Java Simulation Library (JSL): An Open-Source Object-Oriented Library for Discrete-Event Simulation in Java

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Abstract: This paper describes the design and functionality of an open-source object-oriented library for executing discrete-event simulation models in the Java programming language. The structure of the library is described in terms of its packages, class structure, and functionalities. The purpose of this paper is to provide an understanding of the library so that practitioners and researchers can better utilize the library for simulation modelling. In addition, the expository nature of this paper can help new users or students learn the basics of discrete-event simulation from the library’s design. The capabilities of the library are illustrated through a number of code examples.

Keywords: object-oriented, discrete event simulation, library

Reference to this paper should be made as follows: Place appropriate reference here

Biographical notes: Place author biography here

1 INTRODUCTION

According to Booch et al. (1999), a software design framework is “an architectural pattern that provides an extensible template for applications within a domain.” A framework provides a set of classes that can be extended via sub-classing or used directly to solve a particular problem within a particular domain. This paper discusses a software design framework for developing object-oriented simulations. The concepts in the framework have been implemented in open source software called the Java Simulation Library (JSL) under the GNU General Public License (www.gnu.org).

Numerous organizations and individuals have developed object-oriented simulation software tools. These tools have been implemented using languages such as C, C++, and Java. For example, Schwetman’s (1986) CSIM++™ is an extensive set of classes for performing process and event based simulations in C++. Joines and Roberts’ YANSL (1996) supports the development of C++ simulations using the network modelling view. Marzolla (2004) supports the process view in C++. Healy and Kilgore (1997) describe Silk™, a comprehensive commercial extension of the Java simulation language for developing process-based simulations. In addition, Borschev et al. (2000) describe the beginning architecture for AnyLogic™, a comprehensive commercial product built on Java that does discrete-event, agent-based, and dynamic simulation.

The paper by Rossetti et al. (2000) describes an object-oriented framework that is the predecessor for the software discussed in this paper. Some other discrete event libraries implemented in Java include L’Ecuyer et al. (2002), Page and Kreutzer (2005), Jacobs and et al. (2002), Garrido (2001), Kacer (2001), and Sánchez (2006).

It is not the purpose of this paper to contrast the JSL with the plethora of other Java based simulation libraries; however, some similarities and differences are worth pointing out. Both SSJ from L’Ecuyer et al. (2002) and
DesmoJ from Page and Kreutzer (2005) describe software that has very similar overall capabilities as the software discussed in this paper. That is, the ability to model discrete-event systems in Java using the event and process world-views with full support for random variate generation and statistical output collection. DesmoJ has an experiment and modelling paradigm that is similar in concept to the JSL’s. The statistical and random utilities for both of those libraries are on par with what is provided within the JSL.

The libraries PSIM-J by Garrido (2001), J-SIM by Kacer (2001), SSJ by L’Ecuyer et al. (2002) and DesmoJ from Page and Kreutzer (2005) all focus on the process interaction approach implemented on top of Java’s thread mechanism. While the JSL originally had process interaction support based on threads, see Rossetti et al. (2000), that implementation has been deprecated due to problems with the use of Java’s threads. Perhaps the final difference with respect to other libraries has been the emphasis on designing the JSL to be flexible and extendable under an open-source paradigm. For example, the reliance on observer-based collection of statistics is somewhat unique to the JSL and provides great flexibility. In addition, as will be noted in the following sections, the JSL can readily use different random number generators, different event scheduling calendars, different statistical collection techniques, etc., which facilitated research of these topics within a consistent platform.

The Java Simulation Library (JSL) has been used in a number of research and educational settings; however, its implementation has not been fully described in the literature except through its many applications. Examples of the use of the JSL include, Hobbs et al. (2006), which used it to model radio frequency tracking on an air base and Rossetti and Chan (2003), which developed a prototype framework for simulating supply chains. Building on that work, Rossetti and Thomas (2006) developed a framework to simulate supply chains involving spare parts in a multi-echelon, multi-indentured setting. The work in Rossetti, Miman et al. (2006) extends the JSL’s capabilities to handle large-scale multi-echelon inventory systems with any type of inventory policy. Finally, the supply chain work was integrated with a transport layer for modelling transportation networks (e.g. full-truck-load networks) in Rossetti and Nangia (2007). Since the JSL is open source, these implementations are also freely available.

The purpose of this paper is to describe the JSL’s design and to illustrate how to use the JSL for basic discrete-event modelling. This paper is primarily explicative in nature. The notion of simulation libraries is not new; however, much yea still be learned by examining the design and implementation of such software systems. This is especially relevant in an educational and research environment. Students of simulation can develop a deeper understanding of how simulation technology works by studying such designs. This is one of the primary reasons for this paper and why the software is open-source.

Since the JSL is divided into a number of Java packages (random, statistic, modelling, calendar, observer, etc), the paper is organized around the capabilities of these packages. Then, through the use of some examples and a textbook problem, the use of the software is illustrated. Finally, the paper summarizes some ideas for future expansion and use of the JSL.

2 JSL PACKAGES

The general purpose simulation support within the JSL is organized into four major packages: utilities, calendar, modeling, and observers. While Java does not support the notion of sub-packages, the modeling, observer, and utilities packages can be conceptualized as having sub-packages. The utilities package contains the random and statistic packages for random number generation and statistical collection. The modelling package has packages for modelling queues, resources, etc., essentially elements that a user would find in a simulation model. The observer package is built off of Java’s notion of the Observer/Observable pattern to facilitate statistical collection and reports, as well as writing spreadsheet and database output. This section briefly overviews each of the major packages and their sub-packages starting with the utilities package.

2.1 The Utilities Package

The utilities package consists of classes that support the JSL in a general manner. It consists of sub-packages for reporting, forecasting, numerical computation, sampling random variables, and statistical collection. The following subsections provide an overview of the random and statistic packages.

2.1.1 The Random Package

The classes and interfaces within the random package support the sampling of random variables within the JSL. Figure 1 illustrates a few of the key interfaces and classes within the random package. The ability to generate random numbers is represented by the RngIfc interface. This interface combines the generation of pseudo-random numbers (via the randU01() method within the RandU01Ifc interface) with stream control via the RandomStreamIfc interface. Stream control, see L’Ecuyer (2001), allows the user to restart a pseudo-random sequence, jump to sub-sequences, and produce antithetic variates. The RngStream class (based on L’Ecuyer (2001)) provides a concrete implementation of the RngIfc interface. The organization of these interfaces also facilitates the incorporation of pseudo-random number generators that do not easily allow for the manipulation of streams.

Because of the flexibility of the RngIfc interface users of the random package can also easily generate correlated pseudo-random numbers. The generation of correlated processes is discussed in Law (2007). For example, the AR1CorrelatedRng class uses the Normal-to-Anything
The random package provides support for random variable sampling based on probability distributions through the `DistributionIfc` interface. Any probability distribution that works within the JSL must adhere to this interface. An abstract base class, `Distribution`, is provided to facilitate the development of concrete implementations of the `DistributionIfc` interface. The `Distribution` class takes an instance of the `RngIfc` interface to use as its source of pseudo-random numbers.

The JSR currently implements the following continuous distributions: beta, gamma, uniform, lognormal, normal, exponential, triangular, log-logistic, and Weibull. Other distributions can be easily added. In addition, the random package includes a general method to sample from truncated distributions via the `TruncatedDistribution` class. Truncated distributions are discussed on page 342 of Law (2007). The beta and gamma distributions also include static methods for computing the beta function, the gamma function, and the logarithm of the gamma function.

From a class hierarchy perspective, the JSR does not distinguish between continuous and discrete distributions as is done in other libraries (e.g., SSJ). Sub-classing from the Distribution class also provides a number of discrete distributions: Poisson, Constant, Uniform, DEmpirical, NegativeBinomial, Geometric, Bernoulli, and Binomial. The Binomial class also provides a numerically stable method for computing binomial coefficients. The current implementation of these distributions utilizes the inverse transform method for generating random variates but overriding the methods can easily provide other algorithms.

The random package also provides support for shifted distributions, generating permutations, and a number of other useful procedures.

### 2.1.2 The Statistic Package

The statistic package provides functionality to compute a variety of statistical functions (e.g., summary statistics, histograms, etc.) on data. The `AbstractStatistic` class has been designed to tabulate data that is presented to its `collect()` method. The `AbstractStatistic` class provides a series of accessor methods that allow the user to retrieve information from the underlying statistics. These methods implement the `StatisticAccessorIfc` interface, which provides a read only view of the statistical information. Thus, users can sub-class from `AbstractStatistic` to more readily implement this interface. Figure 2 shows the basic functionality of the `AbstractStatistic` class. Instances can return the number of observations, the sample average, sample variance, the minimum, the maximum, etc. for the observations presented via the `collect()` method. The `collect()` method has been overridden to collect Boolean values (true = 1.0, false = 0.0) and can also collect weighted statistics.

The statistic package, as shown in Figure 3, allows for standard statistical collection through the `Statistic` class, as well as statistical collection algorithms designed for simulation data (e.g., standardize time series and batch means methods). Users can easily implement the `AbstractStatistic` base class to provide additional statistical collection algorithms.

### 2.1.3 Example

This section presents a simple example that utilizes the functionality of the random and statistic packages. For a single server queueing system, Lindley’s equation, see Gross and Harris (1998), allows the computation of the waiting times of each of the customers based on knowledge of the arrival and service times. Let \( X_1, X_2, \ldots \) represent the successive service times and \( Y_1, Y_2, \ldots \) represent the successive inter-arrival times for each of the customers that visit the queue. Then, Lindley’s equation is:

\[
W_{\text{ast}} = \max(0, W_r + X_i - Y_i) \quad \text{where} \quad W_r \quad \text{is the waiting time of the} \ r^{th} \text{customer.}
\]

### Insert Code Listing 1 about here

In lines 3 and 4, the inter-arrival time and the service time distributions are defined. For illustrative purposes, the more general interfaces `RandomIfc` and `DistributionIfc` have been used. By default each distribution is given its own stream of random numbers when constructed. Thus, as
indicated in lines 3 and 4, there is no need to create a random number generator. Lines 6-8 specify the number of replications, number of customers, and the customer number to serve as a warm up period indicator. Lines 9-12 define the across replication statistics and the within replication statistics. For illustrative purposes, \( \text{avgw} \) has been declared as type AbstractStatistic. Thus, any sub-class of AbstractStatistic could have been used when creating the instance. The object \( \text{wbar} \) collects each customer’s waiting time, while \( \text{avgw} \) collects the average waiting time for customers across replications. Line 16 implements Lindley’s equation. Lines 17 and 18 collect the within replication statistics. Notice how, in line 18, the Boolean expression \((w > 0.0)\) is observed. Because the collect method of the Statistic class treats \( t = 1.0 \) and \( f = 0.0 \), the statistics on this indicator are easily tallied. Lines 19-22 implement the resetting of the within replication statistics when the warm up indicator is reached. Lines 25 and 26 collect the end of replication averages for the waiting time and the probability of wait, before they are cleared/reset in lines 28-29. After all replications have been executed, the statistics are printed in lines 31-32. Exhibit 1 presents the sample statistical output from the program.

**Insert Exhibit 1 about here**

This program can be easily modified to use different distributions for the inter-arrival and service times by modifying lines 3 and 4. For example, by replacing line 3 with:

```java
RngIfc rng = new ARI1CorrelatedRng(0.8);
RandomIfc y = new Lognormal(1.0, 0.5, rng);
```

the inter-arrival times will be correlated lognormal random variables. Notice that the distribution takes in an instance of classes that implement the RngIfc interface. Thus, any correlation induction strategy can be easily accommodated simply by ensuring that it implements the RngIfc. Also note that the underlying random number streams (created within the distributions) continue for each replication from where they left off. Thus, each replication is independent. The streams for the distributions can be easily manipulated by using the RandomStreamIfc interface.

Code Listing 2 indicates how easy it is to perform an analysis using batch means and standardized time series. In this example, the within replication observations of the customer wait times from Lindley’s equation are captured. Lines 1 and 2 declare instances of the BatchStatistic and StandardizedTimeSeriesStatistic classes to be used to directly observe the waiting time for each customer. Complete statistics based on these methods can easily be reported (not shown here due to space limitations). The default batching algorithm is essentially the same as the algorithm used in Arena™. See the discussion in Fishman (2001) or Kelton et al. (2006) for a description of the algorithm. The important point is that any simulation output analysis technique can be easily incorporated and used by adhering to the structure imposed by the framework’s classes and interfaces.

**Insert Code Listing 2 about here**

Both the random and statistic packages have been designed to enable their use outside of the JSL as a general-purpose utility (e.g. for pure Monte-Carlo studies). The JSL also facilitates discrete-event modelling. The next section briefly describes the JSL’s support for scheduling and executing events.

### 2.2 The Calendar Package

Within discrete-event simulation, the ability to schedule and execute events is a necessity. This ability is found within the Scheduler class and within the calendar package within the JSL. The Scheduler class only provides for processing the events (e.g. scheduling, executing the next event, cancelling events, updating simulated time, tracing events, etc.). The Scheduler class does not provide the data structure to hold events. The calendar package provides the data structures to hold events.

An event is a one-way transmission of information from one object to another that causes an action resulting in a change in state at a given instant in time. Within the JSL, this concept is represented within the JSLEvent class. JSLEvent holds a reference to an object that implements the ActionListenerIfc interface, which requires a method \( \text{action}() \) that supplies the actions associated with the event (in essence the event routine). Besides setting the time of the event, the user can set a priority, a name, and a type. In addition, the JSLEvent class has a reference to an Object, which can be used to send information along with the event when it is scheduled. JSLEvent implements the Java Comparable interface to provide an ordering first by smallest time, then by smallest priority, and finally by the order of creation.

Events are held within a data structure that is represented by the CalendarIfc interface. When constructing an instance of the Scheduler class an instance of a class that implements the CalendarIfc interface must be supplied. The calendar package provides four standard event calendar data structures based on a priority queue, a tree set, a skew heap, and a linked list. The default calendar is based on Java’s PriorityQueue class. Users can easily supply their own calendar by implementing the CalendarIfc (add(), nextEvent(), isEmpty(), cancelAll(), cancel(), and size()) and using the compareTo() method of JSLEvent to properly order the data structure. Thus, the testing and use of different future event data structures can be easily accomplished within the JSL.
2.2.1 Scheduling and Executing Event Actions

As mentioned, the actions associated with an event should be contained within a class that implements the ActionListenerIfc interface. Within the JSL, this is usually accomplished by using an inner class that implements the ActionListenerIfc interface. Then, an instance of that class is supplied when scheduling the event. Code Listing 3 illustrates the event routines (in the form of action listeners) for a discrete event implementation of a simple M/M/1 queue.

Insert Code Listing 3 about here

Line 3 shows how events can be scheduled. An inherited scheduleEvent() method is used to schedule the arrival of the first customer. The object reference variable, myArrivalListener, represents an instance of the inner class, ArrivalListener, shown in lines 6-18. The object reference, myArrivalRV, is used to get the value of the time between arrivals when scheduling the event.

As shown in lines 6-18, the logic for handling an arrival to the system is placed in the action listener. This logic is very standard: if the number of busy servers is less than the number of available servers, then the number of busy servers is incremented and an end of service event is scheduled, else the number in queue is incremented (see lines 8-14.) Line 16 simply schedules the next arrival. Similar logic is presented in lines 20-30 for handling the end of service for a customer and scheduling the next customer to be served if there are customers waiting in the queue.

Code Listing 3 uses a number of object references, e.g. myNumBusy on lines 8 and 9. This object is a reference to a time weighted statistical collection variable represented by the TimeWeighted class. It is an example of a sub-class of ModelElement. The modelling of these types of objects within the JSL is accomplished with the modeling package and its sub-packages, which is discussed in the next section.

2.3 The Modeling and Model Element Packages

The key packages within the JSL for simulation modelling are the model package and its sub-package elements. The model package has classes that implement the functionality associated with simulation events and models. The elements package has classes that define objects that can be added to a simulation model (e.g. queues, resources, variables, etc.). The development of a simulation model is based on sub-classing the ModelElement class that provides the standard recurring actions within a simulation as well as allowing access to an instance of the Scheduler class.

Standard recurring actions are provided so that every model element can execute code prior to an experiment, prior to a replication, upon model initialization, upon warm up, after a replication, and after an experiment. For example, every sub-class of model element should implement an inherited protected method called initialize() to provide logic when the overall model is initialized that is specific to that model element. In Code Listing 3, lines 1-4 illustrate the initialize() method for the surrounding model element. This code is automatically called when the containing model is initialized at the start of each replication. For this example, this ensures that the first customer’s arrival is scheduled when the model is initialized.

Insert Figure 4 about here

Figure 4 shows that a ModelElement may contain other instances of sub-classes of ModelElement. In addition, it shows that Model is a sub-class of ModelElement and that every ModelElement has a reference to a Model. The key to understanding and effectively using the JSL is to understand the recursive composite pattern implemented in Figure 4. It is helpful to conceptualize this type of association as a parent/child relationship. The parent is the composite (the thing that contains) and the children are the things that are contained. The composite pattern implies an object hierarchy. That is, a tree of objects. Within the JSL, an instance of Model serves as the base (root) of the tree, with each node being an instance of a sub-class of ModelElement. This allows model elements to be “hooked” into the model and then to react to standard simulation actions, such as initialization. This is a common pattern in simulation languages. For example, users of the simulation language Arena™ can implement visual basic for application code that occurs prior to and after a replication.

2.1.2 Building and Running a JSL Simulation Model

To build and run a JSL simulation model, the user must first design sub-classes of ModelElement that represent the modelling situation. Then, the user must create instances of their model elements and add them to an instance of a Model. For example, in Code Listing 4, line 4 creates an instance of Model, line 6 creates and instance of JobShop (a sub-class of ModelElement) and supplies the model as its parent. The JobShop model will be discussed further in the next section. Lines 8-12 perform this same procedure for the model element called WorkStation. In this manner, the model’s object hierarchy is built. For readers that are familiar with other simulation languages, this is in concept similar to opening a model building window (creating a model) and dragging and dropping simulation constructs into the model. Within the JSL this process is code oriented; however, it should be clear that a graphical user interface could be constructed to perform such model building activities. Once a model has been constructed, it must be executed.

Code Listing 4 about here

The modeling package has three classes that facilitate the running of simulation models: Replication, Experiment, and ExperimentRunner. These classes are built upon an abstract base class that embodies the
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terative process embodies a sequence of steps that can
be executed. Prior to executing the steps, the iterative
process must be initialized, then the steps can be executed,
and finally some clean up code can be executed after the
iterative process has been ended. Each step can be run
individually or all steps can be run until a condition is met.

The class Replication is an iterative process that
executes events until there are no more events or until some
other stopping condition is met. Within the JSL, it is even
possible to run experiments for a length of real clock time.
The Experiment class is also an iterative process, but its
steps are instances of the class Replication. Thus, an
experiment is simply a sequence of replications. The user
has full control over setting the length of the replications,
the length of the warm up period, running until a condition
is set (e.g. a half-width is reached), etc.

In Code Listing 4, line 34 constructs an instance of an
Experiment, passing in a reference to the model. Then,
in lines 36-38, the experiment’s running conditions are set.
Line 40 turns on some default text file reporting to capture
all statistical information from the experiment. Finally, line
42 tells the experiment to run all of its replications via the
method runAll().

Individual (single) instances of the class Replication
can also be run in this manner. Finally, the class
ExperimentRunner is also an iterative process whose
steps are instances of the class Experiment. The user
provides an iterator that returns experiments, which then
will each be run in turn until all the experiments have been
executed. In this manner, a set of experimental scenarios
can be easily constructed and run within the JSL.

The JSL has a large number of already constructed model
elements for use in simulations. Due to space limitations,
only a few are described in this paper.

• Variable – A class that represents the use of
variables within a model. Variables have an initial
value and will be reset to the initial value automatically
at the beginning of each replication.

• RandomVariable – A sub-class of Variable that can
take on a random value within the simulation model.
The JSL handles stream control for its random
variables. At the end of each replication, the streams of
each random variable are advanced to the next sub-
stream, thereby, improving synchronization for the
purpose of using common random numbers.

• ResponseVariable – A sub-class of Variable that provides observation-based statistical collection.

• TimeWeighted – A sub-class of
ResponseVariable that facilitates the use of time-
based variables. As indicated in Code Listing 3, these
variables can be incremented (line 13) and decremented
(line 24). This enables the automatic collection of
time-weighted statistics on the variable.

• Counter – A sub-class of ResponseVariable
that facilitates the definition of a variable that can be
used to count occurrences and to stop the simulation
when the counter reaches a limit. Other actions can
also be triggered when the counter reaches its limit.

• ResponseVariableAverageObserver, AggregateTimeWeightedVariable, AggregateCounter – These classes are examples
that allow for the automatic collection of aggregate
statistics across responses within a simulation. For
example, by attaching an instance of
AggregateTimeWeightedVariable to multiple
instances of TimeWeighted variables an aggregate
time weighted total is collected. This is facilitated
through the use of the Observer/Observable pattern.
Whenever, the value of the variable changes (e.g. line
24), any listeners will be notified.

• Queue – This class models a queue for holding objects
that must wait within a simulation and provides for
automatic collection of time in queue and number in
queue statistics. The Queue model element
automatically empties any queued entities when it is
initialized at the beginning of a replication. The
runtime switching of queue disciplines is provided
within the framework.

• Resource – This class models a resource having a
common set of units that can be allocated and
automatically tabulates resource usage statistics.

• ResourceSet – This class models a set of resources
that may be requested via various resource selection
rules.

• EventGenerator – This class allows the user to
define a recurring pattern of events, specify the time
between events, the number of events to occur, etc.
This provides the functionality similar to a CREATE
module found in many simulation languages.

In addition to these model elements, the JSL has a
package that facilitates the modelling of objects that move
through space. For example, the user defines a spatial
model (essentially a coordinate reference frame) and uses
model elements that implement the SpatialElementIfc interface. The modelling of
mobile resources is facilitated with classes
(MobileResource, Transporter, TransporterSet, etc.). In addition, as mentioned in the
literature review section, the JSL has packages for
modelling queueing networks, inventory systems, supply
chains, and transportation networks.

Once a JSL model has been built the user can register
observers to any model element within the model. These
observers can be notified when the model element indicates
a change. This mechanism is facilitated within the JSL via
the observers package.
2.4 The Observers Package

The observers package within the JSL is predicated on exploiting, to the extent possible, the already existing Observer/Observable pattern (see Gamma et al. (1995)) implemented within the Java system libraries. With the Observer/Observable pattern, the data is separated from the view of the data. In this pattern, an observable object (an instance of a class that extends the Java class Observable) can be observed by one or more objects called Observers, which implement the Observer interface. The Observable class has methods that allow the registration and management of observers. ModelElement extends from Observable and thus inherits all of its methods. Sub-classes of ModelElement can use the notifyObservers() method to notify any registered observers that it has changed in some manner. This pattern allows for loose coupling between the Observer and the Observable classes. In fact, the Observable object does not need to know the type of the object that is observing it. An observer could be a graphical user interface component, a class that writes to a database, a statistical collection object, etc. This provides for extreme flexibility when extending and developing models based on the JSL.

Statistical collection and output reporting are implemented using the observers package within the JSL. The previously mentioned classes (ResponseVariable and TimeWeighted) both are observed by instances of the StatisticalObserver class. In this case, whenever the value of the variable changes, the instance of a StatisticalObserver is notified. It then is responsible for tabulating the appropriate statistics (batch, within replication, across replication, etc.)

The observer package has many other classes that observe parts of the JSL. Some examples include:

- TimeWeightedObserver – This class observes and collects statistics on TimeWeighted variables.
- VariableTraceTextReport – This class can be used to write the value of Variables and the time that the variable changes to a text file.
- SchedulerTraceReport – This class is used by the Scheduler class to write each event to a text file for tracing events.
- BatchReport – This class facilitates the reporting in a text file the replication batch statistics.
- ExperimentReport – This class reports in a text file statistics and information about the running of an experiment.
- ReplicationReport – This class is used to report information to a text file about the running of a replication and its statistics.
- AccessDBReport, AccessDBBatchReport, AccessDBReplicationReport, AccessDBSummaryReport – These classes provide examples for how to write the statistical information collected during a simulation (e.g. batch statistics, replication statistics, experiment statistics, etc.) to a Microsoft Access™ database. Since Java facilitates the usage of any database through its Java database connectivity functionality, any database can be easily used.

Of course, because there can be multiple observers on the same element, additional observers (e.g. user interface dial, animation, etc) can be easily registered to meet a variety of user needs. Thus, the framework provided by the JSL can be readily extended.

The next section presents an example of a relatively interesting model to illustrate how to model with the JSL.

3 JOB SHOP SIMULATION EXAMPLE

This example is based on the job shop model in Law (2007) page 140. A job shop is essentially a queueing network where the jobs are the customers that must visit a sequence of workstations in order to get some processing completed. Each workstation has a queue and a resource with a specified capacity. A sequence consists of a number of job steps, with each job step representing the machine and the processing time distribution for the given step. There can be a number of different job types in the system, with each job type being assigned a particular sequence to follow through the shop. Jobs that arrive to the shop are assigned a particular job type according to a probability distribution and then the jobs begin to follow the sequence associated with that job type. The system time (total time from creation to exiting the system) must be collected by job type.

For this example, there are 5 workstations in the shop and the job arrival process is Possion with a mean rate 4 per hour. The distribution of job types is (0.3, 0.5, and 0.2) for the respective job types 1, 2, and 3. There are 3 sequences, with job type 1 requiring workstations (3, 1, 2, 5), job type 2 requiring workstations (4, 1, 3), and job type 3 requiring workstations (2, 5, 1, 4, 3). Jobs that arrive to a workstation require 1 unit of the resource and if it is not available will wait in a first in first out queue. The service times at each station are all Erlang order 2 random variables with the mean depending on the type of job and the current station.

To model this situation using the JSL it is useful to conceptualize the classes of objects within the system and how they relate. Then, the model can be built by developing new sub-classes of ModelElement and/or by directly using already existing classes. Figure 5 presents a class diagram for the job shop model. The class JobShop represents the entire system and can hold instances of WorkStation, Sequence, and JobGenerator. The WorkStation class represents the location within the job shop where processing occurs and as indicated in the figure consists of an instance of Queue and an instance of a Resource. The class Sequence represents the sequence of workstations to be visited using job steps (represented by the class JobStep). The class JobStep knows the workstation and a reference to an object that implements the...
The WorkStation class performs in a similar manner as previously described for the single server queue code described in Code Listing 3. Code Listing 6 presents the WorkStation class in its entirety. In line 1, WorkStation extends from the class SchedulingElement. This class provides convenient methods within the JSL for scheduling events. The structure of the class is very standard. First, in lines 3-5 the necessary object references are declared. Then in lines 13-15, the objects are created. For example, line 14 creates an instance of a Resource with the workstation serving as the resource’s parent model element. Lines 18-28, implement the logic to handle the arrival of jobs to the workstation. This is similar to the previously mentioned customer arrival logic. In this case, the job is first enqueued in line 19. Then, if the resource is idle, the job is removed, the units of the resource allocated to the job (line 24), and then the job is started into service. Lines 36-47 implement the end of service logic. In line 38, the currently departing job is retrieved as an object attached to the event. Then, it is used in line 39 to release the resource. If there is a waiting job, then lines 40-44 remove the job and start the job into service. Finally, the departing job is asked to perform its next job step in line 45. This sends the job to the next station in its sequence.

Code Listing 4 already illustrated how to construct and run this model. Recall that each of the individual elements of the model (e.g. JobGenerator, WorkStation, etc.) must be created and associated with an instance of the Model class. Then, an instance of the experiment can be made and executed. Running the model produces statistical output for each queue (time in queue and number in queue), each resource’s number busy statistics, system time by job type, etc.

Table 1 presents the results (sample average (Avg.) and 95% confidence interval half-widths (HW)) from running the model for 100 replications with a warm up period of 5000 hours and a run length of 10000 hours. These settings were chosen arbitrarily for illustrative purposes. The same situation was modelled using Arena™ and executed under the same settings. As can be seen from the table, the results are essentially the same. No formal statistical test was done because it is well known that if enough samples are collected a statistical test of the difference can be made to reject the hypothesis of equality because each system was run under different random numbers. While no formal testing of time to execute was examined, it is interesting to note that the Arena™ model took 2.85 minutes to execute while the Java program took 3.26 minutes on the same computer.

2.1.3 Process View Modelling

To wrap up the modelling capabilities of the JSL, an overview of how the JSL handles process view modelling is presented. In Rossetti et al. (2000) a prototype for using the Java language’s thread mechanism to implement the process interaction approach within the JSL was discussed. The initial testing of this concept proved disappointing. Because of the way that Java implements its threading, the constant
context switching that occurs within a simulation model makes the overhead of using threads in this manner very problematic. In fact, L’Ecuyer et al. (2002) describe this similar problem in their thread-based implementation for processes. Simulations using Java’s thread mechanism take significantly longer to execute. Even Java’s recent revisions of its thread packages have not made an improvement in this regard. The fact is, Java’s thread mechanism was never meant for this use. Weatherly and Page (2004) also discuss this issue and present a very reasonable argument for adding co-routine support to the Java language. Co-routines are the basic mechanism that the languages Simscript™ and ModSim use for their process interaction approach to simulation modelling. Indeed, this would be great improvement for the use of Java for simulation modelling if it was realized. Jacobs and Verbraeck (2004) also discuss the issues related to using threads as the underlying mechanism for performing process interaction in Java. They develop formalisms for mapping process routines on to the event scheduling formalism via a Java interpreter. Their approach is based on class reflection.

For the moment, the original implementation of the JSL’s process interaction approach based on Java’s threads has been depreciated; however, the JSL does support the process description approach to implementing the process view. The approach taken by the JSL is similar (in spirit) to what was done in Jacobs and Verbraeck (2004). The JSL maps the process interaction to a state transition diagram that functions based on event scheduling. The advantage of the JSL’s mechanism is that it does not require an interpreter. The disadvantage is that entity state and its relationship to the process state is more difficult to maintain. For example, the JSL does not store context like a co-routine implementation does.

Simulation languages like Arena™ are built upon the notion of describing the process (or life of an entity) through a series of commands. This is often built via a network representation of the flow of entities as described in Joines and Robert (1996) (e.g. YANSL). The JSL implements the process view by allowing the user to describe the flow of an entity through a series of commands. Essentially, the commands are held in a list and the current command that the entity is executing is always noted so that the next command can be executed. This is similar to Jacobs and Verbraeck’s notion of a control state. The user uses the ProcessDescription class to add various commands (ProcessCommands) to the process. Then, the client can create a process executor (ProcessExecutor) that will iterate through the commands for a given entity. This executes the process for the entity.

The ProcessExecutor is the real workhorse in implementing the JSL’s process description approach. In essence, an instance of a ProcessExecutor acts as a separate “process” that runs an entity through the list of commands associated with a particular ProcessDescription. The ProcessExecutor keeps track of the current state of the “process”, i.e. whether it is created, initialized, suspended, executing, or terminated.

In addition, a ProcessExecutor keeps track of the currently executing command, which enables the suspension, resumption, jumping within, and the termination of the execution of the commands. The ProcessExecutor relies heavily on a rigorous state pattern, Gamma et al. (1995) (see Figure 5) to properly implement the legal processing of the commands. The key to this pattern is the ability to suspend and resume the iteration through the process commands. In the figure, when an instance of a ProcessExecutor is constructed it is immediately placed in the Created state. Then, it may only be initialized. Once in the Initialized state, it is ready to be executed. This is accomplished with the use of the start(command index) method, which tells the executor to start executing the command at the provided index. Once in the Executing state, the process can transition normally to the next command in the process description or jump to other commands. In addition, the process, can be suspended at the current command. If the process has been suspended, it can then be resumed at a particular command. Finally, the process can be terminated. Once terminated the process can be re-used again by using the initialize() method.

Insert Figure 5 about here

Due to space limitations, the coding details of how all this is implemented are omitted; however, Code Listing 7 shows how easy it is to develop a model using these constructs.

Insert Code Listing 7 about here

In lines 4-17 of the listing, the major model elements necessary to model job type 2’s process within the job shop model are constructed and added to the model. In lines 12-17, an instance of a Resource and an instance of a Queue are used to represent a workstation in the job shop. Then, in line 19, an instance of a ProcessDescription is created. This will be used to describe the life of a type 2 job. In line 23, an instance of an EntityProcessGenerator is created. This class will create the entities according to an inter-arrival time and instantiate an instance of the ProcessExecutor class to have the entity execute the process described by the ProcessDescription class.

In lines 26-36, a series of process commands (e.g. Seize, Delay, and Release) are created and attached to the instance of ProcessDescription. These represent the sequence of visits to workstations 4, 1, and 3 required by job type two. When the simulation model is run, entities will be created and flow through these commands according to the process description.

Since the JSL is open source, anyone can add to the features of the process modelling by implementing additional process commands. The JSL process description architecture also supports the use of macro commands (commands consisting of other commands). For example, the three commands Seize, Delay, and Release can be combined into a single command (e.g. like Arena™’s Process module) without much difficulty.
4 FUTURE RESEARCH AND DEVELOPMENT

The JSL represents a readily extendable and useful open source software implementation for developing discrete event simulation models. The only code that is not licensed under the GNU GPL is the random number generator from L’Ecuyer (2001). This code can be found at (http://www.iro.umontreal.ca/~simardr/indexe.html) and is freely available for non-commercial purposes.

Because of the JSL’s extendibility, there always remains room for future software development. The key areas for future development include 1) adding to the range of statistical output techniques, 2) adding to the variety of random number distributions, 3) providing distribution fitting utilities, 4) adding more process commands to the process description modelling elements, 5) re-implementing the process view based on threads for educational and testing purposes, 6) adding animation, and 7) adding graphical user interface support.

Future research within the JSL involves adding to the modelling capabilities for supply chains, queuing networks, and transportation networks. Other addition research work involves adding support packages for simulation optimization techniques, studying the efficiency and memory usage of different JSL design implementations, and integrating other simulation paradigms into the JSL architecture (e.g. agent based modelling and continuous simulation).

A number of tutorial examples for the JSL have been developed based on examples within Law (2007). In particular, there are implementations of the time-sharing computer model, the \((s, S)\) inventory system, the job shop model, and other queuing models. Thus, the JSL would be an excellent complement to the use of Law (2007) for teaching simulation. A complete set of JavaDocs has been generated for the library, and of course, the source is available. The author also plans a textbook based on the JSL.

REFERENCES


JAVA SIMULATION LIBRARY (JSL): AN OPEN-SOURCE OBJECT-ORIENTED LIBRARY FOR DISCRETE-EVENT SIMULATION IN JAVA


WEBSITES

The open source web site will be given here
Figure 1: Key Interfaces and Classes in Random Package
Figure 2: AbstractStatistic and its Read-Only Interface
Figure 3: Classes in the Statistics Package
Figure 4: Key Modelling Classes
Code Listing 1: Lindley’s Equation Example

```java
public static void main(String[] args) {
    // inter-arrival time distribution
    RandomIfc y = new Exponential(1.0);
    // service time distribution
    DistributionIfc x = new Exponential(0.7);
    int r = 30; // number of replications
    int n = 100000; // number of customers
    int d = 10000; // warm up
    AbstractStatistic avgw = new Statistic("Avg waiting time");
    Statistical avgpw = new Statistic("prob of wait");
    AbstractStatistic wbar = new Statistic("Within rep avg waiting time");
    AbstractStatistic pw = new Statistic("Within rep prob of wait");
    for (int i=1;i<=r;i++) {
        double w = 0; // initial waiting time
        for (int j=1;j<=n;j++) {
            w = Math.max(0.0, w + x.getValue() - y.getValue());
            wbar.collect(w); // collect waiting time
            pw.collect((w>0.0)); // collect P(W>0)
            if (j == d) { // clear stats at warmup
                wbar.reset();
                pw.reset();
            }
        }
        // collect across replication statistics
        avgw.collect(wbar.getAverage());
        avgpw.collect(pw.getAverage());
        // clear within replication statistics for next rep
        wbar.reset();
        pw.reset();
    }
    System.out.println(avgw);
    System.out.println(avgpw);
}
```
Exhibit 2: Sample Output for Lindley Equation Example

<table>
<thead>
<tr>
<th>ID</th>
<th>Name Across rep</th>
<th>avg waiting time</th>
<th>Number</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Sum</th>
<th>Average</th>
<th>Variance</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>Confidence Coefficient</th>
<th>Half-width</th>
<th>Weighted Average</th>
<th>Weighted Sum</th>
<th>Sum of Weights</th>
<th>Weighted Sum of Squares</th>
<th>Last value collected</th>
<th>Last weighted collected</th>
<th>Lag 1 Correlation</th>
<th>Von Neumann Lag 1 Test Statistic</th>
<th>Number of missing observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Name Across rep</td>
<td>avg waiting time</td>
<td>30.0</td>
<td>1.5523842361703213</td>
<td>1.7601221186157152</td>
<td>49.42075879668269</td>
<td>1.6473586265560898</td>
<td>0.001860191056515051</td>
<td>0.04312993225725089</td>
<td>0.007874412266988673</td>
<td>1.965</td>
<td>0.015473220104632743</td>
<td>1.6473586265560898</td>
<td>49.42075879668267</td>
<td>30.0</td>
<td>81.46765887530192</td>
<td>1.6325147072873045</td>
<td>1.0</td>
<td>-0.14736789218428864</td>
<td>-0.8121440898730583</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>Name Across rep</td>
<td>prob of wait</td>
<td>30.0</td>
<td>0.6895666666666654</td>
<td>0.7112333333333374</td>
<td>21.026577777777817</td>
<td>0.7008859259259272</td>
<td>0.003954611507877788</td>
<td>1.563895217823943E-5</td>
<td>0.003954611507877788</td>
<td>1.965</td>
<td>0.003954611507877788</td>
<td>0.003954611507877788</td>
<td>21.026577777777817</td>
<td>30.0</td>
<td>14.737685964444502</td>
<td>0.7008859259259272</td>
<td>1.0</td>
<td>-0.1389880977659123</td>
<td>-0.7830506130522926</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Code Listing 2: Batching and Standardized Time Series Analysis

```java
AbstractStatistic wbar = new BatchStatistic("Batch waiting time");
AbstractStatistic wbarSTS = new StandardizedTimeSeriesStatistic("STS waiting time");
double w = 0; // initial waiting time
for(int j=1;j<=n;j++){
    w = Math.max(0.0, w + x.getValue() - y.getValue());
    wbar.collect(w); // collect waiting time
    wbarSTS.collect(w);
    if (j == d){ // clear stats at warmup
        wbar.reset();
        wbarSTS.reset();
    }
}
```
Code Listing 3: Example Event Routines

```java
protected void initialize() {
    // start the arrivals
    super.initialize();
    scheduleEvent(myArrivalListener, myArrivalRV.getValue());
}

class ArrivalListener implements ActionListenerIfc {
    public void action(JSLEvent event) { // new customer arrived
        if (myNumBusy.getValue() < myNumServers) { // server available
            myNumBusy.increment(); // make server busy
            scheduleEvent(myEOSListener, myServiceRV.getValue());
        } else { // no server available
            myNQ.increment(); // place customer in queue
        }
        // always schedule the next arrival
        scheduleEvent(myArrivalListener, myArrivalRV.getValue());
    }
}

class EndServiceListener implements ActionListenerIfc {
    public void action(JSLEvent event) { // customer departing
        myNumBusy.decrement(); // customer is leaving server is freed
        if (myNQ.getValue() > 0) { // queue is not empty
            myNQ.decrement(); // remove from queue
            myNumBusy.increment(); // make server busy
            scheduleEvent(myEOSListener, myServiceRV.getValue());
        }
    }
}
```
public static void main(String[] args) {
    System.out.println("Jobshop Example");
    // create the containing model
    Model m = Model.createModel();
    // create the jobshop
    JobShop shop = new JobShop(m, "JobShop");
    // create the workstations
    WorkStation w1 = shop.addWorkStation(3, "w1");
    WorkStation w2 = shop.addWorkStation(2, "w2");
    WorkStation w3 = shop.addWorkStation(4, "w3");
    WorkStation w4 = shop.addWorkStation(3, "w4");
    WorkStation w5 = shop.addWorkStation(1, "w5");
    // create the sequences
    Sequence s1 = shop.addSequence();
    s1.addJobStep(w3, new Gamma(2.0, 0.5/2.0));
    s1.addJobStep(w1, new Gamma(2.0, 0.6/2.0));
    s1.addJobStep(w2, new Gamma(2.0, 0.85/2.0));
    s1.addJobStep(w5, new Gamma(2.0, 0.5/2.0));
    Sequence s2 = shop.addSequence();
    s2.addJobStep(w4, new Gamma(2.0, 1.1/2.0));
    s2.addJobStep(w1, new Gamma(2.0, 0.8/2.0));
    s2.addJobStep(w3, new Gamma(2.0, 0.75/2.0));
    Sequence s3 = shop.addSequence();
    s3.addJobStep(w2, new Gamma(2.0, 2.2/2.0));
    s3.addJobStep(w5, new Gamma(2.0, 0.25/2.0));
    s3.addJobStep(w1, new Gamma(2.0, 0.7/2.0));
    s3.addJobStep(w4, new Gamma(2.0, 0.9/2.0));
    s3.addJobStep(w3, new Gamma(2.0, 1.0/2.0));
    JobGenerator jg = shop.addJobGenerator(new Exponential(0.25));
    jg.addJobType("A", s1, 0.3);
    jg.addJobType("B", s2, 0.5);
    jg.addLastJobType("C", s3);
    // create the experiment to run the model
    Experiment e = new Experiment(m, "Job Shop");
    // set the parameters of the experiment
    e.setNumberOfReplications(100);
    e.setLengthOfReplication(10000.0);
    e.setLengthOfWarmUp(5000.0);
    // turn on the desired reporting
    e.turnOnExperimentReport();
    // tell the experiment to run
    e.runAll();
    System.out.println("Done!");}
Figure 5: Class Diagram for Job Shop System
Code Listing 5: Generating Jobs in the Job Shop Model

protected void generate(JSLEvent event) {
    if (!myJobTypes.isEmpty()) {
        // create the job
        Job job = new Job();
        // tell it to start its sequence
        job.doNextJobStep();
    }
}

class JobType {
    String myName;
    Sequence mySequence;
    ResponseVariable mySystemTime;
}

class Job extends Request {
    JobType myType;
    Iterator<JobStep> myProcessPlan;

    Job() {
        super();
        myType = myJobTypes.getRandomElement();
        myProcessPlan = myType.mySequence.getIterator();
        setName(myType.myName);
    }

d public void doNextJobStep() {
    initialize();
    if (myProcessPlan.hasNext()) {
        JobStep step = myProcessPlan.next();
        setTimeRequested(step.getProcessingTime());
        WorkStation w = step.getWorkStation();
        w.arrive(this);
    } else {
        myType.mySystemTime.setValue(getTimeSinceCreation());
    }
}
}
Code Listing 6: The WorkStation Class in the Job Shop Model

```java
public class WorkStation extends SchedulingElement {

    private Queue myQueue;
    private Resource myResource;
    private EndServiceListener myEndServiceListener;

    public WorkStation(ModelElement parent){
        this(parent, 1, null);
    }

    public WorkStation(ModelElement parent, int numServers, String name) {
        super(parent, name);
        myQueue = new Queue(this, getName() + "_Q");
        myResource = new Resource(this, numServers, getName() + "_R");
        myEndServiceListener = new EndServiceListener();
    }

    public void arrive(JobGenerator.Job job){
        myQueue.enqueue(job);
        if (myResource.isIdle()){
            Request nextJob = (Request)myQueue.peekNext();
            if (job == nextJob){
                myQueue.removeNext();
                myResource.allocate(job);
                scheduleEndService(job);
            }
        }
    }

    private void scheduleEndService(JobGenerator.Job job) {
        double t = job.getTimeRequested();
        scheduleEvent(myEndServiceListener, t, "Job " + job.getId() + " End Service at " + getName(), job);
    }

    class EndServiceListener implements ActionListenerIfc {
        public void action(JSLEvent event) {
            JobGenerator.Job job = (JobGenerator.Job)event.getMessage();
            myResource.release(job);
            if (myQueue.size() > 0) {// queue has a job
                JobGenerator.Job nextJob = (JobGenerator.Job)myQueue.removeNext();
                myResource.allocate(nextJob);
                scheduleEndService(nextJob);
                job.doNextJobStep();
            }
        }
    }
}
```
Table 1: Sample Output for Job Shop Model

<table>
<thead>
<tr>
<th></th>
<th>JSL Event View</th>
<th>Arena</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg</td>
<td>HW</td>
</tr>
<tr>
<td>Waiting time in Q1</td>
<td>3.415</td>
<td>0.18</td>
</tr>
<tr>
<td>Waiting time in Q2</td>
<td>31.968</td>
<td>4.36</td>
</tr>
<tr>
<td>Waiting time in Q3</td>
<td>0.188</td>
<td>0.00</td>
</tr>
<tr>
<td>Waiting time in Q4</td>
<td>9.014</td>
<td>0.81</td>
</tr>
<tr>
<td>Waiting time in Q5</td>
<td>0.965</td>
<td>0.02</td>
</tr>
<tr>
<td>Number in Q1</td>
<td>13.688</td>
<td>0.75</td>
</tr>
<tr>
<td>Number in Q2</td>
<td>64.157</td>
<td>8.85</td>
</tr>
<tr>
<td>Number in Q3</td>
<td>0.752</td>
<td>0.01</td>
</tr>
<tr>
<td>Number in Q4</td>
<td>25.286</td>
<td>2.29</td>
</tr>
<tr>
<td>Number in Q5</td>
<td>1.929</td>
<td>0.04</td>
</tr>
<tr>
<td>Number Busy at W1</td>
<td>2.883</td>
<td>0.00</td>
</tr>
<tr>
<td>Number Busy at W2</td>
<td>1.979</td>
<td>0.00</td>
</tr>
<tr>
<td>Number Busy at W3</td>
<td>2.902</td>
<td>0.00</td>
</tr>
<tr>
<td>Number Busy at W4</td>
<td>2.922</td>
<td>0.00</td>
</tr>
<tr>
<td>Number Busy at W5</td>
<td>0.799</td>
<td>0.00</td>
</tr>
<tr>
<td>System Time Type 1</td>
<td>39.055</td>
<td>4.42</td>
</tr>
<tr>
<td>System Time Type 2</td>
<td>15.264</td>
<td>0.83</td>
</tr>
<tr>
<td>System Time Type 3</td>
<td>49.496</td>
<td>4.51</td>
</tr>
</tbody>
</table>
Figure 5: Process State Transition Diagram
Code Listing 7: Job Shop Model with Process View

```java
// create the containing model
Model m = Model.createModel();
// create the elements in the model
Variable v1 = new Variable(m, 1.0, "amt requested");
RandomIfc s2w4 = new Gamma(2.0, 1.1/2.0);
RandomVariable sts2w4 = new RandomVariable(m, s2w4, "ST S2 W4");
RandomIfc s2w1 = new Gamma(2.0, 0.8/2.0);
RandomVariable sts2w1 = new RandomVariable(m, s2w1, "ST S2 W1");
RandomIfc s2w3 = new Gamma(2.0, 0.75/2.0);
RandomVariable sts2w3 = new RandomVariable(m, s2w3, "ST S2 W3");
// create the resources and queues for each workstation
Resource r1 = new Resource(m, 3, "W1");
Queue q1 = new Queue(m, "W1 Queue");
Resource r3 = new Resource(m, 4, "W3");
Queue q3 = new Queue(m, "W3 Queue");
Resource r4 = new Resource(m, 3, "W4");
Queue q4 = new Queue(m, "W4 Queue");
// create the process description
ProcessDescription jt2 = new ProcessDescription(m, "Job Type 2");
// create the time btw arrivals
DistributionIfc tbajt2 = new Exponential((10.0/5.0)*0.25);
// create the model element to generate type 2 jobs
new EntityProcessGenerator(m, jt2, tbajt2, tbajt2);
// create the commands used in the process description
// workstation 4
jt2.addProcessCommand(new Seize(m, v1, r4, q4));
jt2.addProcessCommand(new Delay(m, sts2w4));
jt2.addProcessCommand(new Release(m, r4, q4));
// workstation 1
jt2.addProcessCommand(new Seize(m, v1, r1, q1));
jt2.addProcessCommand(new Delay(m, sts2w1));
jt2.addProcessCommand(new Release(m, r1, q1));
// workstation 3
jt2.addProcessCommand(new Seize(m, v1, r3, q3));
jt2.addProcessCommand(new Delay(m, sts2w3));
jt2.addProcessCommand(new Release(m, r3, q3));
```