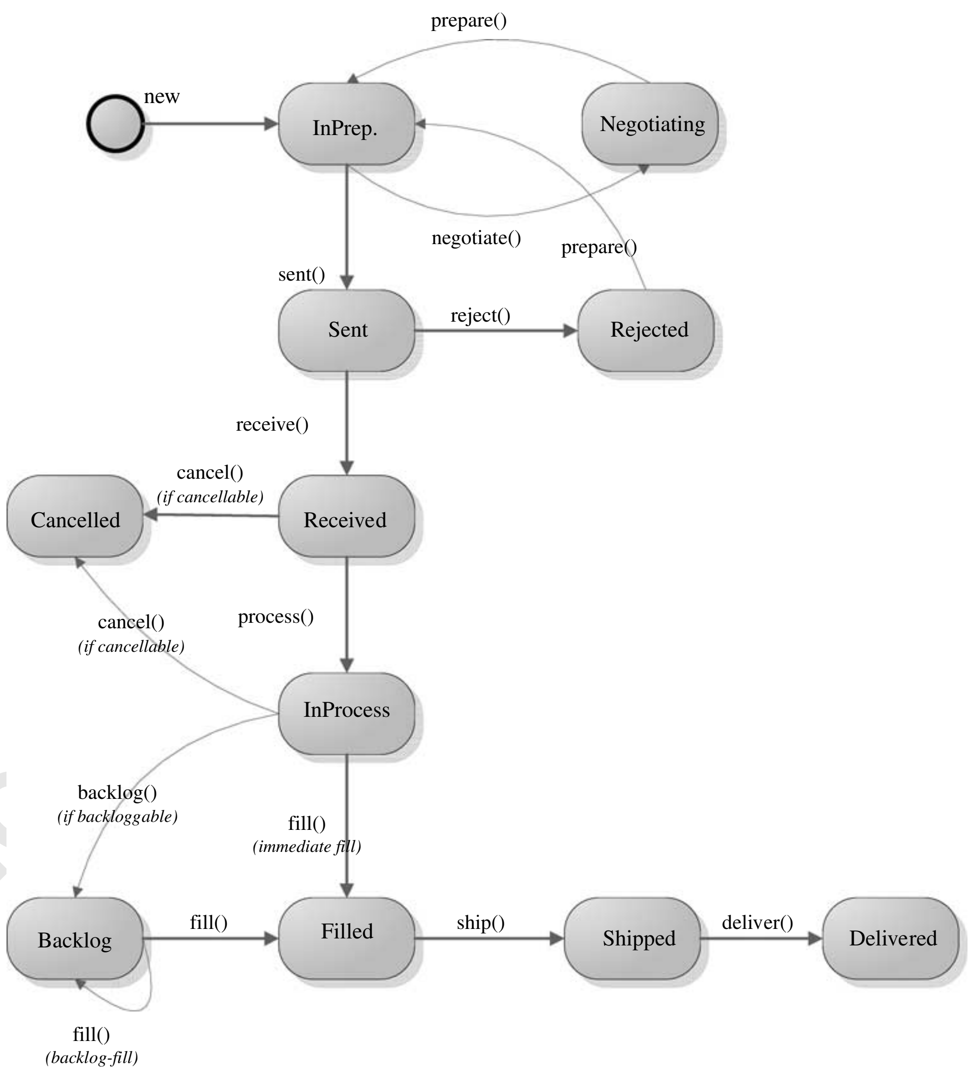

Figure 3 State diagram for demand.

We model the possibility of a time delay in acknowledging receipt by a demand filler.

From the sent state, the demand can either be placed in the rejected state or placed in the received state. In our modelling, demands can be rejected for a number of reasons. For example, if a demand is sent to a filler that does not stock the indicated item type, the demand will be rejected. Or, for example, if a demand that does not allow back-logging is sent to a filler that permits backlogging but the demand cannot be immediately filled, the demand will be rejected. This is like the concept of a lost sale; however, the burden is placed on the sender of the demand to properly respond to the rejection. The user can provide preferred actions to react to the rejection via a listener attached to the rejection state. For instance, in the case of the 'lost sale' rejection, the user could try to find another filler for the demand or simply tabulate the number of lost sales.

A demand is placed in the received state once a filler has acknowledged the request. During the receiving, the filler may indicate what will happen to the demand if the filler is asked to fill the demand at the current time. For example, the demand has a status attribute that indicates what might happen (eg immediate fill, backlog, rejection, etc). Thus, receiving only acknowledges the demand and sets up the demand to be filled. Once the demand has been received, it is up to a listener attached to the demand's received state to decide whether or not to proceed with asking the indicated filler to commit to filling the demand. Thus, from the received state the demand can either be cancelled or it may be placed in the process state at the filler. If the demand is cancelled, the state of the filler never changes. It will be as if the demand never was sent/received. If the demand is placed in process at the filler, then this represents a commitment by the filler to eventually fill the demand's requirements. For example, once the demand is placed in process at the filler, the sender knows 'for sure' that the quantity associated with the item type is on order. While the demand is in process at the filler, it may still be cancelled or it may be backlogged or filled. If a demand that allows cancellation is cancelled, it is placed in the cancelled state, otherwise, an exception is thrown. A demand that enters the cancelled state will notify a listener on the demand that it has been cancelled. This allows the sender to properly react to the cancellation.

If the demand allows backlogging and the filler provides backlogging, the demand will be placed in the backlogged state if it cannot be immediately filled in its entirety. While in the backlogged state, if the demand permits partial filling, then it can be given increments of the amount requested until it becomes filled. If it does not allow partial filling, it is up to the filler to not violate the no partial filling requirement by only allocating the entire amount needed to the demand when it becomes available. Once a demand has received all that it has requested, it is placed in the filled state. A listener can be attached to the demand's filled state to initiate transport once the demand is filled. A demand cannot be transported until the entire amount that was originally requested by the demand has been filled. Transport may take simulated time. Thus, when a demand is placed in the shipped state, it is considered in transit to its delivery location. Once it arrives at the delivery location, it must be placed in the delivered state. A listener can be attached to the delivered state to react to the delivery of the demand. For example, once a demand is delivered, the amount filled on the demand can be used at the delivery location (eg to replenish inventory on hand).

3.3. Inventory and demand filling

Now that the details of the underlying state transitions for demand has been covered, we can proceed to the details about how to fill the demand. The interface, DemandFiller-Ifc, defines the expectations of a demand filler through its *receive*(*Demand d*) and *fillDemand*(*Demand d*) methods. A demand sender will call a demand filler's *receive*( ) method with the demand that it wants the filler to receive. The receive( ) method places the demand in the received state. Once the demand has been received (placed in the received state), a demand sender should call the *fillDemand*( ) method of the filler. The *fillDemand*( ) method places the demand in the 'in process' state. The amount requested for the demand is now 'on order' at the filler. In the case that the filler is an instance of Inventory, the inventory will try to fill the incoming demand based on its current state. Because the class Inventory can both fill demands and may send demands for replenishment, it implements both of the DemandFillerIfc and the DemandSenderIfc interfaces. In other words, it acts as both a sender and a filler of demand. The demand sender interface simply indicates what type of item the sender may request.

The current state of inventory is represented by four key variables: amount of inventory on hand ($I(t)$), the amount on order ($IO(t)$), the amount backordered ($B(t)$), and the inventory position ($IP(t) = I(t) + IO(t) - B(t)$). Inventory must have an inventory control policy attached to govern when and how much it should order. Whenever any of the variables constituting the inventory position change, the inventory policy is notified. It is up to the inventory policy to appropriately react (or not react) to the change in inventory position. For example, in the case of continuous review reorder point policies, the inventory position will be checked against the reorder point and if it is equal to or below the reorder point a replenishment demand will be made. In the case of periodic review, the notification can be ignored since the inventory position is only checked at the end of review periods. Note that our design allows the inventory policy to change during the run and allows the inventory policy parameters to be updated during the simulation.

Because demand may not necessarily be in units of one, inventory can handle partial filling if the demand permits partial filling. In the case of non-single unit demand, the filling of backorders can be complicated. For example, suppose there are demands waiting in the backlog queue for the following amounts (2, 4, 1, 5), with 5 being the demand that has been in the queue the longest. Suppose that a replenishment amount occurs for the quantity 4, how should the four units be allocated to the waiting orders? Should the demand waiting for 5 units get 4 of the units and continue waiting? Should the demand for 4 be given all of the units? Or, should the demands for 1 and 2 units be filled? Because a user may want to have complex allocation rules for processing the backlog queue, the design allows different backlog policies to be implemented by sub-classing from BackLogPolicyAbstract. The default backlog policy gives all the units that it can fill to the demand that has waited the longest. Note that an instance of Inventory may or may not have a backlog policy attached. If it does not have a backlog policy attached, then $B(t)$ will be zero. If it does have a backlog policy attached, not only is $B(t)$ tabulated, but the number of demands waiting is also tabulated since the amount backordered can be different from the number of demands backordered when demand is not in units of one.

To make the discussion more concrete and to illustrate the use of the framework, we present the implementation of a continuous review, reorder point (s), order up to level (S) model. In this example, an item is managed with ($s = 3$, $S = 5$). The demand occurs according to a Poisson process with rate 3.6 per month. The lead time from the supplier to fill a replenishment order is (0.5) months. We are interested in estimating the average on hand, average amount back-ordered, the average amount on order, the fill rate, the portion of time out of stock, and the number of replenishment orders made.

Exhibit 1 illustrates how simple it is to create a model for this situation using the framework. First, the item type is defined. Then, a LeadTimeDemandFiller is created. A LeadTimeDemandFiller is a class that implements the DemandFillerIfc and can fill any demand that is sent to it for its defined item types after a delay that can be stochastic. It represents the location that will satisfy replenishment demand for the inventory when inventory reaches its reorder point. After setting up the supplier, we can define the inventory by creating its back log policy, its inventory policy, and telling it to use the instance of LeadTimeDemandFiller as its supplier. Finally, an instance of a DemandGenerator is used to create demands and send them to inventory to be filled. A DemandGenerator acts similarly to the CREATE block in many common commercial simulation languages. The user can specify the time between demands as a random quantity as well as the number of demands to generate, etc. The demand generator creates instances of Demand, sets their requirements and then calls its specified filler to request that the demand be received and then filled.

The simulation was run for 30 replications of 3360 months with a warm up period of 360 months. The results of the simulation are given in Table 1. The results are the average, standard error, 95% half-width, minimum, and maximum over the 30 replications for each of the performance measures. These results match the theoretical results for this simple case. These performance statistics are available as a standard product of the inventory package and the JSL. Although a rigorous analysis can be employed to determine the number of replications and the replication length, we picked the run-length and warm-up period based on convenience for the examples within this paper. We did this because our purpose is to illustrate the modelling, not the analysis of the results. Despite this intuitive selection of simulation run parameters, our results can be validated against the analytical solutions, when appropriate.

```
// create the containing model
Model m = Model.createModel();
// define the type
ItemType typeA = new ItemType(m, "Type-A");
// define the filler for the inventory
LeadTimeDemandFiller supplier = new LeadTimeDemandFiller(m);
RandomIfc leadTime = new Constant(0.5);
// specify the lead time for the item
supplier.addLeadTime(typeA,leadTime);
// set up the back log policy
BackLogQueue bpolicy = new BackLogQueue(m, "BacklogQ");
// set up the inventory policy
int reorderPt = 3;
int orderUpToLevel = 5;
InventoryPolicyAbstract ipolicy = new
InventoryPolicyReorderPointOrderUpToLevel(m, reorderPt, orderUpToLevel);
// set up the inventory
int initialLevel = 0;
Inventory inventory = new Inventory(m, typeA, ipolicy, bpolicy, initialLevel);
// hook the inventory to the supplier
inventory.setDemandFiller(supplier);
// define the demand generator
RandomIfc timebtwDemand = new Exponential(1.0/3.6);
DemandGenerator generator = new DemandGenerator(m, typeA, timebtwDemand,
timebtwDemand);
// tell the generator to send demand to the inventory
generator.setDemandFiller(inventory);
return(m);
```

Exhibit 1 Simple reorder point, order up to level inventory model.

Table 1 Results for simple reorder point, order up to level inventory model

	Avg.	*Std error*	*Half-width*	*Min*	*Max*
On hand	2.731	0.003	0.006	2.697	2.766
On order	1.801	0.003	0.006	1.765	1.836
Amount backordered	0.033	0.00029	0.00058	0.029	0.035
Backorder waiting time	0.122	0.00065	0.0012	0.115	0.129
Fill rate	0.926	0.00056	0.0011	0.912	0.932
Out of stock time	0.073	0.00049	0.00096	0.067	0.077
Number of replenishments	5404.43	9.301	18.277	5295.0	5509.0

Based on the model of Exhibit 1, it should be clear that to model many item types at a single location, we can simply repeat the code and build a bigger model. To build on this idea, we created a class called InventoryHolderAbstract that facilitates the holding of any number of instances of Inventory. Instances of concrete sub-classes of Inventory HolderAbstract then serve as the nodes in a supply chain (eg Figure 1). In the next section, we discuss the application of these concepts to supply chain modelling.

4. Supply chain modelling

The class InventoryHolderAbstract represents something that can hold inventory by item type. Figure 4 is a class diagram that illustrates the behaviours and attributes of the classes and the relationship between each of the class that are used in supply chain modelling.

As shown in the figure, InventoryHolderAbstract is a sub-class of DemandFillerAbstract, which implements the DemandFillerIfc interface. Thus, sub-classes of Inventory HolderAbstract (ie inventory holders) are also demand fillers. It is also apparent from the figure that Inventory HolderAbstract acts like a demand sender because it implements the DemandSenderIfc interface. In fact, both of these roles are given to an IHP because it holds instances of inventory. External demands that are sent to an inventory holder, are essentially routed to the appropriate instance of inventory in order to be filled. From the outside, sub-classes of InventoryHolderAbstract are simply demand fillers (ie something that promises to fill demand). It does not really matter how the demand requests are filled, only that they are eventually filled once the *fillDemand*() method (behaviour implemented from the DemandFillerIfc) is called. An inventory holder delegates the demand filling to the appropriate inventory for the item type associated with the demand. Thus, the building of a complex supply chain is a matter of hooking up demand fillers and demand senders in a similar manner as shown in Exhibit 1 using the *setDemandFiller*() method. It is important to note that to extend this modelling, users simply have to implement the appropriate interfaces or abstract base classes. Thus, a wider variety of inventory system modelling than shown here is very feasible. The next section explains the interactions between TimeBasedShippingMultiEchelonIHPNetwork, LeadTimeDemandFiller and TimeBasedDemandCarrier with the other classes in Figure 4.

4.1. Multi-item, multi-location example

In this section, we illustrate how to model a multi-item, multi-location supply system as shown in Figure 5. In this system, there are four different types of items, each of which can be produced and delivered by an external supplier (eg manufacturer). The time to produce each of the items may be stochastic and different as shown in the figure. The time to transport an item from the factory to the warehouse is set to 3 days in our example. Table 2 gives the time between arrivals for the retailers for each of the items as well as the stocking policies for each of the locations. The transport time from the warehouse to any of the retailers is 1 day.

An instance of the TimeBasedShippingMultiEchelonI-HPNetwork class was used to model the example. A multi-echelon inventory network consists of a network of InventoryHoldingPoints (IHP), which is a concrete sub-class of InventoryHolderAbstract. In this type of network, each IHP can have one parent IHP that fills its replenishment requests. It can have many child IHPs for which it fills replenishments. No checking is done to ensure that the IHPs are compatible in terms of their ability to supply certain item types. Any demands sent to an IHP that cannot be handled by the IHP will be rejected. The default rejection behaviour for an IHP is to throw an exception. To override this behaviour the client can supply a DemandListenerRejecte-dIfc for the IHP or DemandGenerator. This listener could have logic that incorporates sense and respond logistics features into the supply chain. For example, let us consider a logistic network in a war zone. If the demand filler is destroyed, then the default behaviour can be overridden to choose another demand filler based on the current state of the network.

The top-level supplier is modelled with a LeadTime-DemandFiller and is considered an external supplier to the network. The external supplier has an infinite supply of the item types added to the network, which can be produced and delivered after a given lead time, which may depend on

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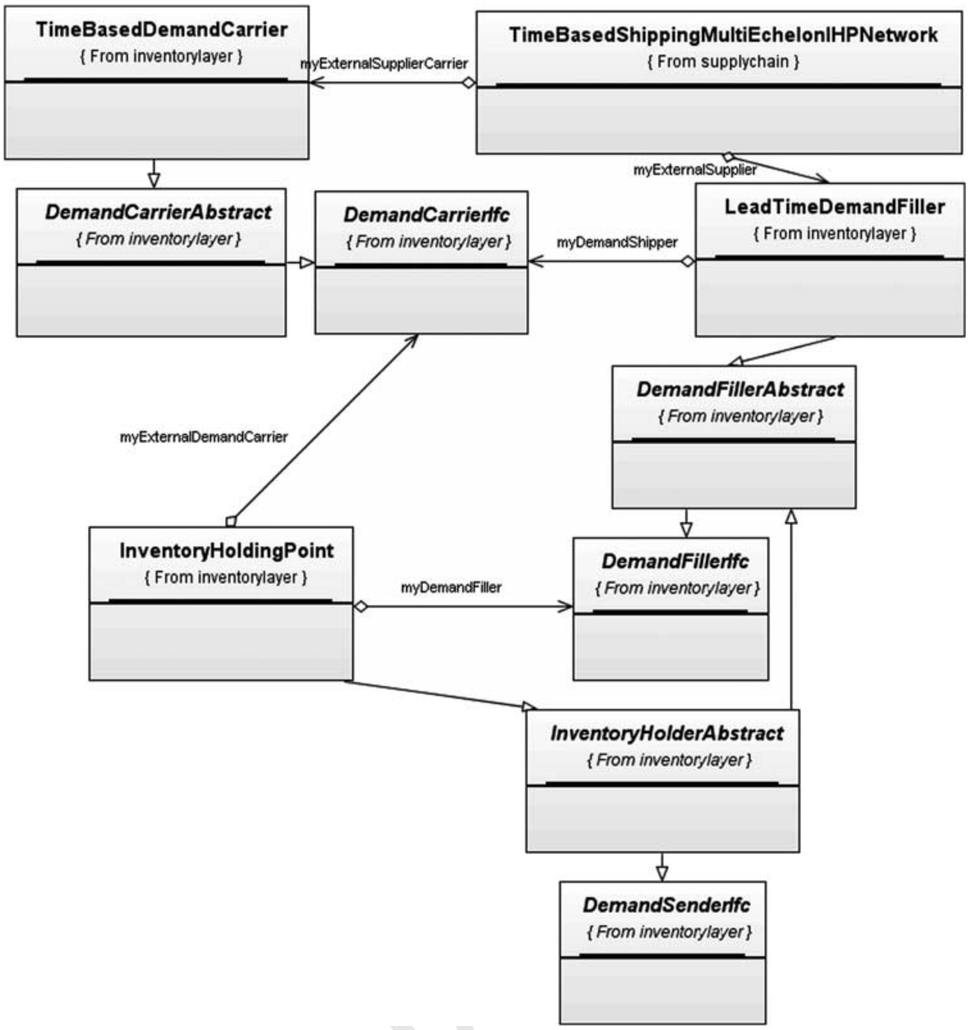
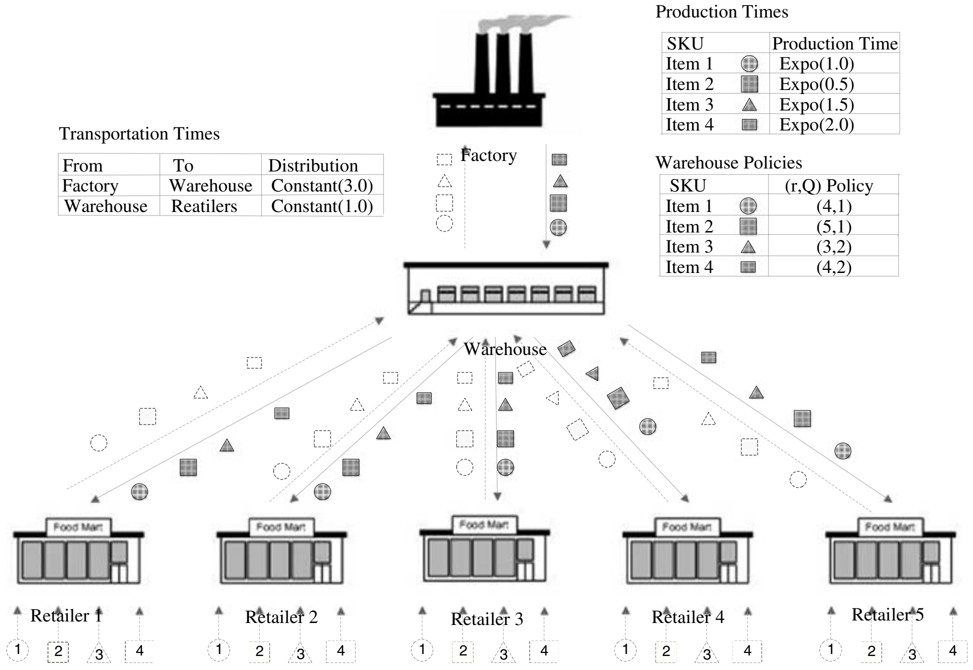


Figure 4 Key classes and their relationships for supply chain modelling.

the item type. Since the top level supplier is external to the network, the lead time represents the time to produce the item. If no item types are added, then all demands sent to the external supplier will be rejected.

The time to transport from the external supplier may depend on the location of the customer (IHP) (eg warehouse in the example) and is thus modelled as a separate transport time which may depend upon the customer and its location relative to the external supplier. If the time for the transport depends upon the link between the external supplier and the customer, then a TimeBasedDemandCarrier is used to model the transport time from the external supplier to the top level IHPs. The generation of external demand to the IHPs is modelled through the use of instances of the DemandGenerator class. Each IHP may have zero or more demand generators attached to it, and each DemandGenerator may be attached to one or more IHPs. This may occur for any IHP at any level of the network to represent external demand sent to that IHP. During the attachment process, the client is responsible for specifying the time that it may take to transport the demand to the demand generator once it is filled. If no demand generators are attached to any IHP (or to the network) then nothing will happen, since IHPs must have demands sent to them to begin processing.

In addition, external demand generators may be attached to the network by calling the *allowExternalDemandGenerators*() method which allows the IHPs to transport the items to the external demand generators with zero delay. The external demand generators must know where to send their demands (typically through a DemandFillerFinderIfc to which they have access). The DemandFillerFinderIfc interface defines a general procedure by which a demand filler can be found for a demand sender. The demand generator in this example does not use the demand filler finder because we have attached a demand filler directly to it. However, it is possible to attach a demand filler finder, which encapsulates the logic to find a supplier for the demand generator. Thus, we can easily handle a situation that involves multiple



Transportation Times

From	To	Distribution
Factory	Warehouse	Constant(3.0)
Warehouse	Reatilers	Constant(1.0)

Production Times

SKU		Production Time
Item 1	●	Expo(1.0)
Item 2	▨	Expo(0.5)
Item 3	▲	Expo(1.5)
Item 4	■	Expo(2.0)

Warehouse Policies

SKU		(r,Q) Policy
Item 1	●	(4,1)
Item 2	▨	(5,1)
Item 3	▲	(3,2)
Item 4	■	(4,2)

Figure 5 Multi item multi location example problem.

Table 2 Multi-item multi-location example problem data

	Item 1	*Item 2*	*Item 3*	*Item 4*
Retailer 1	TBA ~ expo(2.0) (s, S) = (2, 3)	TBA ~ expo(1.0) (s, S) = (1, 2)	TBA ~ expo(1.5) (s, S) = (2, 4)	TBA ~ expo(3.0) (s, S) = (3, 6)
Retailer 2	TBA ~ expo(1.0) (s, S) = (1, 3)	TBA ~ expo(2.0) (s, S) = (2, 4)	TBA ~ expo(2.5) (s, S) = (2, 5)	TBA ~ expo(1.5) (s, S) = (2, 3)
Retailer 3	TBA ~ expo(2.5) (s, S) = (2, 4)	TBA ~ expo(1.5) (s, S) = (1, 2)	TBA ~ expo(2.0) (s, S) = (2, 3)	TBA ~ expo(2.0) (s, S) = (2, 3)
Retailer 4	TBA ~ expo(3.0) (s, S) = (3, 6)	TBA ~ expo(2.5) (s, S) = (3, 4)	TBA ~ expo(1.0) (s, S) = (1, 2)	TBA ~ expo(2.5) (s, S) = (2, 3)
Retailer 5	TBA ~ expo(1.5) (s, S) = (2, 3)	TBA ~ expo(0.5) (s, S) = (0, 1)	TBA ~ expo(3.0) (s, S) = (3, 6)	TBA ~ expo(0.5) (s, S) = (1, 2)

suppliers for a location. It is a simple matter to supply the logic for choosing between suppliers within the class that implements the DemandFillerFinderIfc interface. In the current architecture, if the demand generator has a demand filler finder attached, it uses the finder to find an appropriate filler, otherwise, it must have a DemandFillerIfc directly attached. If no demand filler is attached or a demand filler finder is not supplied, an exception will be thrown.

Note that the dashed lines and parts in Figure 5 refer to the information flow upwards in the network with regard to associated item-requests for replenishments while the solid shapes imply the actual physical entities that flow downward in the system.

Exhibit 2 is self-explanatory and illustrates how easily the components of the system, such as for those retailer 1 and item type 1 can be built using the classes within the framework. The other components can be instantiated in a similar fashion.

The simulation was run for 30 replications of 5400 days (10 years) with a warm-up period of 1800 days (5 years). A sample of the simulation results is given in Table 3 (additional descriptive statistics are readily available). These results represent the aggregate performance for each of the locations across the item types stocked at the locations. In addition to these aggregate statistics, which are automatically tabulated, all individual statistics (as per Table 1) for each item type for each location are readily available. The numbers in parentheses in the table represent the standard error.

As one can imagine, for a large network a large amount of individual and aggregate statistics can be generated. Fill rate, expected number of back orders, customer wait time are just

```
// build the containing model
Model m = Model.createModel();
// define the network
TimeBasedShippingMultiEchelonIHPNetwork n = new
TimeBasedShippingMultiEchelonIHPNetwork(m, "ME-Inventory-Network");
// define item types with associated leadtime for production
DistributionIfc ltp1 = new Exponential(1.0);
ItemType type1 = n.addItemType("Type-1", ltp1);
// define the Warehouse
InventoryHoldingPoint warehouse = n.addInventoryHoldingPoint("Warehouse");
// addInventory to warehouse with a specified policy
warehouse.addReorderPointReorderQuantityInventory(type1,4,1,20);
// define the retailers which use the warehouse as its filler
InventoryHoldingPoint retailer1 = n.addInventoryHoldingPoint("R1");
// define the inventory for each item type
// with a specified policy at each retailer
retailer1.addReorderPointOrderUpToLevelInventory(type1,2,3,10);
// construct to the structure of the network
// attach the warehouse to the external supplier
// with a specified transportation time of 3.0
DistributionIfc t1 = new Constant(3.0);
n.attachIHPToExternalSupplier(warehouse,t1);
// attach the retailers to the warehouse,
// with a specified transportation time of 1.0
DistributionIfc t2 = new Constant(1.0);
n.attachIHPToSupplier(warehouse, retailer1, t2);
// attach the demand generators
// for specified item type to each retailer
DistributionIfc dA11 = new Exponential(2.0);
n.attachDemandGeneratorToIHP(retailer1, type1, dA11);
```

Exhibit 2 Example code for building the multi-item, multi-location model.

Table 3 Illustrative results for multi-item, multi-location model

	R1	*R2*	*R3*	*R4*	*R5*	*W*	*N*
On hand	6.35 (0.03)	4.92 (0.03)	4.97 (0.03)	7.77 (0.03)	4.68 (0.03)	0.83 (0.01)	29.52 (0.07)
On order	9.13 (0.05)	10.72 (0.05)	7.76 (0.04)	8.19 (0.05)	19.00 (0.07)	60.13 (0.10)	114.93 (0.22)
Fill rate	0.53 (0.00)	0.48 (0.00)	0.61 (0.00)	0.54 (0.00)	0.16 (0.00)	0.10 (0.00)	0.27 (0.00)

some of the operational performance measures that are relevant to a supply network both at an individual and an aggregated level. Individual performance refers to a single item at a particular facility, say fill rate associated with an item at a particular facility. Aggregated statistics are those associated across the items at a facility or across the facilities in the network. The JSL supports the writing of all the statistics to a database for post processing by the analyst. In the following section, we present another example model to illustrate how the framework can be used to model a system involving the repair of spare parts.

4.3. Multi-echelon spare parts network example

In this section, we describe the modelling of a multi-echelon spare parts supply system similar to the class of systems examined via the METRIC (multi-echelon technique for recoverable item control). For further information on METRIC, we refer the reader to Sherbrooke (1992) or to Muckstadt (2005). Since analytical results for METRIC-like systems exist, our purpose is again expository. The system can be conceptualized as a set of air bases served by a depot. The air bases have flying activity that causes spare parts to be required. Both the depot and the bases, stock inventory and repair defective parts. Parts that are removed from the aircraft are called line replaceable units (LRUs). When an LRU fails on an aircraft at a base, it is removed from an aircraft and a replacement LRU is withdrawn from inventory at the base (called base stock). The new part is placed on the aircraft so that it can continue its operation. If a replacement part is not available in base supply, a backorder for the part is issued. The failed part that had been removed from the aircraft will be either repaired at the base or at the depot according to a probabilistic process. There is a chance r_{ij} that an LRU of type i will be repaired at base j. Whenever the failed part is transported to the depot for repair, a request is made to ship a replacement LRU to the base. If such a unit is on hand at the depot, then it will be immediately shipped. If such a unit is not available at the depot, then a backorder occurs at the depot, which will be served on a first come first served basis. Figure 6 illustrates this process. In essence, this system is a multi-echelon system with one-for-one replenishment (S-1, S) at each location and the possible lead-time based on repair activity.

The depot and bases in this example stock the inventory and hence can be constructed using an IHP. However, in this case, the depot and base also must handle repair activities. In order to accommodate the repair, we sub-classed the

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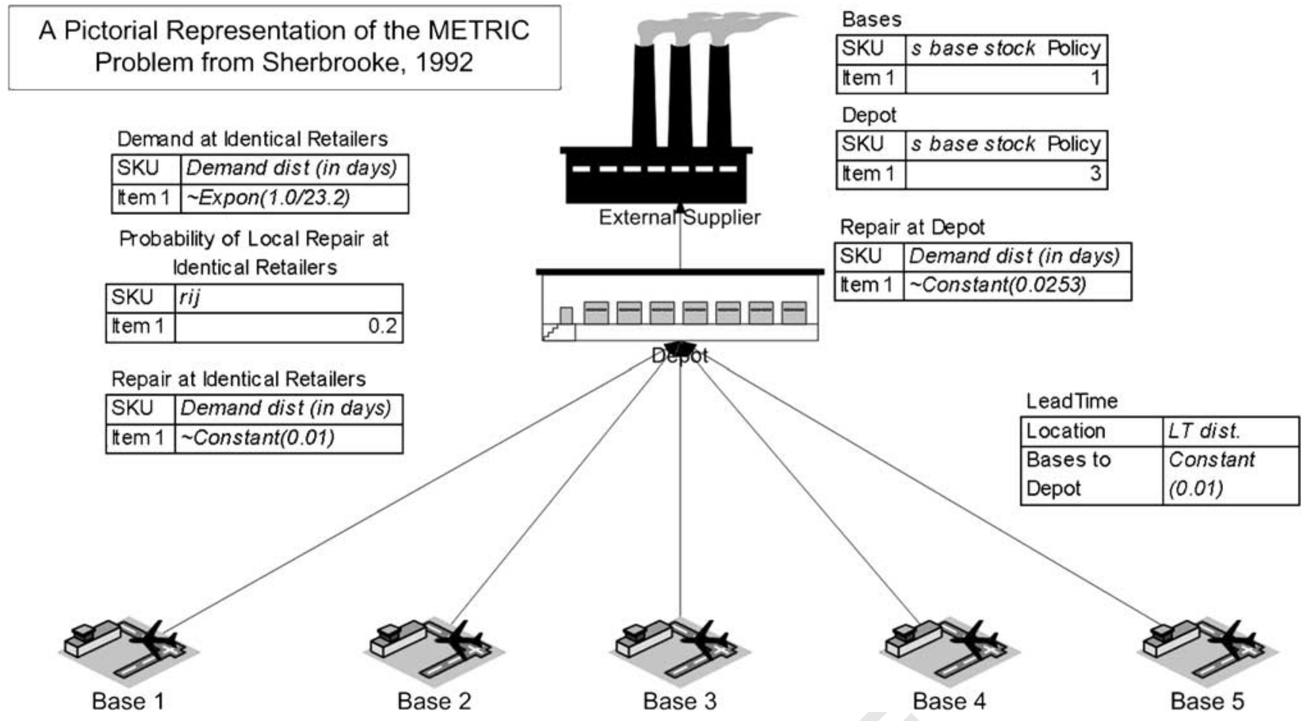
A Pictorial Representation of the METRIC Problem from Sherbrooke, 1992
Demand at Identical Retailers
SKU | Demand dist (in days)
Item 1 | ~Expon(1.0/23.2)
Probability of Local Repair at Identical Retailers
SKU | rij
Item 1 | 0.2
Repair at Identical Retailers
SKU | Demand dist (in days)
Item 1 | ~Constant(0.01)
External Supplier
Depot
Bases
SKU | s base stock Policy
Item 1 | 1
Depot
SKU | s base stock Policy
Item 1 | 3
Repair at Depot
SKU | Demand dist (in days)
Item 1 | ~Constant(0.0253)
LeadTime
Location | LT dist.
Bases to Depot | Constant (0.01)
Base 1
Base 2
Base 3
Base 4
Base 5

Figure 6 Multi-echelon spare parts supply system.

```
//Create the network
TimeBasedShippingMultiEchelonIHRPNetwork n = new
TimeBasedShippingMultiEchelonIHRPNetwork(m, "ME-Inventory-METRIC-Network");
//Define item types
ItemType type1 = n.addItemType("Type-1");
//Define Depot
InventoryRepairingHoldingPoint depot =
n.addInventoryRepairingHoldingPoint("Depot");
//addInventory to depot
depot.addReorderPointReorderQuantityInventory(type1,1,1,2,"Depot Type-1");
depot.setRepairStation(type1,new Bernoulli(1.0),new Constant(0.0253));
// Create the bases which use the depot as its filler
InventoryRepairingHoldingPoint base1 =
n.addInventoryRepairingHoldingPoint("Base1");
//Create the inventory at each depot
base1.addReorderPointReorderQuantityInventory(type1,0,1,0,"Base1 Type-1");
base1.setRepairStation(type1,new Bernoulli(0.2), new Constant(0.01));
// create the structure of the network
// attach the depot to the external supplier
n.attachIHRPToExternalSupplier(depot);
// attach the bases to the depot, reuse the constant leadtime of 1.0
DistributionIfc d = new Constant(0.01);
n.attachIHRPToSupplier(depot, base1, d);
// create the demand generators for the bases
DistributionIfc dA = new Exponential(1.0/23.2);
DemandGenerator dg1 = n.addDemandGeneratorToIHRP(type1, dA);
n.attachDemandGeneratorToIHRP(base1,dg1);
```

Exhibit 3 Example code for building multi-echelon spare parts supply system.

InventoryHoldingPoint into InventoryRepairingHolding-Point. It decides whether the failed part (equivalent to a demand arrival and demand arrival process equivalent to the failure process) can be repaired locally and this probability for each item type is specified and stored within the class. The repair time distribution for each item type is modelled using an instance of LeadTimeDemandFiller class within this class. The repair probability and repair time distribution for each item are specified by calling the setRepairStation method of the InventoryRepairingHoldingPoint class.

The simulation model of the METRIC model in Figure 6 was modelled using TimeBasedShippingMultiEchelon-IHRPNetwork and is similar to TimeBasedShippingMul-tiEchelonIHPNetwork class which we discussed earlier. Both of the network building classes are similar except that the former holds the InventoryRepairingHoldingPoint and the

Table 4 Illustrative results for multi-echelon spare parts model

	Expected back orders			*Stock out frequency*		
	METRIC	*VARIMETRIC*	*Simulation*	*METRIC*	*VARIMETRIC*	*Simulation*
Depot	0.3471	0.3472	0.3477	0.4169	0.4169	0.4165
Base						
1	0.0412	0.0453	0.0452	0.2602	0.2561	0.2562
2	0.0412	0.0453	0.0453	0.2602	0.2561	0.2564
3	0.0412	0.0453	0.0451	0.2602	0.2561	0.2563
4	0.0412	0.0453	0.0454	0.2602	0.2561	0.2564
5	0.0412	0.0453	0.0452	0.2602	0.2561	0.2567

latter holds InventoryHoldingPoint. The instance in the Figure 6 was modelled as shown in the Exhibit 3. The simulation was run for 10 replications of 3650 time period with a warm up period of 100 time period.

Table 4 tabulates the expected back order and the stock out frequency from the simulation model (many additional performance measures are available). The standard error is negligible (of the order of 4 zeroes) and hence not listed. The analytical results from the METRIC and VARIMETRIC computations are listed for comparison. We observe that the simulation output is within statistical error of the analytical results.

5. Summary and future research

In this paper, we have introduced and illustrated the use of an object-oriented framework for simulating supply chains. We did not provide a complete discussion of all of the implementation details of all classes in the framework; instead we provide enough detail on important classes along with their important behaviours in order to illustrate their use and functionality through a number of examples. Hence, the reader can make conceptual modelling with the framework more concrete. In addition, it should be clear that a variety of complex systems can be modelled where at each echelon, at each IHP, as well as for each item type a variety of different inventory policies, backlogging policies, and demand transport options can be used.

The framework is built upon the JSL, which is an object-oriented open source framework for simulating within Java. Because the framework is object-oriented and built on Java, the modeller can use all the power of the object-oriented modelling and Java to develop additional models and behaviours. The JSL is licensed under the GNU General Purpose License (www.gnu.org). This license is stronger than the Lesser GPL that is often used for libraries. The use of the ordinary GPL limits the proprietary use of the JSL and makes it more readily available to the open-source community. Since the JSL is licensed under the GPL and this framework is based on the JSL, this framework is also available via the GPL. This makes it a potential valuable resource for researchers and practitioners working in the area of supply chain simulation.

We are continuing our modelling efforts on the framework. In particular, we are examining the modelling of unreliable systems (where the demand filler may be unavailable), auction based supply/demand situations, integrating forecasting methods into the supply chain system, cost modelling, and integrated truck-load or less-than-truck load transport between locations.

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