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JMT

Java Modelling Tools

JMVA - JSIMwiz - JSIMgraph - JMCH - JABA - JWAT

user manual

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for JMT version 0.9.2 and above

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Chapter 1

Introduction

Java Modelling Tools (JMT) is a free open source suite consisting of *six tools* for performance evaluation, capacity planning, workload characterization, and modelling of computer and communication systems. The suite implements several state-of-the-art algorithms for the exact, approximate, asymptotic and simulative analysis of queueing network models, either with or without product-form solution. Models can be described either through *wizard* dialogs or with a *graphical* user-friendly interface. The workload analysis tool is based on clustering techniques. The suite uses an XML data layer that enables full reusability of the computational engines.

The JMT suite is composed by the following tools:

 **JSIMwiz:** a wizard-based interface for the discrete-event simulator JSIM for the analysis of queueing network models. A sequence of *wizard* windows helps in the definition of the network properties. The JSIM simulation engine supports several probability distributions for characterizing service and inter-arrival times. Load-dependent strategies using arbitrary functions of the current queue-length can be specified. JSIM *wiz* supports state-independent routing strategies, e.g., Markovian or round robin, as well as state-dependent strategies, e.g., routing to the server with minimum utilization, or with the shortest response time or with minimum queue-length, and load dependent routing. The simulation engine supports several extended features not allowed in product-form models, namely, finite capacity regions (blocking), fork-join servers (parallelism), class switching and priority classes. The JSIM performs automatically the transient detection, based on spectral analysis, computes and plots on-line the estimated values within the confidence intervals. What-if analyses, where a sequence of simulations is run for different values of control parameters, are also supported.

 **JSIMgraph:** a *graphical* user-friendly interface for the same simulator engine JSIM used by JSIM *wiz*. It integrates the same functionalities of JSIM *wiz* with an intuitive graphical workspace. This allows an easy description of network structure, as well as a simplified definition of the input and execution parameters. Network topologies can be exported in vectorial or raster image formats.

 **JMVA:** for the *exact* and *approximate* analysis of single-class or multiclass product-form queueing networks, processing *open*, *closed* or *mixed* workloads. Several *exact* algorithms are available for *closed* networks: MVA (Mean-Value Analysis), RECAL (Recursion by Chain Algorithm), MoM (Method of Moments), CoMoM (Class-Oriented Method of Moments). A stabilized version of the Mean Value Analysis MVA algorithm is used. Several *approximate* solution algorithms are also available (Chow, Bard-Schweitzer, AQL, Linearizer, De Souza-Muntz Linearizer). Network structure is specified by textual *wizards*. What-if analyses and graphical representation of the results are provided.

 **JMCH:** it applies a simulation technique to solve a single station model, with finite ($M/M/1/k$) or infinite queue ($M/M/1$), and multiple servers with unlimited ($M/M/c$) or limited queue size k ($M/M/c/k$). The animation of the underlying *Markov Chain* is also shown. It is possible to dynamically change the arrival rate, the service time and the queue size of the system.

 **JABA:** for the identification of *bottlenecks* in multiclass closed product-form networks using efficient convex hull algorithms. Up to three customer classes are supported. It is possible to identify potential bottlenecks corresponding to the different mixes of customer classes in execution. Models with thousands of queues can be analyzed efficiently. *Optimization* studies (e.g., throughput maximization, minimization of response time, identification of the optimal load) can be performed through the identification of the *saturation sectors*, i.e., the mixes of customer classes in execution that saturate more than one resource simultaneously.

 **JWAT:** supports the *workload characterization* process. Some standard formats for input file are provided (e.g., Apache HTTP and IIS log files), customized formats may also be specified. The imported data can initially be analyzed using descriptive statistical techniques (e.g, means, correlations, histograms, boxplots, scatterplots), either for univariate or multivariate data. Algorithms for data scaling, sample extraction, outlier filtering, k-means and fuzzy k-means clustering for identifying similarities in the input data are provided. These techniques allow the identification of cluster of customers having similar characteristics. The clusters centroids represent the mean values of the parameters of the classes (e.g., CPU time, n.o of I/Os, n.o of web pages pages accessed) that can be used for the workload parameterization.

1.1 A brief history of JMT

JMT started in 2002 at Politecnico di Milano as a project to extend an existing set of tools for performance evaluation called Windows Modelling Tools (WMT). The first MSc theses developed a MVA tool and date 1990. Initially, C was used as a programming language, then C++, and since 2002 all the code was converted to Java and the JMT project was started. Fortran was used originally for coding the clustering algorithms K-means and Fuzzy K-means of the JWAT tool (1983) and the code was later migrated to Java in 2006.

Tens of students and several research assistants were involved in the project mainly from the Politecnico di Milano, Italy, and more recently also from Imperial College London, UK.

At present, JMT consists of six tools JSIMwiz, JSIMgraph, JMVA, JMCH, JABA and JWAT. The total number of Java lines of code is 112962 (as of Jan.18th 2013). Since 2006 JMT was downloaded more than 45,000 times by researchers, teachers, practitioners and students.

We are still planning new features and upgrades! We hope you will enjoy using it.

The **Development Team:** G.Casale, G.Serazzi (coordinators), M.Bertoli (system maintainer).

1.2 How to install JMT

You can install all the components of the *Java Modelling Tools* (JMT) downloading them free from <http://jmt.sourceforge.net/Download.html>. JMT is *free* software; it can be used under the terms of the GNU General Public License either version 2 of the License, or any later version.

It is recommended to uninstall any previous version of JMT before installing a new release.

The FULL Version includes all the JMT tools, the graphical installer, the user manual, examples, shortcuts. JMT is platform-independent and requires only the Oracle/Sun Java Runtime Environment (version 1.6 or later) to be installed on the machine. The Java Runtime Environment may be downloaded from <http://www.oracle.com/technetwork/java/javase/downloads/index.html>.

All required libraries are included in the download packages.

JMT has been successfully tested with:

- Microsoft Windows XP/VISTA/7 on Intel and Amd cpu with JRE 1.6
- Mac OS X 10.4.5 and 10.4.6 on G4 cpu
- Linux Fedora Core 5 and Ubuntu 5.10 (requires Sun Java Runtime Environment)
- Linux Ubuntu-PPC 6.06 on G4 cpu using IBM J2SE/JDK

The user may select the **directory** in which **install** the JMT.

Another **new** folder is created in the home directory of the user for the examples and for some working files of JMT. Also the files created by the **Loggers** (*xxx.csv* files) are located in this folder. The location of the **JMT working folder** depends on the operating system of the machine and the user name:

- on **Linux** and **Unix** os in general, the user home is located in path `/home/<user name>/JMT`
- on **Windows XP** the working folder is `C:\Documents and Settings\<user name>\JMT`
- on **Windows Vista, Windows 7 and later** the folder is `C:\Users\<user name>\JMT`

- on Mac OS X the folder is `/Users/<user name>/JMT`.

Two new subdirectories are created in this folder: `JMT\examples` and `JMT\jwatFormat`. The subdirectory `\example` contains some models implemented with the JMT tools. The subdirectory `\jwatFormat` contains the description of the formats (in Perl5) of the data that are supplied as input for the demo of JWAT tool.

This manual and several other documents can be found in the sourceforge page of JMT.

1.3 Starting with the JMT suite

Double click on the JMT icon  on your *program group* or on the *desktop*, or open the *command prompt* and type from the installation directory:

```
java -jar JMT.jar
```

The window of Figure 1.1 will appear.

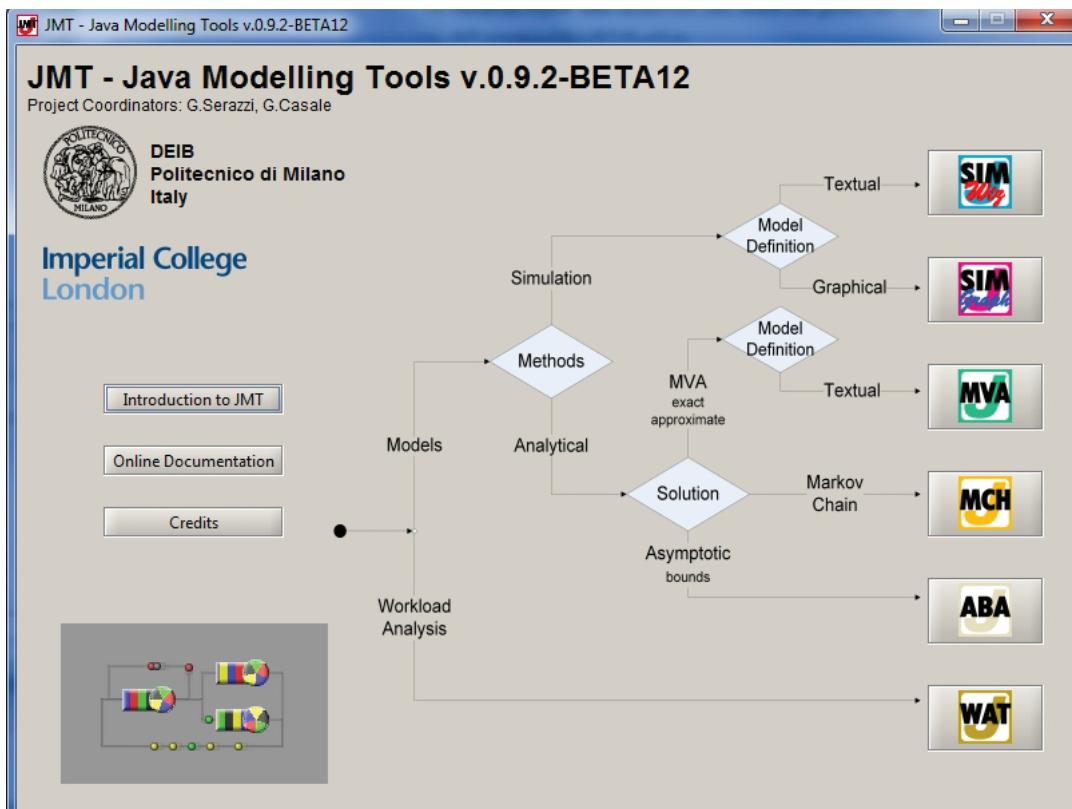


Figure 1.1: The JMT suite Starting Screen

This starting screen is used to select the application of the suite to be executed by clicking on the corresponding button. The flow chart should help the user to select the application that best fits its needs.

In the following chapters the tools will be examined in details and some examples are given. This manual is intended for the general user that wants to learn how to interact with JMT. Advanced users that want to learn details on internal data structures, computational engines and XML interfaces should refer to *JMT system manual*.

Several other documents related to JMT description and applications are provided with the suite. Click on **Online Documentation** button to access the library.

Chapter 2

JMVA – Exact and Approximate Solution Techniques

2.1 Introduction

JMVA solves open, closed and mixed product form queuing networks [BCMP75]. Several solution algorithms are available. Open models are solved applying the classical queuing networks algorithms (QN), see e.g. [Kle75] [Ste09][Tri02]. The *exact* solution algorithms available for closed queuing networks are: MVA (Mean-Value Analysis) [RL80], RECAL (Recursion by Chain Algorithm) [CG86], MoM (Method of Moments) [Cas06] [Cas11], CoMoM (Class-Oriented Method of Moments) [Cas09], RGF (Recursive Generating Function) [HL04] . In order to avoid numerical instabilities of the solutions when the model contains load dependent stations, the implemented exact MVA algorithm is a *stabilized* version [BBC⁺81] of the classic MVA version. The *approximate* AMVA algorithms available are: Chow [Cho83], Bard-Schweitzer [Sch79], Linearizer [CN82], DeSouza-Muntz Linearizer [dSeSM90], Aggregate Queue Length (AQL) [ZES88] , Monte Carlo [KW97] .

The use of some of the exact and approximate solution algorithms is motivated by the *very large* time and space requirements of the exact MVA algorithm when the models have large dimensions (high number of classes, of resources, and of customers), a case commonly encountered in modern web and cloud applications.

Resources may be of two types: *queueing* (either with `load independent` or `load dependent` service times) and *delay*. The model is described in alphanumeric way: user is guided through the definition process by steps of a *wizard* interface. *What-if* analyses, where a sequence of model is solved for different values of the parameters, are also possible (see subsection 2.2.6). The solutions provided by several approximate algorithms and by the exact MVA can be compared through suitable graphical representation.

A graphical interface to describe the model in a user-friendly environment is also available, see JSIM`graph` for details.

2.1.1 Starting the alphanumeric MVA solver

Selecting  button on the starting screen, Figure 2.1 window shows up. Three main areas are shown:

Menu : it is organized into three groups of functions. To use a menu, click on the menu heading and choose the appropriate option. For the description of menu entries, see section 2.6

Toolbar : it contains some buttons to speed up access to JMVA functions (e.g. New model, Open, Save... See section 2.6 for details). If you move the mouse pointer over a button a tooltip will be shown up.

Page Area : this is the core of the window. All MVA parameters are grouped in different tabs. You can modify only a subset of them by selecting the right tab, as will be shown later.

2.2 Model definition

Models with one or multiple customer classes provide estimates of performance measures. For a brief description of basic terminology please refer to Appendix A.

In the case of single class models, the workload is characterized by two inputs: the set of service demands, one for each resource, and the workload intensity. On the other hand, in multiple class models, a matrix of service demands is requested [LZGS84].

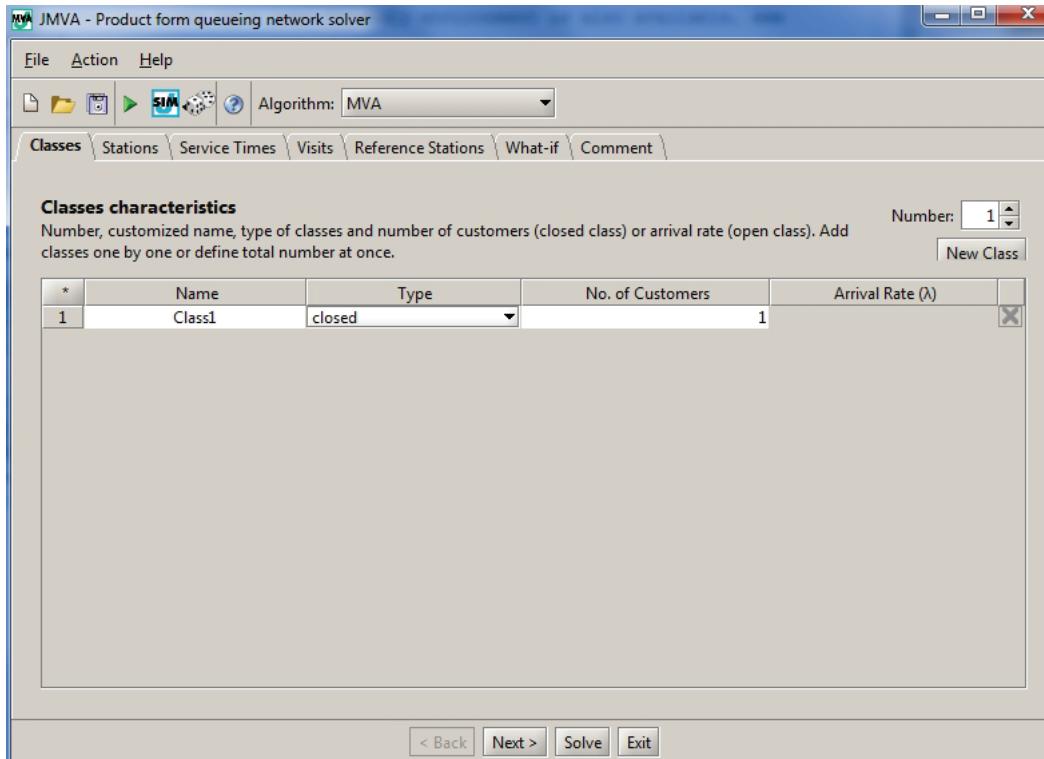


Figure 2.1: Classes tab

2.2.1 Defining a new model

To define a new model select toolbar button or the *New* command from *File* menu. The following parameters must be defined:

1. **Classes** with their workload intensities (number of customer N for closed classes and arrival rate λ for open classes)
2. **Stations** (service centers)
3. **Service times and Visits** (or **Service demands**)
4. **Reference Stations**
5. **What-if**
6. Optional short **Comment**

The execution of JMVA provides, for each class and each station, the following performance indices:

- Throughput
- Queue Length
- Residence Time
- Utilization
- System Power (throughput/response time for *each class*) [Kle79]

The following *aggregate* indices are provided:

- System Throughput
- System Response Time
- Average number of customers in the system
- System Power: Aggregate System Throughput (i.e., sum of the per-class throughputs) / Aggregate System Response Time (i.e., sum of the per-class response times weighted by the relative throughputs)

Input tabs

As can be seen in Figure 2.1, the parameters that must be entered in order to define a new model are divided in the following tabs: **Classes**, **Stations**, **Service times**, **Visits**, (or **Service Demands**), **Reference Stations**, **What-if**, and **Comment**.

You may input the **Service Times** and **Visits** for the stations, if you know, or alternatively the **Service Demands** (that are the products of **Service times** and **Visits**). As a function of your choice, the **Service Demands Tab** or the **Service Times** and **Visits Tabs** will be hidden, see subsection 2.2.4. You can navigate through tabs:

- using sequential wizard buttons, if enabled, at the bottom of the window (Figure 2.2)
- using sequential buttons located in menu
- using the tab selector, clicking on the corresponding tab (Figure 2.3)

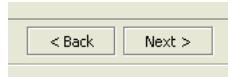


Figure 2.2: Wizard buttons



Figure 2.3: Tab selector

2.2.2 Classes Tab

An example screenshot of this tab can be seen in Figure 2.1. This tab allows to characterize customer classes of the model. Your model will be a single class model if and only if there will be only one class, closed or open. On the contrary multiple class models will have at least two classes, closed and/or open.

The number of classes in the model can be specified in the corresponding input area, shown in Figure 2.4 and can be modified using the keyboard or using the spin controls.

Figure 2.4: Number of classes

Using the delete button associated to a specific class, a class can be removed provided that there will be at least one class after the deletion. Similar result may be obtained using spin controls, decreasing classes number; in this case last inserted class will be removed.

Default class names are *Class1*, *Class2*, ... *ClassR*. A model can be customized by changing these names: this can be done by clicking directly on the name that should be changed.

In Figure 2.5 there are three classes of customers, two closed and one open. The third class has the default name *Class3* while the other two classes have customized names, namely *ClosedClass* and *OpenClass*.

A class type can be **Open** or **Closed**. It is important to define each class type because a closed class workload is described by a constant number of customers in each class, while the open classes workload is described by the customer arrival rate for each class which does not imply limits on the maximum number of customers.

As can be seen in Figure 2.5, a class type can be selected in a combo-box. The input boxes *No. of Customers* (*N*) referring to closed classes accept only positive integer numbers; the input boxes of the *Arrival Rate* (λ) referring to open classes, accept positive real numbers (Figure 2.6).

2.2.3 Stations Tab

The number of stations of the model can be specified in the corresponding input area (Figure 2.7) and can be modified using the keyboard or the spin controls.

Using the delete button associated to a specific station, a station can be removed provided that there will be at least one station after the deletion. A similar result may be obtained using spin controls, decreasing stations number; in this case last inserted station will be removed.

Default station names are *Station1*, *Station2*, ... *StationM*. In order to personalize your model, you can change and give names other than default ones.

In Figure 2.8 there is only one station with default name *Station4* and there are three stations with customized names: *CPU*, *Disk1* and *Disk2*.

*	Name	Type	No. of Customers	Arrival Rate (λ)	
1	ClosedClass	closed	100		X
2	OpenClass	open		3.140000	X
3	Class3	closed	66		X
		closed			
		open			

Figure 2.5: Defining the classes types

No. of Customers	Arrival Rate (λ)
100	3.140000

Figure 2.6: Workload definition of the number of customers of a closed class ($N = 100$) and the arrival rate of an open class ($\lambda = 3.14$)

Number:

Figure 2.7: Number of stations

*	Name	Type	
1	CPU	Load Independent	X
2	Disk1	Load Independent	X
3	Disk2	Load Independent	X
4	Station4	Load Independent	X
		Delay (Infinite Server)	
		Load Independent	
		Load Dependent	

Figure 2.8: Defining the stations type

A station type can be **Load Independent**, **Load Dependent** or **Delay**. You can insert in your model a **Load Depend** center only if there is a unique closed class¹; in all other cases the combo-box will be disabled.

It is important to define each station type because if a station is **Load Dependent** a set of service demand - or a set of service times and the number of visit - must be defined (one service demand/time for each possible value of queue length inside the station).

In subsection 2.2.4 we will explain this concept with more details.

2.2.4 Service Demands, Service Times and Visits Tabs

Service Demands can be defined in two ways:

- directly, by entering Service Demands (D_{kc})
- indirectly, by entering Service Times (S_{kc}) and Visits (V_{kc})

Service demand D_{kc} is the total service requirement, that is the average amount of time that a customer of class c spends in service at station k during one interaction with the system, i.e. it completes execution. Service time S_{kc} is the average *execution* time spent by a customer of class c at station k for a single visit at that station (it *does not include* the waiting time in queue!) while V_{kc} is the average number of visits at that station during a complete execution of the job.

Remember that it is $D_{kc} = V_{kc} * S_{kc}$ so it is simple to compute the service demands matrix starting from service times and visits matrices. Inverse calculation is performed with the following algorithm:

$$V_{kj} = \begin{cases} 1 & \text{if } D_{kc} > 0 \\ 0 & \text{if } D_{kc} = 0 \end{cases}$$

$$S_{kc} = \begin{cases} D_{kc} & \text{if } D_{kc} > 0 \\ 0 & \text{if } D_{kc} = 0 \end{cases}$$

ATTENTION: if you define a model with the parameters **Service Times** and **Visits**, and later you will use the **Service Demands**, the values of the **Visits** will be lost (because, as above explained, they are set to 1).

Service Demands Tab

In this tab, you can insert directly the **Service Demands** D_{kc} for each pair {station k , class c }. In Figure 2.9 a reference screenshot can be seen: notice that the values of the D_{kc} elements of the D -matrix have already been specified because the *default* value assigned to *newly created stations* is *zero*.

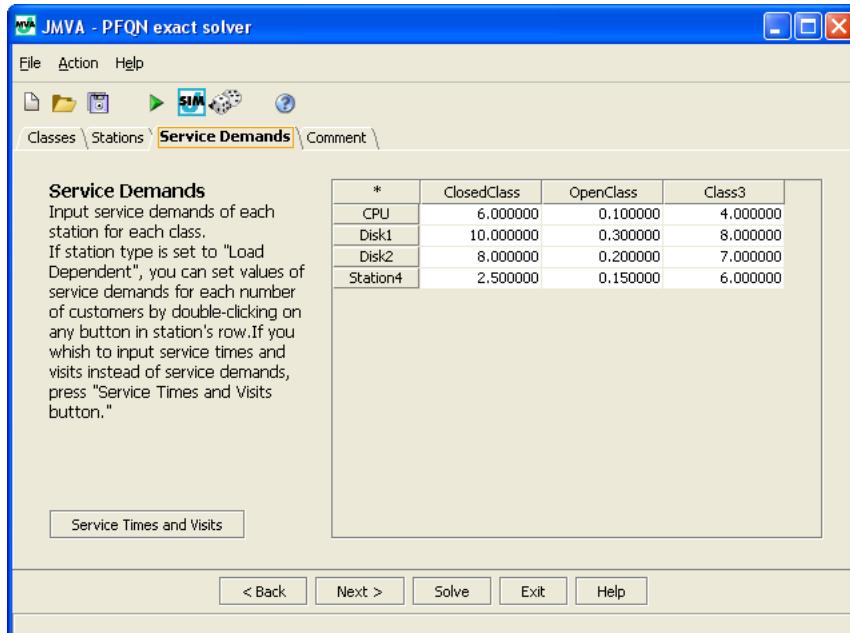


Figure 2.9: Example of the Service Demands Tab

¹Multiclass, open and mixed models with load dependent stations are not supported yet

In the example of Figure 2.9, each job of type *ClosedClass* requires an average service demand time of 6 sec to *CPU*, 10 sec to *Disk1*, 8 sec to *Disk2* and 2.5 sec to *Station4*. On the other hand, a job of type *OpenClass* requires on average 0.1 sec of *CPU* time, 0.3 sec of *Disk1* time, 0.2 sec of *Disk2* time and 0.15 sec of *Station4* time to be processed by the system.

If the model contains any load dependent station, the behavior of Figure 2.10 will be shown. By double-

*	ClosedClass
Station1	LD Settings...

Figure 2.10: Defining a *load dependent* station service demand

clicking on *LD Settings...* button a window will show up and that can be used to insert the values of the service demands for each possible number of customer inside the station. That values can be computed by evaluating an analytic function as shown in Figure 2.11. The list of supported operators and more details are reported in subsection 2.2.8.

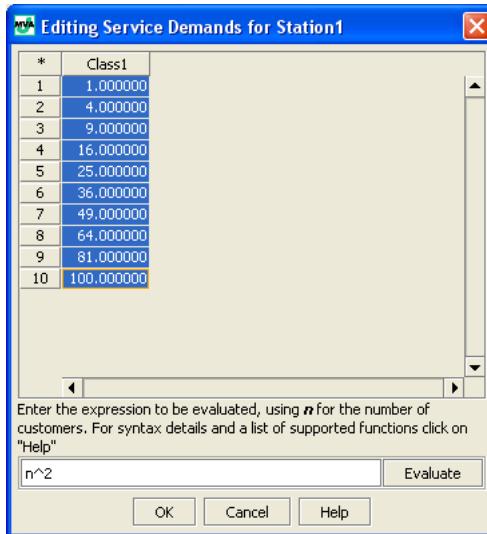


Figure 2.11: Load Dependent editing window

Service Times and Visits Tabs

*	ClosedClass	OpenClass	Class3
CPU	1.000000	1.000000	1.000000
Disk1	1.000000	1.000000	1.000000
Disk2	1.000000	1.000000	1.000000
Station4	1.000000	1.000000	1.000000

Figure 2.12: Visits Tab

In the former tab you can insert the **Service Times** S_{kc} for each pair {station k -class c } in the model, in the latter you can enter the visit count V_{kc} (See Figure 2.12).

The layout of these tabs is similar to the one of the **Service Demand Tab** described in the previous paragraph. The default value for each element of the **Service Times** (S) matrix is zero, while it is one for **Visits**' matrix elements.

If current model contains load dependent stations, the behavior of **Service Times Tab** for their parameterization will be identical to the one described on the previous paragraph for **Service Demands Tab**. On the other hand **Visits Tab** behavior will not change as load dependency is a property of service times and not of visits.

2.2.5 Reference Stations Tab

The concept of **Reference Station** is often obscure, and sometimes doubts arise about the actual need of its introduction. A user may argue that s/he may define and solve a model without knowing the existence of such a station. S/he may think that it is sufficient to parameterize the workload (type of classes and intensity), the Service Times and Visits, the Stations, and then select a solution algorithm. However, the knowledge of these parameters implies several assumption that were made *implicitly*:

- the user knows the number of times that a job visit each station during its complete execution
- the existence of a station external to the model that jobs leave when submitted for execution and join when their execution is completed and exit the model
- this external station, that may be explicitly represented in the model (typically is a delay station representing the users) or assumed existing by default, by definition is *visited only once* by the jobs that have completed their execution
- this external station, referred to as **Reference Station**, is used to measure the *throughput X* and *response time R* (or *cycle time*) at the *system level*

However, depending on the problem to be solved, it is sometimes necessary to adopt a different level of detail for the analysis of performance than the one of the entire system (typically represented by the **Users Station**). So, you may need to consider a **Reference Station** different from the one defined above (external to the system) that could have a number of visits greater than one. To compute the correct values of throughput and response time with respect to this new station it is necessary to scale the value of the visits of all the stations of the model in order to make the visits to it equal to one.

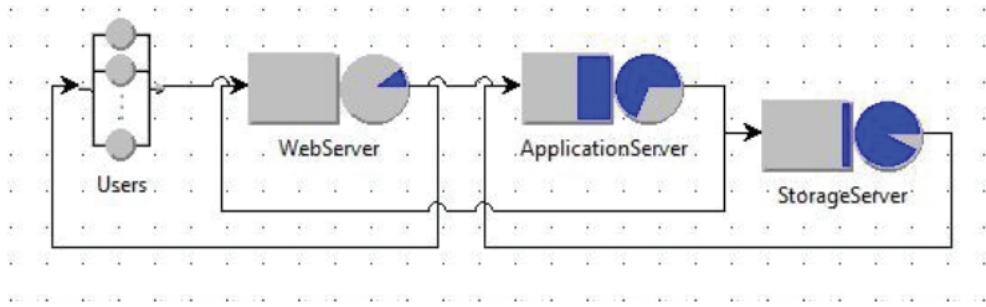


Figure 2.13: Example of a three tier intranet with a **Reference Station** representing the *Users*

In the model of Fig.2.13 is reported a three tier intranet in which the Reference Station is explicitly represented through the **Users** station (a delay station). In Fig.2.14 is shown the selection of the **Users** station as **Reference Station**. The corresponding **System Response Time** is 97.055 sec. A job during its complete execution visit the **Web Server** 10 times ($V_{WebServer} = 10$). If the problem requires the computation of the **System Response Time** with respect to the **Web Server** (i.e., the time between two consecutive passages in the **Web Server** by the same job) with the scaling of the visits the new value of **System Response Time** will be 9.751 sec (see Fig.2.16).

WARNINGS:

- if the workload consists of multiple *closed classes* all the classes must have the *same Reference Station*
- the *visits* to the **Reference Station** of *all* the classes must be different from 0
- the **Reference Station** of *open classes* is selected by default on the **Source Station**
- if you parameterize the model with the **Service Demands** D_i , then it is not important which station is selected as **Reference** because all of them are visited only *once* with service times S_i equal to the D_i .

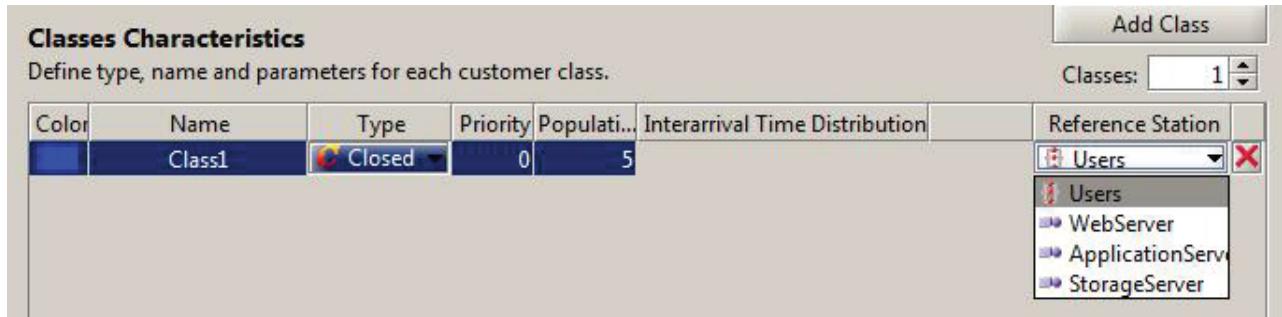


Figure 2.14: Selection of the Users station as Reference Station

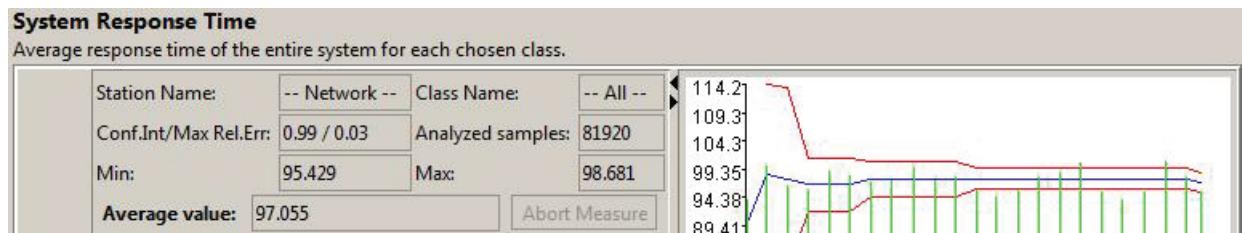


Figure 2.15: System Response Time of the model of Fig.2.13 with the Users Station as Reference Station.

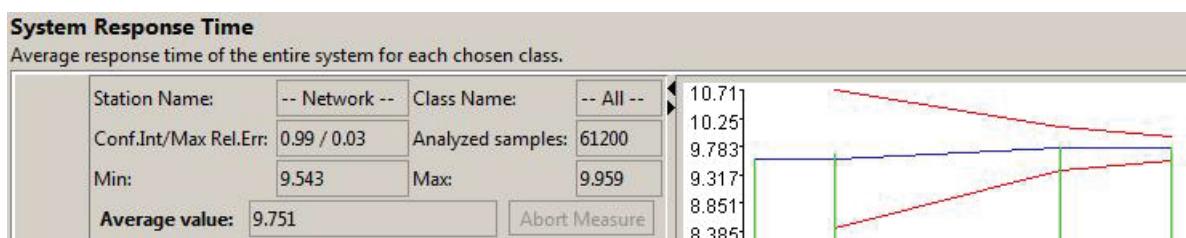


Figure 2.16: System Response Time of the model of Fig.2.13 with the Web Server Station as Reference Station.

2.2.6 What-if Tab

This Tab is used to perform a **what-if** analysis, i.e., to solve multiple models with different values of a **control parameter**. Figure 2.17 shows the what-if panel when what-if analysis is disabled. In Figure 2.17 is shown this panel when what-if analysis is disabled.

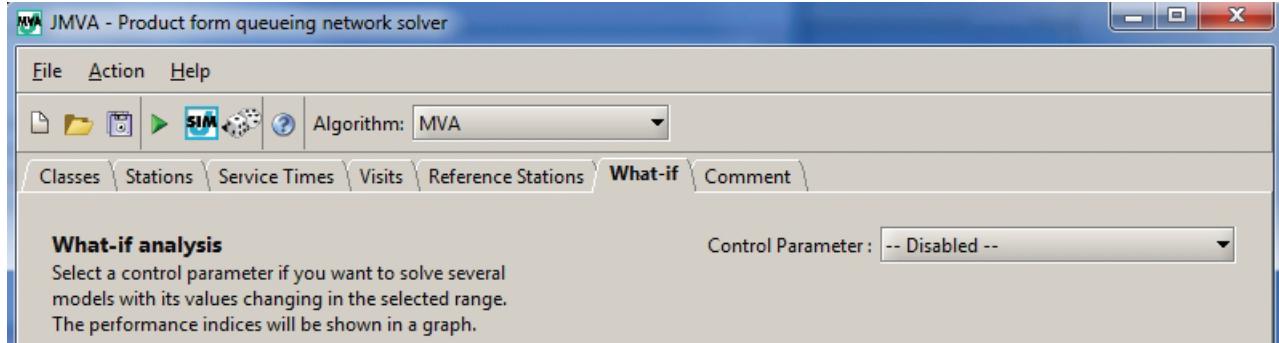


Figure 2.17: What-if Tab - to enable the analysis of several models

The first parameter to be set is the **control parameter** i.e. the parameter that will be changed to solve different models in a selected range. Five choices are possible:

Disabled : disables what-if analysis, so only a single queueing network model, specified in the previous steps, will be solved. This is the *default* option.

Number of Customers : different models will be executed by changing the **number of customers** of a single **closed** class or of every closed class proportionally. This option is available only when current model has at least one closed class.

Arrival Rates : different models will be executed by changing **arrival rate** of a single **open** class or of every open class proportionally. This option is available only when the current model has at least one open class.

Population Mix : the total number of customers will be kept constant, but the population mix (i.e. the ratio between **number of customers** of selected closed class i and the total number of customers in the system $\beta_i = N_i / \sum_k N_k$). This option is available only when the current model has two closed classes.

Service Demands : different models will be solved changing the **service demand** value of a given station for a given class or for all classes proportionally. This option is available only for **load independent** and **delay** stations.

Whenever a control parameter is selected, the window layout will be changed to allow the selection of a valid range of values for it. For example in Figure 2.18, the **Service Demands** control parameter was selected. On the bottom of the window, a summarizing table is presented: depending on the selected control parameter, that table is used to show the *initial state* of the involved parameters. Every class currently selected for what-if analysis is shown in red.

A brief description of each field is now presented:

Station : available only with **Service Demands** control parameter. This combo box allows to select at which station service demand values will be modified.

Class : allows to select for which class the selected parameter will be changed. A special value, namely **All classes proportionally**, is used to modify the control parameter for each class keeping constant the proportion between different classes². This special value is not available in **Population Mix** analysis as we are changing the proportion of jobs between two closed classes.

From : the initial value of what-if analysis. It was chosen to leave this value fixed to the initial value specified by the user in the previous steps to avoid confusions, so this field acts as a reminder. The only exception is when **Population Mix** is changed, in that case it is allowed to modify this value too.

To : the final value of what-if analysis. Please notice that this value can be greater or smaller than **From** value and is expressed in the same measure unit. Whenever **All classes proportionally** option is selected, both **From** and **To** values are expressed as percentages of initial values (specified in the previous steps and reminded in the table at the bottom of the panel, see Figure 2.18), in the other situations they are considered as absolute values for the chosen parameter.

²for example, in a model with two closed classes with population vector (2,6), the following models can be executed: (1,3), (2,6), (3,9), (4, 12), ...

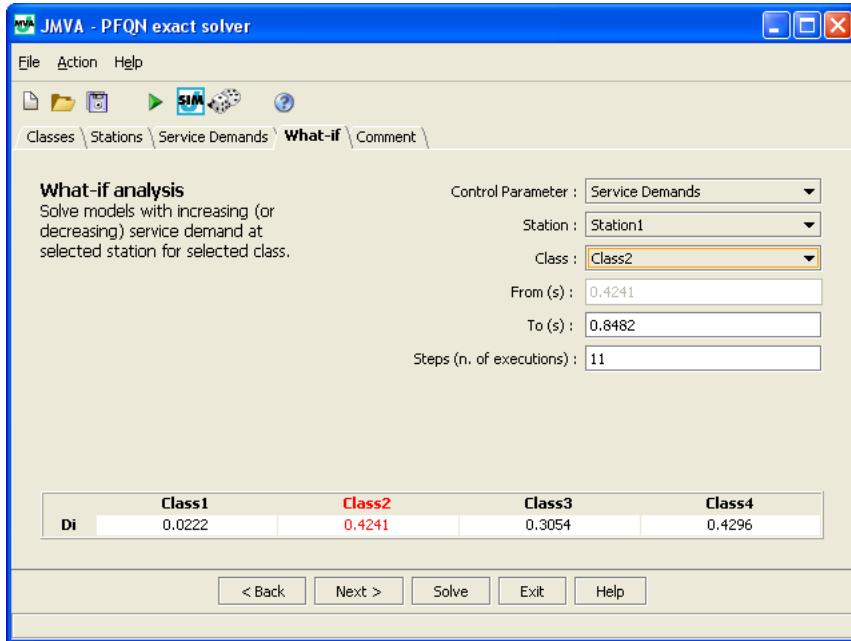


Figure 2.18: What-if Tab - Service Demands

Steps : this is the chosen number of executions i.e. the number of different models that will be solved. When control parameter is **Customer Numbers** or **Population Mix**, the model can be correctly specified only for integer values of population. JMVA will perform a fast computation to find the maximum allowed number of executions given current **From** and **To** values: if the user specifies a value bigger than that, JMVA will use the computed value.

2.2.7 Comment Tab

In this Tab, a short - optional - comment about the model can be inserted; it will be saved with the other model parameters.

2.2.8 Expression Evaluator

An expression evaluator is used for the definition of service demands or service times of a load dependent station. It allows to specify times as an analytic function of n where n is the number of customer inside the station.

Expression are evaluated using *JFEP*³ (Java Fast Expression Parser) package which supports all operators enumerated in Table 2.1 and all functions enumerated in Table 2.2.

Operator	Symbol
Power	$^$
Unary Plus, Unary Minus	$+n, -n$
Modulus	$\%$
Division	$/$
Multiplication	$*$
Addition, Subtraction	$+, -$

Table 2.1: List of all supported operators ordered by priority

2.2.9 Model Solution

The window of Figure 2.19 allows the selection of the algorithm to be used to solve the models. If the model is open, standard queuing network algorithms are used (identified with QN). If the model is closed, several exact and approximate solution algorithms are proposed. Fig.2.19 shows the exact algorithms. Once selected the algorithm, use **Solve** command to solve the model. If the model specifies a what-if analysis, please refer to

³<http://jfep.sourceforge.net/>

Function	Symbol
Sine	$\sin()$
Cosine	$\cos()$
Tangent	$\tan()$
Arc Sine	$\text{asin}()$
Arc Cosine	$\text{acos}()$
Arc Tangent	$\text{atan}()$
Hyperbolic Sine	$\sinh()$
Hyperbolic Cosine	$\cosh()$
Hyperbolic Tangent	$\tanh()$
Inverse Hyperbolic Sine	$\text{asinh}()$
Inverse Hyperbolic Cosine	$\text{acosh}()$
Inverse Hyperbolic Tangent	$\text{atanh}()$
Exponential	$\exp()$
Natural Logarithm	$\ln()$
Logarithm base 10	$\log()$
Absolute Value / Magnitude	$\text{abs}()$
Random number [0, 1]	$\text{rand}()$
Square Root	$\text{sqrt}()$
Sum	$\text{sum}()$

Table 2.2: List of supported functions for the load dependent service times

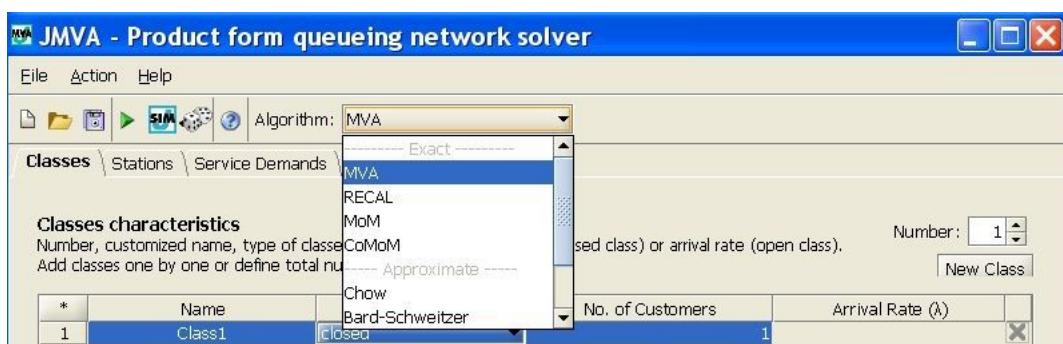


Figure 2.19: Drop-down box for the selection of the exact solution algorithm for closed classes

subsection 2.2.10. Model results will be shown on a separate window, like the one of Figure 2.20.

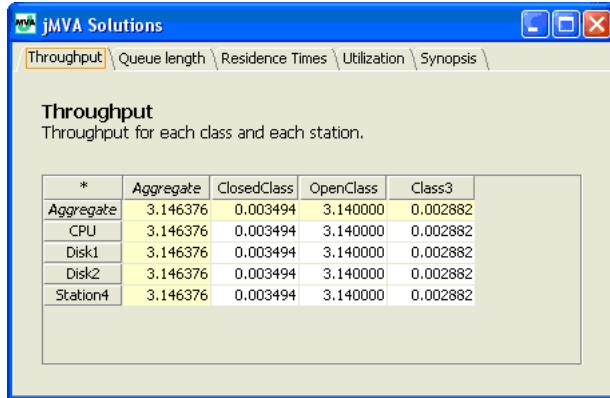


Figure 2.20: Model Solution (Throughput Tab)

Using the tab selector, all the other computed performance indices can be seen: Throughput, Queue lengths, Residence Times, Utilizations and a synopsis panel with schematic report of input model. Both results and synopsis tab data can be copied to clipboard with the standard **CTRL+C** keyboard shortcut.

When open classes are used, the resource saturation control is performed. For multiple class models, the following inequality must be satisfied:

$$\max_k \sum_c \lambda_c * D_{kc} < 1$$

where c is the class index and k is the station index. This inequality ensures that no service center is saturated as a result of the combined loads of all the classes. Let us consider, as example, the model with the classes shown in Figure 2.5 with the D -matrix shown in Figure 2.9 Since $\lambda = 3.14 < 3.33 = 1/0.3 = 1/D_{max}$ the model is not in saturation and the **Solve** command will be executed correctly.

In this example, substituting $D_{Disk1-OpenClass}$ with values $\geq 1/3.14 \approx 0.318$ will cause the saturation of resource *Disk1* and the error message of Figure 2.21 will appear.

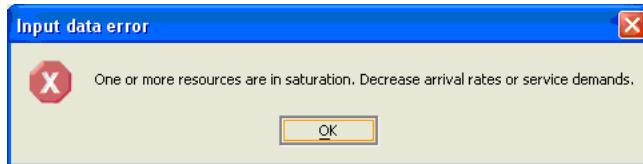


Figure 2.21: Input data error message

2.2.10 Model Solution - What-if analysis

Use the **Solve** command to solve the model. During model solution, a progress window, see Figure 2.22, shows up. It displays the cumulative number of models currently solved, the total number of models to be solved and the elapsed time.

At the end of the solution, results will be shown in a separate window, see Figure 2.23. This tab allows to show in a plot the relation between the chosen control parameter (see subsection 2.2.6) and the performance indices computed by the analytic engine.

The combo box **Performance Index** allows to select the performance index to be plotted in the graph, while in the table below, users can select the resource and the class considered.

- The first column is fixed and lists all available colors to be used in the graph.
- The second column, named **Class**, is used to select the class considered in the graph. The special value **Aggregate** is used for the aggregate measure for all classes. If input model is single-class, the class is selected by default for each row.
- The final column, named **Station**, is used to select the station considered in the graph. The special value **Aggregate** is used for the aggregate measure for the entire network. Note that the **Aggregate** value is not valid when the **Utilization** performance index is selected.

In addition to the *center* performance indices (i.e. Throughput, Queue length, Residence Times, Utilization), three *system* performance indices are provided in the **Performance Index** combo box (System Response Time,

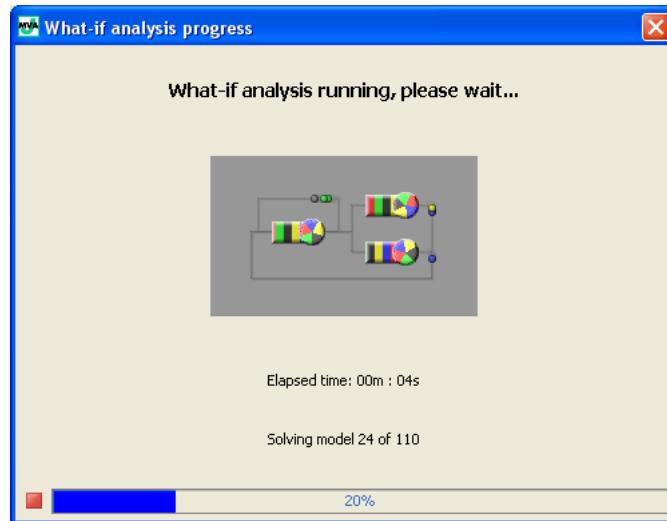


Figure 2.22: Model Solution progress window

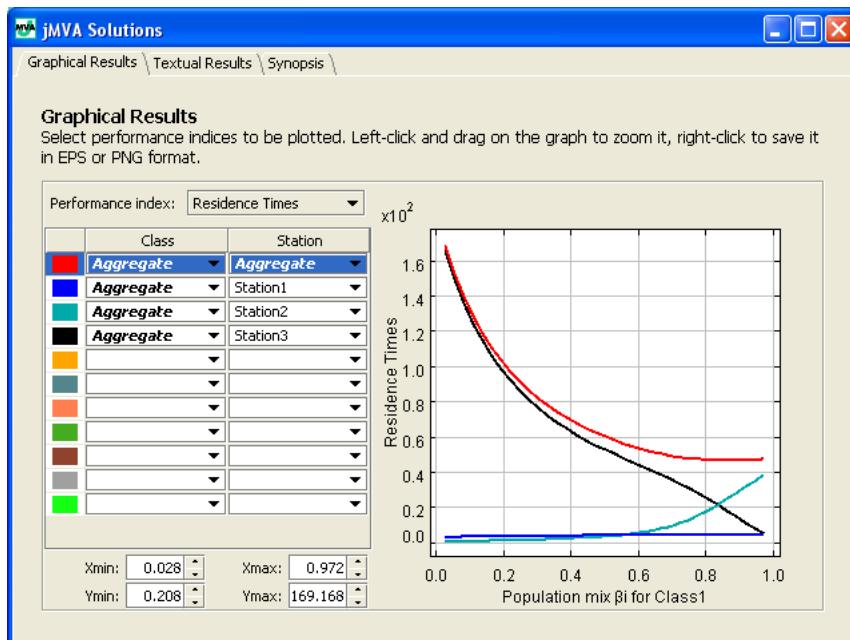


Figure 2.23: Model Solution - Graphical Results Tab

System Throughput, Number of Customers). This *system* indices can be easily obtained by selecting the special **Aggregate** value for both **Class** and **Station** columns of the corresponding center indices (see Appendix A for the definition of the performance indices), but they were provided here as *shortcuts*. As we are referring to aggregate measures, the selection of reference class and station is not significant and, in this case, the table in the left of Figure 2.23 will not be shown.

On the bottom-left corner of the window, users can modify minimum and maximum value of both the horizontal and vertical axes of the plot. JMVA is designed to automatically best-fit the plot in the window but this controls allow the user to specify a custom range or zoom on the plot. Another fast method to perform a zoom operation is to left-click and drag a rectangle on the graphic window (see Figure 2.24) or right-click on it and select **Zoom in** or **Zoom out** options. To automatically reset the best-fit scale users can right-click on the graphic window and select **Original view** option.

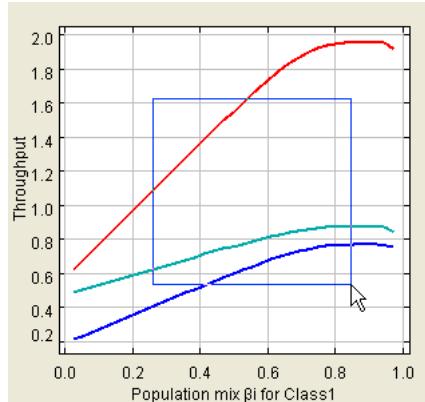


Figure 2.24: Zoom operation on the plot

The graphic window allows to export plots as image to be included in documents and presentations. To save current graph as image, right-click on the graphic and select **Save as...** option. A dialog will be shown to request the name of the file and the format. Currently supported format are Portable Network Graphics - PNG - (raster) and Encapsulated PostScript - EPS - (vectorial, currently only black and white).

The second tab of the solution window, shown in Figure 2.25, is used to display the solutions of each execution of the analytic algorithm.

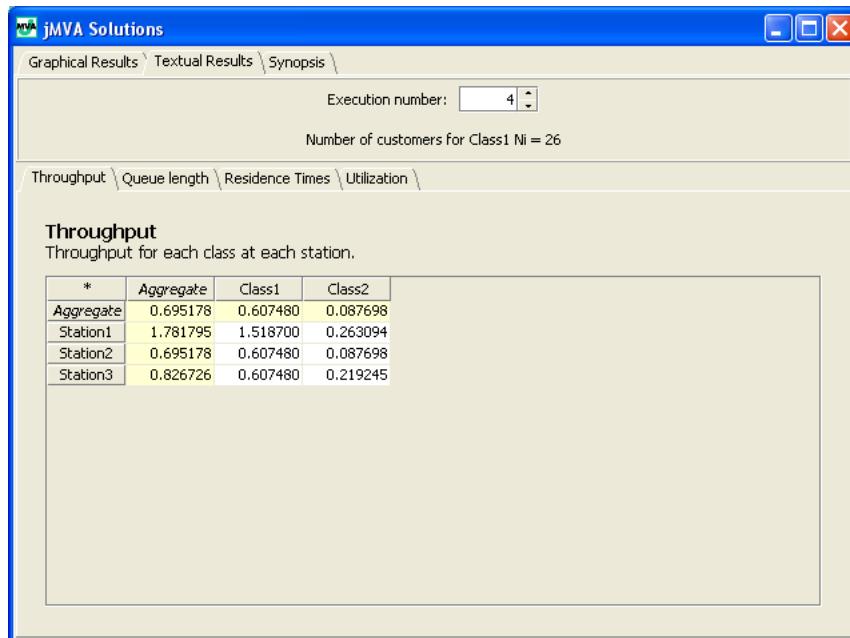


Figure 2.25: Model Solution - Textual Results Tab

This Tab has the same structure of the results window without What-if analysis (described in subsection 2.2.9) but allows to select the execution to be shown in the field **Execution Number**. By entering requested execution number in the spinner, or using the *up* and *down* arrows, user can cycle between all the computed

performance indices for each execution. Just below the spinner, a label gives information on the value of the control parameter for the currently selected execution.

2.2.11 Modification of a model

To modify system parameters return to the main window and enter new data. After the modifications, if you use **Solve** command, a new window with model result will show. You can **save** this new model with the previous name - overwriting the previous one - or **save** it with a different name or in a different directory.

2.3 RGF (not released with 0.9.2)

For this exact method, we are going to calculate the model using normalizing constant. This method is similar to RECAL [CG86], but it excels in situations when the queueing networks are grouped together. I.e. when it has multiple stations of the same service demands. The algorithm is an exact-solution technique, as any values calculated via this algorithm would be the exact value. The generating function for the normalizing constant can be represented as:

$$H_q(M, X; z) = \prod_{i=1}^N \frac{1}{(1 - \rho_i z)^{m_i}} \quad (2.1)$$

where $z = (z_1, \dots, z_q)$, $M = (m_1, \dots, m_N)$, $X = (\rho_1, \dots, \rho_N)$, $\rho_i z = \sum_{a=1}^q \rho_{ia} z_a$. This is the normalising constant for a q-class network with I number of stations. ρ_{iq} is represented as the service demand of class q at class i divided by the number of visits ratio of class q at station i. The model output can then be calculated via specifying different queueing networks and calculating their normalising constant. Equation 2.1 can also be represented as the following recurrence:

$$\begin{aligned} H_q(M, X; z) &= \sum_{i=1}^N \sum_{j=1}^{m_i} (-1)^{j+1} C_{k_q}^{m_i+k_q-j} \rho_{iq}^{k_q} \\ &\times \prod_{l \neq i} \left(\frac{\rho_{iq}}{\rho_{iq} - \rho_{lj}} \right)^{m_l} \\ &\times \sum_{\sum_{l \neq i} j_l = j-1} \left[\prod_{l \neq i} C_{j_l}^{m_l+j_l-1} \left(\frac{\rho_{lj}}{\rho_{iq} - \rho_{lj}} \right)^{j_l} \right] \\ &\times H_{q-1}(M + J, X_i; z') \end{aligned}$$

k_q is the population of class q customers in the network, m_i is the number of stations that are identical to station i. New load matrices are calculated via each iteration, and this is represented in the equation as x_i .

The normalizing constant is calculated by reducing it down to equations that calculates the normalizing constant of single class networks. Single-class networks can be calculated in this case by Buzen's algorithm [J.P73], Reiser and Kobayashi's algorithm. [RK76].

To choose the algorithm to be used, simply choose the algorithm from the drop-down list in the exact section and specify the parameters. The algorithm currently does not support delay stations. If any delays are specified, it will be ignored.

2.4 AMVA - Approximate algorithms for closed models

The exact MVA is an iterative algorithm. The solution of a closed model with N customers requires the values of indexes computed for the same model with N-1 customers. Thus, to obtain the performance indexes with N customers it is required to solve N models with customer number increasing from 0 to N. The key equation, with a single class workload, that introduces the iterative characteristic of MVA is:

$$A_i(N) = N_i(N - 1) \quad (2.2)$$

that states that the number of customers $A_i(N)$ seen by a customer at arrival to station i in a closed model with N customers is equal to the mean number N_i of customers in station i of the same model with $N - 1$ customers. As a consequence, the computation time and space required are non negligible, and become very

very large with models having multiple class workloads, and high number of resources and customers. Approximate algorithms recursively estimate station queue lengths for models with one less customer to compute statistics for models with full population until convergence is reached. The *stopping criterion* (referred to as **Tolerance** in the AMVA window, see, e.g., Fig.2.27) is based on the differences between successive queue lengths that must be less than the tolerance value. The AMVA algorithms replace eq.2.2 (or its versions for multiple class workloads) with *non-recursive* approximations of the type

$$A_i(N) \sim h[N_i(N)] \quad (2.3)$$

with suitable functions for h .

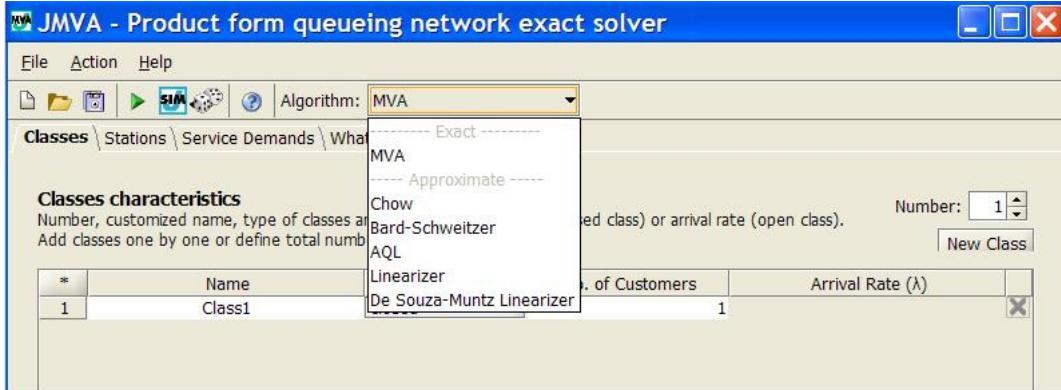


Figure 2.26: Drop-down box for the selection of the *approximate* solution algorithm

The approximate methods available are listed in the drop-down box of the JMVA window (see Fig.2.26). Different algorithms can be selected concurrently using the checkboxes shown in the **what-if** analysis window (see Fig.2.27) and their results can be compared directly. The graphics of the performance indexes generated by the algorithms selected in the checkboxes are shown in Fig.2.28.

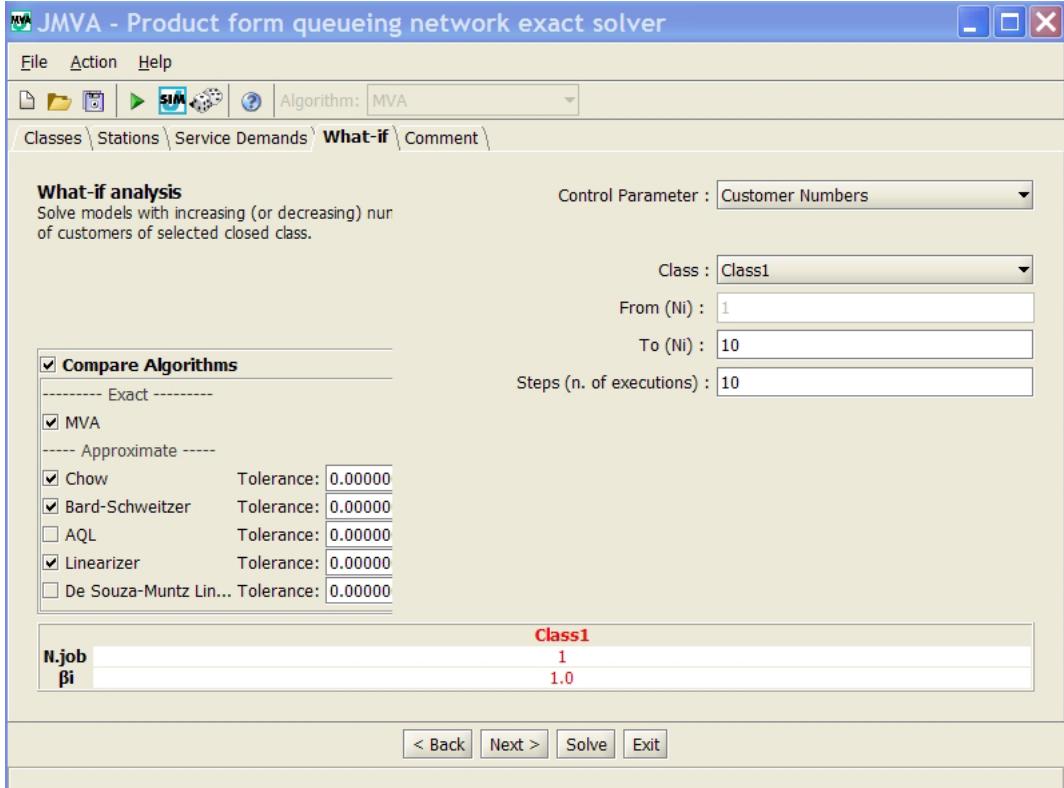


Figure 2.27: Checkboxes for the selection of the algorithms used in the **what-if** analysis

For each class of customers c , the *input* parameters are the number of customers N_c , the service demands $D_{r,c}$, and the tolerance. For each station r , the *outputs* are the throughput $X_{r,c}$, the number of customers $N_{r,c}$,

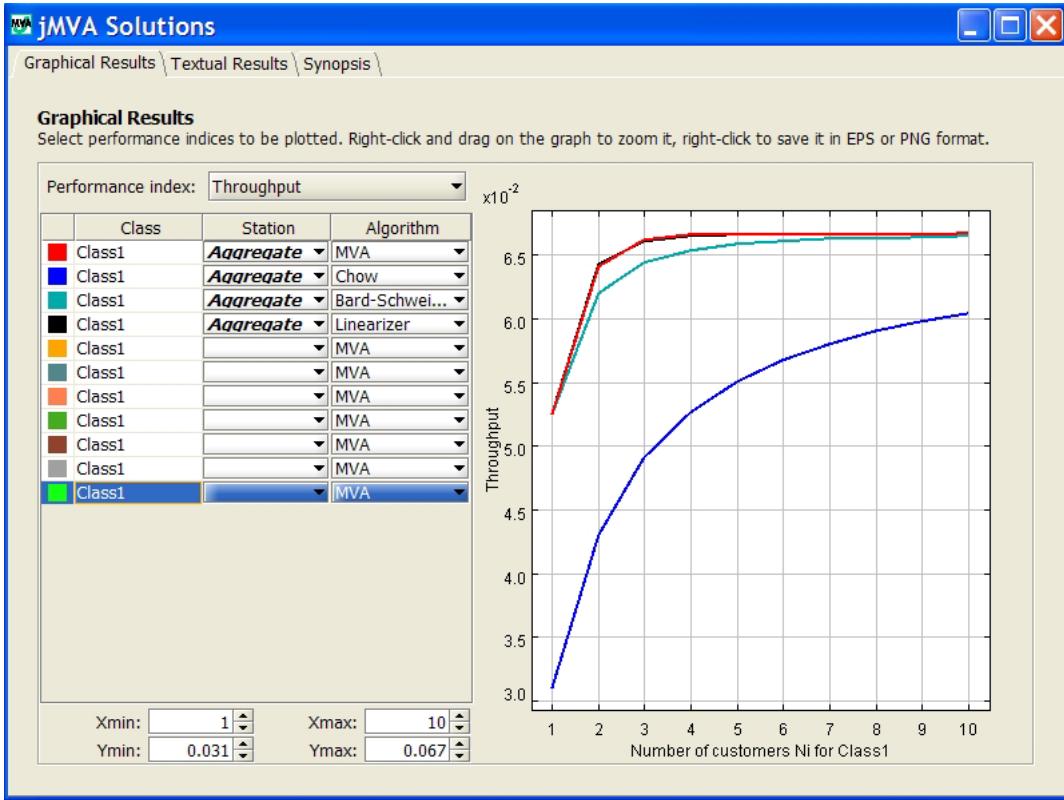


Figure 2.28: Graphics for the comparison of the performance indexes generated by the algorithms selected in the checkboxes of Fig.2.27.

the response time $R_{r,c}$, and the station utilization $U_{r,c}$.

The approximate algorithms available are:

- **Chow** [Cho83]: assumes that the station queue lengths are identical in the model with full customer population and in the model with one less customer.
- **Bard-Schweitzer** [Sch79]: assumes that removing a customer from a class affects the queue lengths of only that class and no others. It is more accurate than *Chow's* algorithm.
- **Linearizer** [CN82]: approximates queue lengths for populations with one less customer using information about full population. Using these estimates, new values are computed for full population, and the process is repeated.
- **De Souza-Muntz Linearizer** [dSeSM90]: reduces complexity of *Linearizer* by a factor of C (no. of classes). Instead of computing queue lengths for each class and station for N-1 populations, only computes them for each station, as only those are ever used.
- **AQL (Aggregated Queue Length)** [ZES88]: improves the *Linearizer* by a factor of C in terms of time and space, while maintaining almost same accuracy. It uses aggregate per-server queue lengths instead of per-class queue lengths as in *Linearizer*.
- **MonteCarlo algorithm** [JD82]

The class structure implemented in AMVA is shown in Fig.2.29.

2.5 Monte Carlo algorithm (not released with 0.9.2)

The normalizing constant can also be represented as an integral [JD82], represented as follows:

$$g = \frac{1}{\prod_{j=1}^J N_j!} \int_{\mathbb{Q}^+} e^{-1' u} \prod_{j=1}^J (\rho_{j0} + \rho'_{ju})^{N_j} du \quad (2.4)$$

N_j is the number of class j customers in the network.

This algorithm can be used to calculate networks with First Come First Serve (FCFS) stations as well as IS stations. However, the number of servers at FCFS stations needs to be 1. The IS stations is represented

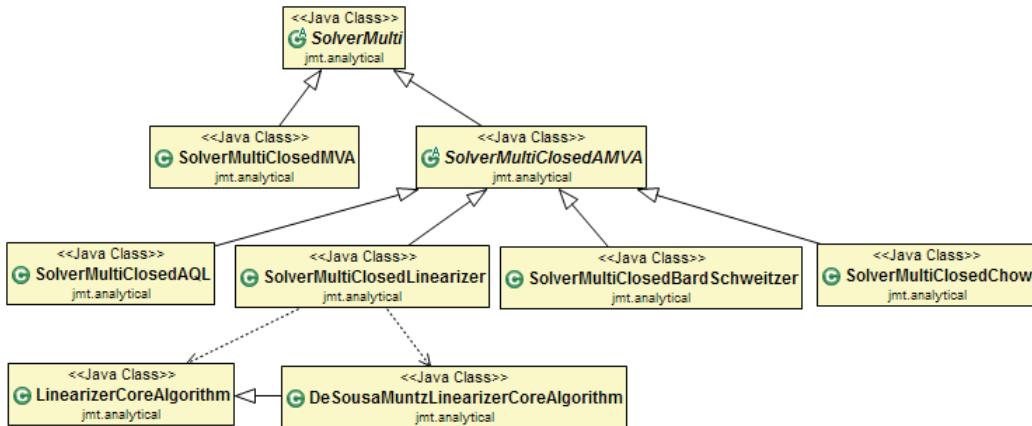


Figure 2.29: Class structure used in AMVA algorithms.

as 1, as if there are more than one IS stations we can combine their delay into one station, as each customer would receive its own server immediately.

To use the algorithm, simply select Monte Carlo from the algorithms list. Similar to the AMVA algorithms,

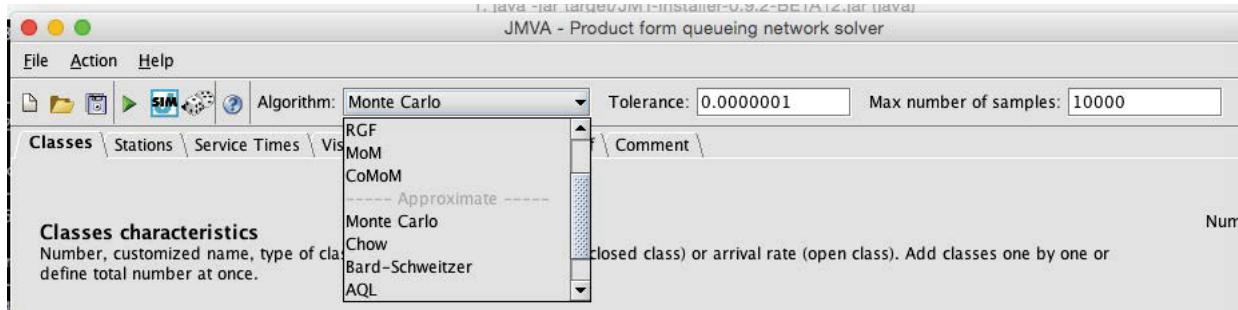


Figure 2.30: Selecting Monte Carlo from algorithms list

one can specify the tolerance, in this case, the accuracy of the normalizing constant. One can also specify the *maximum number of samples* to take. Monte Carlo Integration works by taking a number of samples and estimate the solution by taking the mean of the results. The default for tolerance is 0.0000001 - same as the AMVA one, and the default for maximum number of samples is 10000. The current time takes for the sampling to complete is 5 seconds roughly. To achieve a better result, simply specify a higher number for maximum number of samples. The algorithm will stop when the tolerance is met or when the maximum number of samples has drawn. Inputting a higher maximum number of samples would ensure a more accurate result, however, the time it takes for the analysis to complete would also be longer.

2.6 Menu entries

2.6.1 File

New

Use this command in order to create a new JMVA model.

Shortcut on Toolbar:

Accelerator Key: CTRL+N

Open

Use this command to open an existing model. You can only open one model at time, to edit two or more models start more than one instance of JMVA. If the current model was modified since its creation or last save action, a popup window will be shown for confirmation.

It is possible to open not only models saved with JMVA (*.jmva), but also with other programs of the suite (for

example JABA *.jaba, JSIM *.jsim and JMODEL⁴ *.jmodel). Whenever a data file of another tool is opened, a conversion is performed and error/warnings occurred during conversion will be reported in a window. Models are stored in XML format, see *JMT system manual* for a detailed description.

Shortcut on Toolbar:  Accelerator Key: CTRL+O

Save

Use this command in order to save the active document with its current name in the selected directory. When you save a document for the first time, JMVA displays the Save As dialog box so you can rename your document. If you save a model after its resolution, results are stored with model definition data.

Shortcut on Toolbar:  Accelerator Key: CTRL+S

Exit

Use this command in order to end a JMVA session. You can also use the Close command on the application Control menu. If current model was modified since its creation or last save action, a popup window will be shown for confirmation.

Accelerator Key: CTRL+Q

2.6.2 Action

Solve

Use this command when model description is terminated and you want to start the solution of the model. At the end of the process the window in Figure 2.20 will popup.

Shortcut on Toolbar:  Accelerator Key: CTRL+L

Randomize

Use this command in order to insert random values into Service Demands - or Service Times - table. Generated values are automatically adjusted to avoid saturation of resources.

Shortcut on Toolbar:  Accelerator Key: CTRL+R

Import in JSIM

This command will import the current model into JSIM to solve it using simulator. A simple parallel topology is derived from the number of visits at each station and the generated model is equivalent to original one.

Shortcut on Toolbar:  Accelerator Key: CTRL+G

2.6.3 Help

JMVA Help

Use this command to display application help. When you click on a line of the table of content you may access directly to the pages of the manual that describe the argument selected.

Shortcut on Toolbar:  Accelerator Key: CTRL+H

About

Use it in order to display information about JMVA version and credits.

⁴In previous versions of the JMT suite, JMODEL was the name of the JSIMgraph application. Thus, *.jmodel files are files saved in previous versions of the tool.

2.7 Examples

In this section we will describe some examples of model parametrization and solution using MVA exact solver. Step-by-step instructions are provided in five examples:

1. A single class closed model with three load independent stations and a delay service center (subsection 2.7.1)
2. A multiclass open model with two classes and three load independent stations (subsection 2.7.2)
3. A single class closed model with a load dependent station and a delay (subsection 2.7.3)
4. A multiclass mixed model with three stations (subsection 2.7.4)
5. A multiclass closed model where a what-if analysis is used to find optimal Population Mix values (subsection 2.7.5)

2.7.1 Example 1 - A model with a single closed class

Solve the single class model specified in Figure 2.31. The customer class, named *ClosedClass* has a population

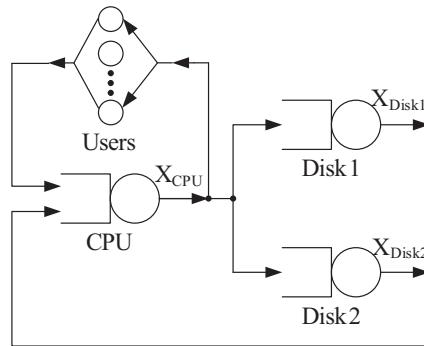


Figure 2.31: Example 1 - network topology

of $N = 3$ customers.

There are four stations, three are of load independent type (named *CPU*, *Disk1* and *Disk2*) and one is of delay type (named *Users*). *Users* delay station represents user's *think time* ($Z = 16$ s) between interaction with the system. Service times and visits for stations are reported in Table 2.3.

	CPU	Disk1	Disk2	Users
Service Times [s]	0.006	0.038	0.030	16.000
Visits	101.000	60.000	40.000	1.000

Table 2.3: Example 1 - service times and visits

Step 1 - Classes Tab

- use New command to create a new jMVA document
- by default, you have already a *Closed* class
- if you like, substitute default *Class1* name with a customized one (*ClosedClass* in our example)
- complete the table with workload intensity (number of customers). Remember that intensity of a closed class N must be a positive integer number; in this case, 3 customers

At the end of this step, the **Classes** Tab should look like in Figure 2.32.

Step 2 - Stations Tab

- click on **Next >** to switch to **Stations Tab**
- digit number 4 into stations number textbox or select number 4 using spin controls or push *New Station* button three times. Now your model has four *Load Independent* stations with a default name
- if you want you can change station names. Substitute *CPU* for default name *Station1*, substitute *Disk1* for default name *Station2*, substitute *Disk2* for default name *Station3* and substitute *Users* for default name *Station4*

*	Name	Type	No. of Customers	Arrival Rate (λ)
1	ClosedClass	closed	3	

Figure 2.32: Example 1 - input data (Classes Tab)

- change the type of last inserted station; *Users* station is a **Delay (Infinite Server)**

At the end of this step, the **Stations** Tab should look like Figure 2.33.

*	Name	Type
1	CPU	Load Independent
2	Disk1	Load Independent
3	Disk2	Load Independent
4	Users	Delay (Infinite Server)

Figure 2.33: Example 1 - input data (Stations Tab)

Step 3 - Service Times and Visits Tabs

- use **Next >** command to switch to **Service Demands** Tab
- press **Service Time and Visit** button as you do not know the Service Demands of the three stations: in this case Service Times and number of Visits should be typed. After button pressure, the **Service Demands** Tab will be hidden and **Service times** Tab and **Visit** Tab will appear
- you can input all Service Times in the table. Remember that Service Time of the *Users* station, of delay type, is *think time Z*, in this case 16 s

At this point, the **Service Times** Tab should look like Figure 2.34.

- use **Next >** command to switch to **Visits** Tab
- input numbers of visits for all centers in the table. In this case the number of visits of the *Users*, the infinite server station, is equal to 1 since a customer at the end of an interaction with the system visits this station.

At the end of this step, the **Visits** Tab looks like Figure 2.35.

Step 4 - Model Resolution

Use **Solve** command to start the solution of the input model. Model results will be displayed in a new window like the one of Figure 2.36.

Service Times	
Input service times of each station for each class.	
Class	ClosedClass
CPU	0.006000
Disk1	0.038000
Disk2	0.030000
Users	16.000000

Service Demands

Figure 2.34: Example 1 - input data (Service Times Tab)

Visits	
Average number of accesses of each class to the station.	
Class	ClosedClass
CPU	101.000000
Disk1	60.000000
Disk2	40.000000
Users	1.000000

Figure 2.35: Example 1 - input data (Visits Tab)

Throughput		
Throughput for each class at each station.		
*	Aggregate	ClosedClass
Aggregate	0.143961	0.143961
CPU	14.540104	14.540104
Disk1	8.637686	8.637686
Disk2	5.758457	5.758457
Users	0.143961	0.143961

Figure 2.36: Example 1 - output data (Throughput Tab)

Since we are considering a single-class model, all results in the column *Aggregate* correspond to the results in the *ClosedClass* column.

JMVA computes Residence Times W_k , Throughputs X_k , Queue lengths Q_k and Utilizations U_k for all stations k . The algorithm begins with the known solution for the network with zero customers, and progressively increases the population up to N that, in this example, is three. Note that the aggregate *Residence Time* is the *System Response Time* measure and the aggregate *Queue Length* (in the new versions this index has been referred to as *Number of Customers*) is the average number of customers in the system.

Using tab selector, you can change tab and see *Queue length*, *Residence Times*, *Utilizations* and a synopsis panel with a schematic report of the model (Figure 2.37).

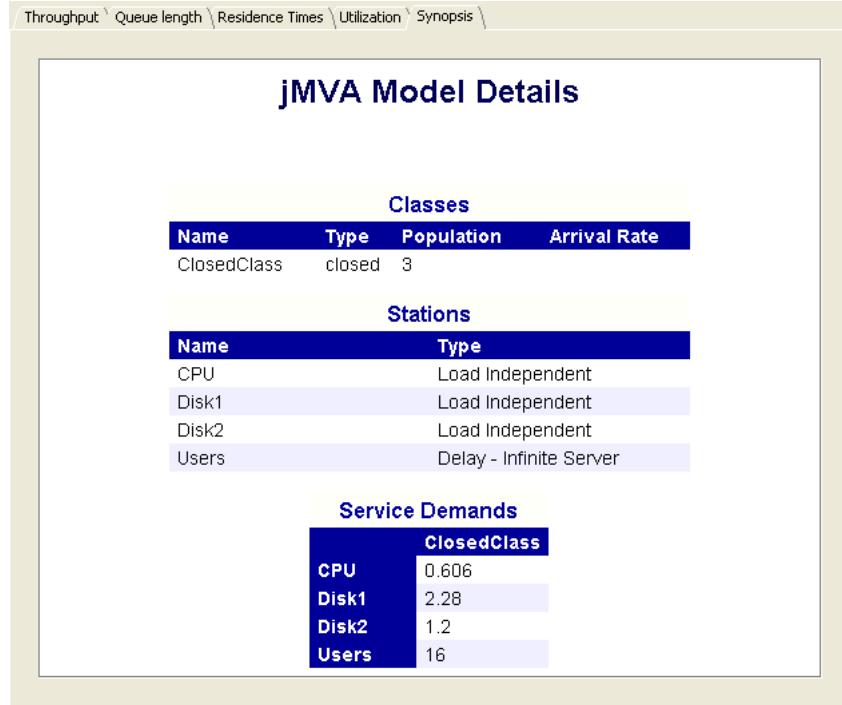


Figure 2.37: Example 1 - output data (Synopsis Tab)

The computed performance indices are shown in Table 2.4. Note that the *utilization* of a delay station (*users*) is the average number of customers in the station, therefore it may be greater than 1.

	Aggregate	CPU	Disk1	Disk2	Users
Throughput [job/s]	0.144	14.540	8.637	5.758	0.144
Queue Length [job]	3.000	0.193	0.410	0.194	2.303
Residence Time [s]	20.839	0.643	2.847	1.349	16.000
Utilization	-	0.087	0.328	0.172	2.303

Table 2.4: Example 1 - model outputs

2.7.2 Example 2 - A model with two open classes

Solve the multiclass open model specified in Figure 2.38. The model is characterized by two open classes A and

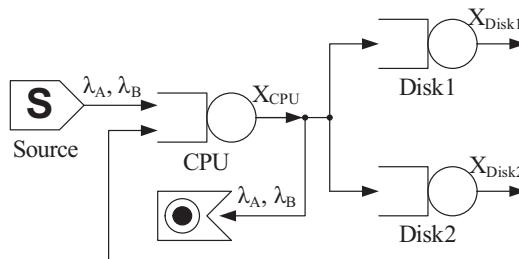


Figure 2.38: Example 2 - network topology

B with arrival rate (the workload intensity λ) respectively of $\lambda_A = 0.15$ job/s and $\lambda_B = 0.32$ job/s. There are three stations of load independent type, identified with names *CPU*, *Disk1* and *Disk2*. Service times and visits for stations are shown in Table 2.5 and Table 2.6.

	CPU	Disk1	Disk2
Class A [s]	0.006	0.038	0.030
Class B [s]	0.014	0.062	0.080

Table 2.5: Example 2 - service times

	CPU	Disk1	Disk2
Class A	101.0	60.0	40.0
Class B	44.0	16.0	27.0

Table 2.6: Example 2 - number of visits

Since this model is similar to the network of Figure 2.31 solved in subsection 2.7.1, we will show how to easily create it from a saved copy of Example 1:

1. Open the saved instance of Example 1 model
2. Go to **Classes** Tab, change *ClosedClass* name to *A*, change its type to **Open** and set its arrival rate to $\lambda_A = 0.15$ job/s.
3. Click on *New Class* button, set name of new class to *B*, change its type to **Open** and set its arrival rate to $\lambda_B = 0.32$ job/s.
4. Go to **Stations** Tab and remove *Users* delay center.
5. Go to **Service Times** Tab and set service times for Class *B* according to Table 2.5.
6. Go to **Visits** Tab and set visits for Class *B* according to Table 2.6.
7. Select **Solve** action.

The **Synopsis** Tab with a schematic report of the model created is shown on Figure 2.39, while the computed performance indices of this model are shown in Table 2.7.

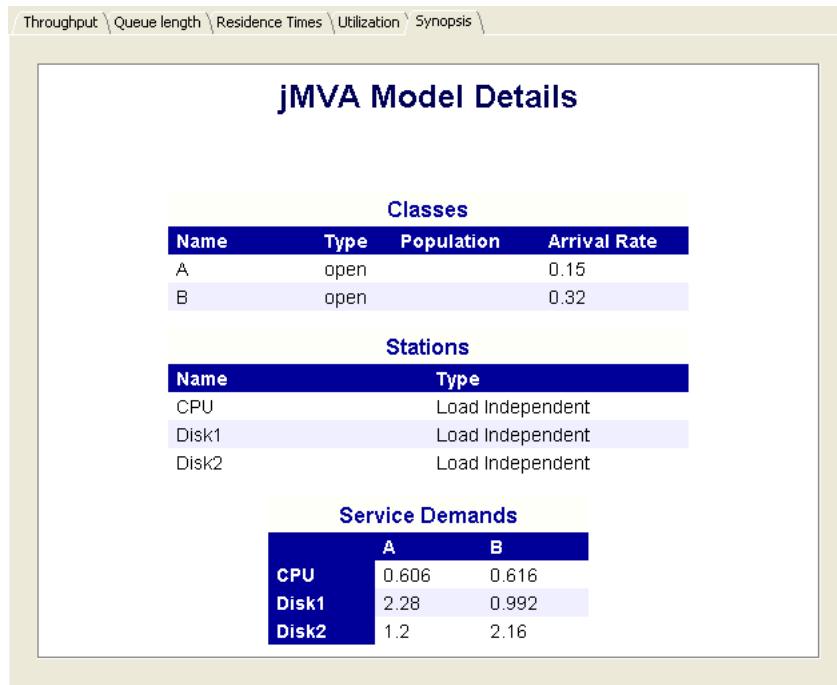


Figure 2.39: Example 2 - output data (Synopsis Tab)

2.7.3 Example 3 - A model with a load dependent station

The network is shown in Figure 2.40. It comprises only two stations: one is of delay type (named *Users*)

	Aggregate	Class A		
	CPU	Disk1	Disk2	
Throughput [job/s]	0.150	15.150	9.000	6.000
Queue Length [job]	2.529	0.128	1.004	1.398
Residence Time [s]	16.863	0.851	6.695	9.317
Utilization	-	0.091	0.342	0.180

	Aggregate	Class B		
	CPU	Disk1	Disk2	
Throughput [job/s]	0.320	14.080	5.120	8.640
Queue Length [job]	6.575	0.277	0.932	5.366
Residence Time [s]	20.548	0.865	2.913	16.770
Utilization	-	0.197	0.317	0.691

Table 2.7: Example 2 - model outputs

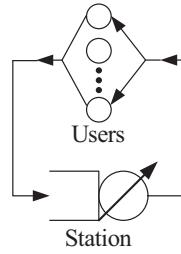


Figure 2.40: Example 3 - network topology

and the other is a load dependent station (named *Station*). This model has one closed class only with $N = 8$ customers. The user's *think time* is $Z = 21$ s, while the service demands for the load dependent *Station*, shown in Table 2.8, are function of n : number of customers in the station ($D(n) = n + 1/n$).

n	1	2	3	4	5	6	7	8
$D(n)$ [s]	2.00	2.50	3.33	4.25	5.20	6.17	7.14	8.13

Table 2.8: Example 3 - service demands for *Station*, a load-dependent service center

Step 1 - Classes Tab

The instructions that are the same given in Step 1 of subsection 2.7.1; in this case N must be 8.

Step 2 - Stations Tab

The instructions are given in Step 2 of subsection 2.7.1; in this case the model has two stations: a Load Dependent station and a Delay Center.

Step 3 - Service Demands Tab

- use **Next >** command to switch to **Service Demands Tab**
- double-click on cell with text *LD Setting...* to open the editor of load dependent service demands in a separate window, shown in Figure 2.41.
- it is not mandatory to insert all values one-by-one. You can click or drag to select cells, enter the expression $n + 1/n$ into the textbox at the bottom of the window and click the *Evaluate* button.
- at the end of this phase, editor window looks like Figure 2.42. Now you may press *OK* button to confirm changes and return to JMVA main window.

Step 4 - Model Resolution

Use **Solve** command to resolve the model, results are shown in Table 2.9.

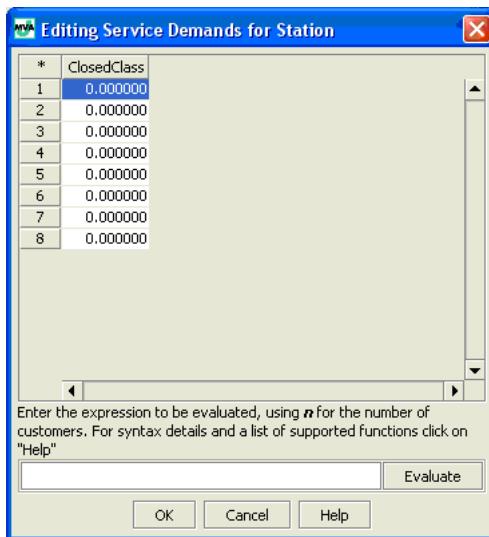


Figure 2.41: Example 3 - editor for the description of service demands for a load dependent station corresponding to the different number of customers before the parametrization

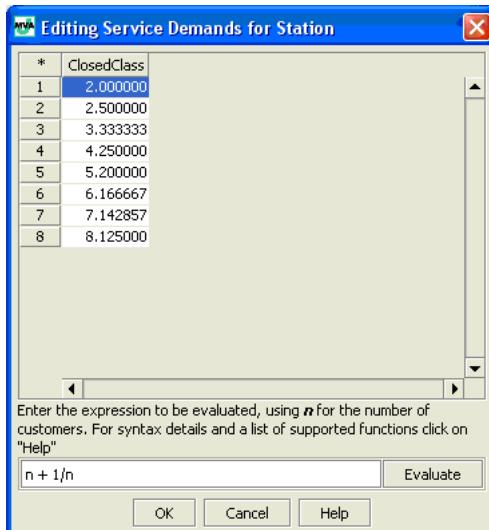


Figure 2.42: Example 3 - editor for the description of service demands for a load dependent station. In this case an arithmetic function has been defined: $S(n) = n + 1/n$

	Aggregate	Station	Users
Throughput [job/s]	0.234	0.234	0.234
Queue Length [job]	8.000	3.080	4.920
Residence Time [s]	34.149	13.149	21.000
Utilization	-	0.810	0.973

Table 2.9: Example 4 - model outputs

2.7.4 Example 4 - A model with one open and one closed class

The mixed queueing network model is shown in Figure 2.43. Workload intensities: the open class has an arrival

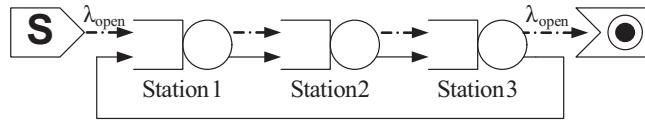


Figure 2.43: Example 4 - network topology

rate $\lambda = 1$ job/s, the closed class has a customers number $N = 57$. Service demands are shown in Table 2.10.

	Station1	Station2	Station3
OpenClass [s]	0.5	0.8	0.6
ClosedClass [s]	10.0	4.0	8.0

Table 2.10: Example 4 - service demands

Step 1 - Classes Tab

Follow the instructions of Step 1 in the previous examples; the **Classes Tab** is shown in Figure 2.44.

*	Name	Type	No. of Customers	Arrival Rate (λ)
1	OpenClass	open		1.000000 X
2	ClosedClass	closed	57	X

Figure 2.44: Example 4 - Class Tab

Step 2 - Stations Tab

Follow the instructions of Step 2 in the previous examples; in this case the model has three Load Independent stations (see Figure 2.45).

Step 3 - Service Demands Tab

Follow the instructions of Step 3 in the previous examples and define service demands for both classes as illustrated in Table 2.10 (see Figure 2.46).

Step 4 - Model Solution

Use **Solve** command. Results can be verified by computing the *equivalent model*, where the open class “slows down” the closed class by subtracting utilization to it:

$$\begin{aligned}
 D_1^{eq} &= \frac{D_{1,ClosedClass}}{1 - \lambda * D_{1,OpenClass}} = 20s \\
 D_2^{eq} &= \frac{D_{2,ClosedClass}}{1 - \lambda * D_{2,OpenClass}} = 20s \\
 D_3^{eq} &= \frac{D_{3,ClosedClass}}{1 - \lambda * D_{3,OpenClass}} = 20s
 \end{aligned}$$

The MVA algorithm is used to solve the equivalent closed model. The number of customers of the closed class is 57, and the exact MVA technique should require the solution of other 56 models with smaller population.

Classes \ Stations \ Service Demands \ Comment \

Stations characteristics
Number, customized name and type of stations.
You can add stations one by one or define total number at once.

Number: 3

*	Name	Type
1	Station1	Load Independent
2	Station2	Load Independent
3	Station3	Load Independent

Figure 2.45: Example 4 - Stations Tab

Classes \ Stations \ Service Demands \ Comment \

Service Demands
Input service demands of each station for each class.
If station type is set to "Load Dependent", you can set values of service demands for each number of customers by double-clicking on any button in station's row. If you wish to input service times and visits instead of service demands, press "Service Times and Visits" button.

*	OpenClass	ClosedClass
Station1	0.500000	10.000000
Station2	0.800000	4.000000
Station3	0.600000	8.000000

Figure 2.46: Example 4 - Service Demands Tab

In this particular case, the formula used to compute the throughput can be simplified because the Service Demands are all identical:

$$\begin{aligned}
 X^{eq}(N) &= \frac{N}{\sum_{k=1}^3 D_k^{eq} + \sum_{k=1}^3 [D_k^{eq} * Q_k^{eq}(N-1)]} \\
 &= \frac{N}{60 + 20 * \sum_{k=1}^3 Q_k^{eq}(N-1)} \\
 &= \frac{N}{60 + 20 * (N-1)}
 \end{aligned}$$

$$X^{eq}(57) = 0.048305 \text{ job/s}$$

The throughput for the closed class is $X_{ClosedClass} = X^{eq} = 0.048305$ job/s while the throughput for the open class coincide with its arrival rate $X_{OpenClass} = \lambda$. As visits were not specified, they have been considered equal to one: that is why throughput is equal at each station for each class (see Figure 2.47), i.e. the solved model consists of 3 stations that are sequentially connected with feedback.

Throughput \ Queue length \ Residence Times \ Utilization \ Synopsis \

Throughput
Throughput for each class at each station.

*	Aggregate	OpenClass	ClosedClass
Aggregate	1.048305	1.000000	0.048305
Station1	1.048305	1.000000	0.048305
Station2	1.048305	1.000000	0.048305
Station3	1.048305	1.000000	0.048305

Figure 2.47: Example 4 - throughput

Queue lengths can be computed with the following formulas:

$$\begin{aligned} Q_{k,ClosedClass}(N) &= Q_k^{eq}(N) \\ Q_{k,OpenClass}(N) &= \frac{\lambda * D_{k,OpenClass} * [1 + Q_{k,ClosedClass}(N)]}{1 - \lambda * D_{k,OpenClass}} \end{aligned}$$

And the results will be equal to the ones shown in Figure 2.48.

*	Aggregate	OpenClass	ClosedClass
Aggregate	187.000000	130.000000	57.000000
Station1	39.000000	20.000000	19.000000
Station2	99.000000	80.000000	19.000000
Station3	49.000000	30.000000	19.000000

Figure 2.48: Example 4 - queue lengths

2.7.5 Example 5 - Identification of the Optimal Population Mix with a two-class workload

Let us perform a what-if analysis to find the optimal population mix that will maximize System Throughput and minimize System Response Time in the model shown in Figure 2.49. This point corresponds to the maximum value of System Power (see par.3.6). This model consists of two closed classes of customers *Class1*



Figure 2.49: Example 5 - network topology

and *Class2*, and three load independent stations *Station1*, *Station2* and *Station3* with the service demands shown in Table 2.11. The total population of the model, i.e., the global number of customers of the two classes, is fixed to $N = 20$.

	Station1	Station2	Station3
Class1 [s]	1.0	5.0	1.0
Class2 [s]	5.0	1.0	5.0

Table 2.11: Example 5 - service demands

Step 1 - Classes Tab

Follow the instructions of Step 1 in the previous examples; as we will change population mix, initial allocation of the $N = 20$ jobs is irrelevant. For example we can allocate $N_1 = 10$ jobs to *Class1* and $N_2 = 10$ jobs to *Class2*. The **Classes** Tab is shown in Figure 2.50.

Step 2 - Stations Tab

Follow the instructions of Step 2 in the previous examples; in this case the model has three Load Independent stations (see Figure 2.51).

Step 3 - Service Demands Tab

Follow the instructions of Step 3 in the previous examples and define service demands for both classes as illustrated in Table 2.11 (see Figure 2.52).

Classes characteristics
Number, customized name, type of classes and number of customers (closed class) or arrival rate (open class). Add classes one by one or define total number at once.

*	Name	Type	No. of Customers	Arrival Rate (λ)
1	Class1	closed	10	X
2	Class2	closed	10	X

Figure 2.50: Example 5 - Class Tab

Stations characteristics
Number, customized name and type of stations. Add stations one by one or define total number at once.

*	Name	Type
1	Station1	Load Independent
2	Station2	Load Independent
3	Station3	Load Independent

Figure 2.51: Example 5 - Stations Tab

Service Demands
Input service demands of each station and class.
If the station is "Load Dependent" you can set the service demands for each number of customers by double-click on "LD Settings..." button.
Press "Service Times and Visits" button to enter service times and visits instead of service demands.

*	Class1	Class2
Station1	1.000000	5.000000
Station2	5.000000	1.000000
Station3	1.000000	5.000000

Service Times and Visits

Figure 2.52: Example 5 - Service Demands Tab

Step 4 - What-if Tab

1. use Next > to switch to **What-if Tab**
2. Select **Population Mix** as a *control parameter* of the analysis in the combo box, several fields will be shown below.
3. *Class1* is already selected, by default, as reference class for the what-if analysis. This means that β_i values in **From** and **To** fields are referred to *Class1*.
4. By default, JMVA suggests the minimum allowed value of β_1 in the **From** field and its the maximum value in the **To** field⁵. Since we want to find the optimal value in the entire interval, we leave this unchanged.
5. we want to perform the maximum number of allowed executions, so we enter a big number in the **Steps** field (100 for example). JMVA will automatically calculate the maximum number of allowed executions provided that the number of customers for each class must be an integer and will report 19.

At the end of this phase, the What-if Tab will look like Figure 2.53.

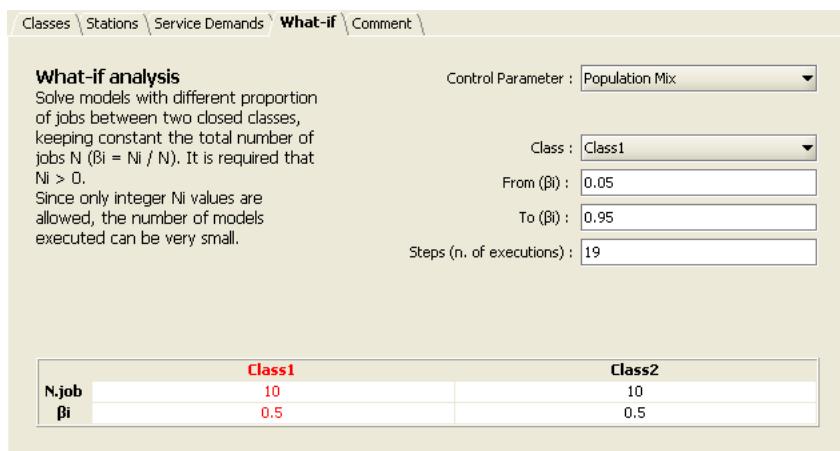


Figure 2.53: Example 5 - What-if Tab

Step 5 - Model Solution

Use **Solve** command. In the **Graphical Results Tab** select **System Response Time** and **System Throughput** as *Performance Index* (Figure 2.54 and Figure 2.55). Zooming on the plot, allows to identify the maximum value of System Throughput (0.32 job/s) and the minimum value of System Response Time (62.50 s). They both corresponds to the execution with population mix $\beta_1 = 0.40$ for *Class1*, which means that the optimal population values are $N_1 = 8$ and $N_2 = 12$.

2.8 Command line for JMVA

JMVA has been designed to be very flexible. One important feature is the complete separation between GUI and computation engine obtained through an XML layer as shown in Figure 2.56. This architecture allows reuse of the analytic engine in other projects by simply providing a suitable XML input file (see subsection 2.8.1 for details). The model solution with analytical engine can be started with the *JMT.jar* file invoked as following:

```
java -cp JMT.JAR jmt.commandline.Jmt mva < File.xml >
```

The *JMT.jar* file is located in the same directory where you installed the JMT tool.

The *File.xml* parameter is a well formed XML File according to the *JMTmodel.xsd* schema described in subsection 2.8.1. At the end of the computation, performance indices will be placed into the **solutions** element of a new file which has the same filename with the input file but with "-result.jmva" appended.

2.8.1 XML format

JMVA XML format is simple and can be written even manually. The syntax of that file is specified in *JMT-Model.xsd* and is graphically represented in Figure 2.57.

⁵Since it is requested that one class has at least one job and customer number must be integer, the minimum value is $1/N$ and the maximum value is $(N - 1)/N$.

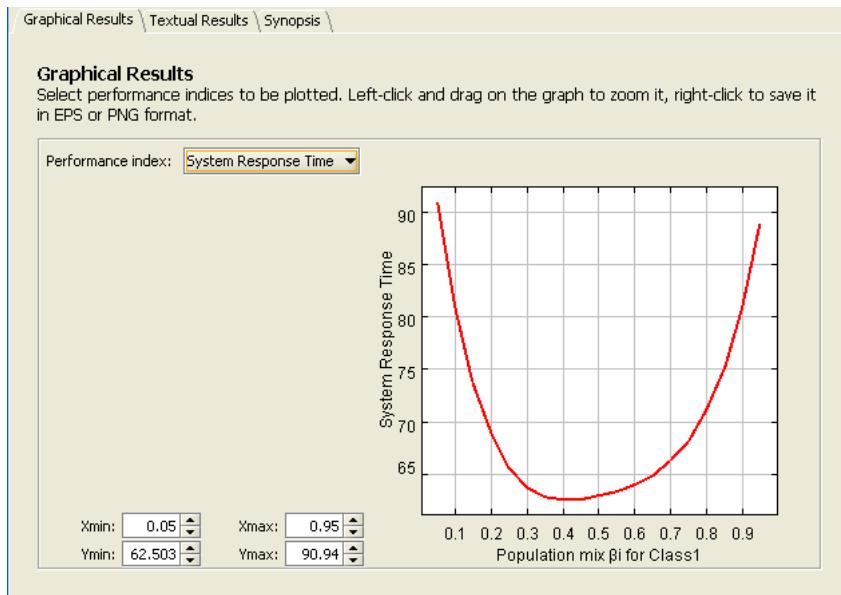


Figure 2.54: Example 5 - System Response Time

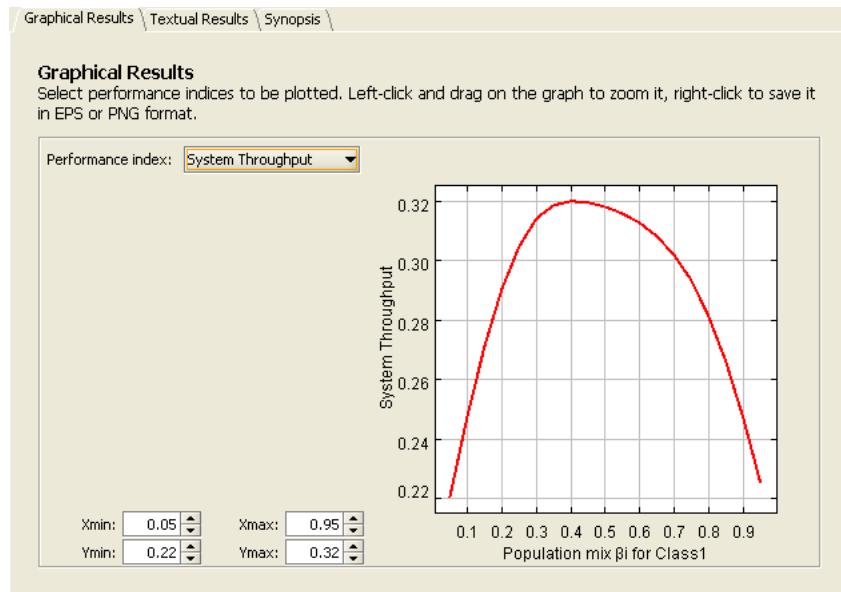


Figure 2.55: Example 5 - System Throughput

The root element is **model** and can include an optional **description** of the model, a section with **solutions** (that is parameterized by the solver engine) and the section **parameters** used to specify the network to be solved.

The section **parameters** contains the section **classes** that has for attribute the global **number** of classes and can include from one to infinite **openclass** or **closedclass**. **openclass** must specify a **name** and arrival **rate**, while **closedclass** must specify a **name** and **population**.

For example to define one closed class with $N = 10$ and one open class with $\lambda = 0.5$ the code will be:

```
<classes number="2">
  <closedclass name="ClosedClass" population="10" />
  <openclass name="OpenClass" rate="0.5" />
</classes>
```

The other section of **parameters** is **stations**. This element has **number** as attribute (like **classes**) and is composed from one to infinite elements of the following types:

delaystation is a delay station (infinite server)

listation is a load independent station

ldstation is a load dependent station

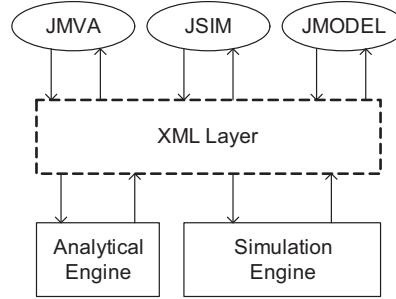


Figure 2.56: JMT Architecture

All the elements are defined with the same procedure. For each station the **name** attribute should be specified and two elements named **servicetimes** and **visits** must be included. **servicetimes** must include a list of at least one **servicetime** element and **visits** must include a list of at least one **visit** element. Both **visit** and **servicetime** elements have a **double** numeric value and each element has an attribute named **customerclass** that is used to associate a value of service time/visit with the corresponding customer class.

The only exception is **servicetime** parameter for a load dependent station. In this case the value is not a double but is a list of **double** separated by the special character ; . The list is ordered for ascending values of number of jobs in the station, starting from 1 to number of customer N of the closed class of the model.

For example in a model with one closed class, named *Class1*, with $N = 5$ customers and three stations: a load independent with service demand 1, a delay with service demand 2 and a load dependent with $D(N) = N + 2$, the following code should be used for the station definition:

```

<stations number="3">
    <listation name="LoadIndependent">
        <servicetimes>
            <servicetime customerclass="Class1">
                1.0</servicetime>
            </servicetimes>
            <visits>
                <visit customerclass="Class1">1.0</visit>
            </visits>
        </listation>
        <delaystation name="Delay">
            <servicetimes>
                <servicetime customerclass="Class1">
                    2.0</servicetime>
            </servicetimes>
            <visits>
                <visit customerclass="Class1">1.0</visit>
            </visits>
        </delaystation>
        <ldstation name="LoadDependent">
            <servicetimes>
                <servicetimes customerclass="Class1">
                    3.0;4.0;5.0;6.0;7.0</servicetimes>
            </servicetimes>
            <visits>
                <visit customerclass="Class1">1.0</visit>
            </visits>
        </ldstation>
    </stations>

```

Also the computed performance indices are stored in the same XML document. **solutions** has two attributes: **ok** that indicates if the computation was successful and **solutionMethod** that indicates if solution was obtained through analytical engine or simulator. Inside a **solutions** element there is a list of one or more **stationresults**, an element with station **name** as its attribute that contains one or more **classresults**, an element with class name (**customerclass**) as its attribute. This peculiar structure is needed to store a matrix of results. Each **classresults** element contains any number of **measure** elements that are used to store computed performance

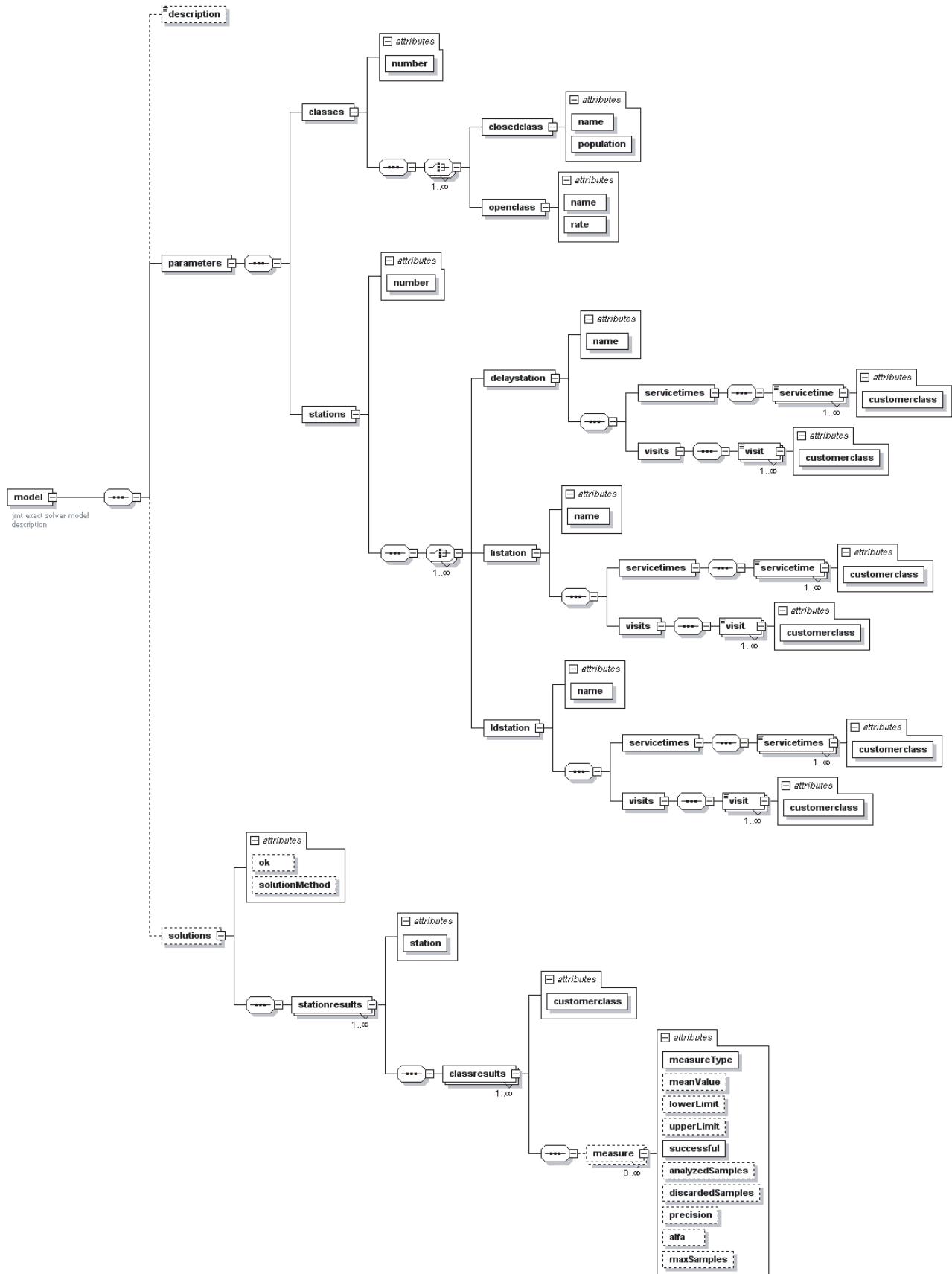


Figure 2.57: JMTModel.xsd stylesheet graphic representation

indices. **measure** has the following attributes:

measureType type of performance index, it can be one of the following *Queue length*, *Throughput*, *Residence time*, *Utilization*, and *Power*

successful boolean field that indicates if measure was computed correctly

meanValue (optional) computed value. This field is optional and will be always present if successful=true

lowerLimit (optional) lower limit of confidence interval. As MVA produces *exact* solution, this field is used only when model is solved with simulator

upperLimit (optional) upper limit of confidence interval. As MVA produces *exact* solution, this field is used only when model is solved with simulator

analyzedSamples (optional) number of samples analyzed by the simulator

discardedSamples (optional) number of samples discarded by the simulator

precision (optional) maximum relative error allowed by simulator

alfa (optional) confidence interval required to simulator

maxSamples (optional) maximum number of samples allowed by simulator

Note that only the first three elements of the above description will be saved by JMVA. The others are used when the model is solved using the simulator JSIM. For example, a model with one class (named *Class1*) and two stations (named *Station1* and *Station2*) will produce the following results:

```
<solutions ok="true" solutionMethod="analytical">
  <stationresults station="Station1">
    <classresults customerclass="Class1">
      <measure meanValue="9.930828575679609"
               measureType="Queue_length"
               successful="true"/>
      <measure meanValue="5.467534818643117"
               measureType="Throughput"
               successful="true"/>
      <measure meanValue="1.8163265356477696"
               measureType="Residence_time"
               successful="true"/>
      <measure meanValue="0.9999999999987986"
               measureType="Utilization"
               successful="true"/>
    </classresults>
  </stationresults>
  <stationresults station="Station2">
    <classresults customerclass="Class1">
      <measure meanValue="0.06917142432039082"
               measureType="Queue_length"
               successful="true"/>
      <measure meanValue="5.467534818643117"
               measureType="Throughput"
               successful="true"/>
      <measure meanValue="0.01265130019557098"
               measureType="Residence_time"
               successful="true"/>
      <measure meanValue="0.06469628980696993"
               measureType="Utilization"
               successful="true"/>
    </classresults>
  </stationresults>
</solutions>
```

It is important to point out that JMVA stores and loads model and results in *exactly* the same XML format used to dialogue with the analytical engine. The best practice to learn rapidly its syntax is to create a model using JMVA GUI, store it in any place and open it with a text editor.

Chapter 3

JSIMgraph (Simulation - Graphical)

3.1 Overview

In the JMT *suite* a discrete-event simulator for the analysis of queueing network models is provided. Two user interfaces are available: alphanumerical (JSIMwiz) and graphical (JSIMgraph).

JSIMgraph is the GUI front-end to JMT simulation engine. It helps the users to perform an evaluation study in two ways. Firstly, critical statistical decisions, such as transient detection and removal, variance estimation, and simulation length control, have been *completely automated*, thus freeing the users from taking decisions about parameters s/he may not be familiar with. The simulation is automatically stopped when all performance indexes can be estimated with the required accuracy. Secondly, a user-friendly graphical interface allows the user to describe, both the network layout and the input parameters. Furthermore, the graphical interface also provides support for the use of advanced features (several of them are for networks with very general characteristics, usually referred to as *non-product-form* networks) like fork and join of customers, blocking mechanisms, regions with capacity constraints on population, state-dependent routing strategies, user-defined general distributions, import and reuse of log data. A module for *What-If Analysis*, where a sequence of simulations is run for different values of control parameters, particularly useful in capacity planning, tuning and optimization studies, is also provided.

The simulation engine performs on-line the statistical analysis of measured performance indices, plots the collected values, discards the initial transient periods and computes the confidence intervals.

Network topologies implemented and solved using JSIMgraph can be exported in vector (e.g., eps, pdf) or raster (e.g., jpeg, png) image formats.

Main Features

Arrival rates for open classes of customers generated by Source stations and station *service times* (for any type of station in open and closed models) can be generated according to the following distributions: Burst (General, Modulated Markov Poisson Process MMPP2), Constant, Erlang, Exponential, Gamma, Hyperexponential, Normal, Pareto, Poisson, Student-T, Uniform

Queueing discipline: the following strategies are available: First Come First Served (FCFS) , Last Come First Served (LCFS), Random (RAND), Shortest Job First (SJF), Longest Job First (LJF), all with or without priority.

Routing of the customers in the network, i.e., the path followed by the requests among the resources, can be described either probabilistically or according to the following strategies: Fastest service, Least utilization, Load Dependent routing, Random, Round robin, Join the Shortest Queue, Shortest response time (the values of the control parameters are evaluated on the stations connected in output to the considered one), Load Dependent Routing. These strategies can be further combined among themselves through the use of a *routing station*.

Other peculiar features of the simulator are:

- Load dependent service time strategies
- Fork-and-join stations to model parallelism
- Simulation of complex traffic pattern and service times (e.g., burst)
- Blocking regions (in which the number of customer is limited)

- What-if analysis (with various control parameters)
- Customization of default values
- Import/Export of the model from/to JMVA, the exact solver (when the required analytic assumptions are satisfied)
- Logging of the data flowing in any part of the model (*Logger* station)
- Graphical visualization of the evaluated performance indices together with their confidence intervals
- automatic transient detection and removal
- automatic stop of the simulation when all performance metrics can be estimated with the required accuracy.

JSIMgraph has a modular Java-based architecture that allows the introduction of new Java classes in the simulation engine without any modification to the source codes of the other classes.

3.2 The home window

In the initial window of the JSIMgraph (Figure 3.1), all the icons in the toolbar except the first two (Create a new model and Open a previously saved model) are inactive. Choosing Create a new model from the toolbar or New from the File menu bar activates the other icons in the toolbar. From Figure 3.1, we can see that the

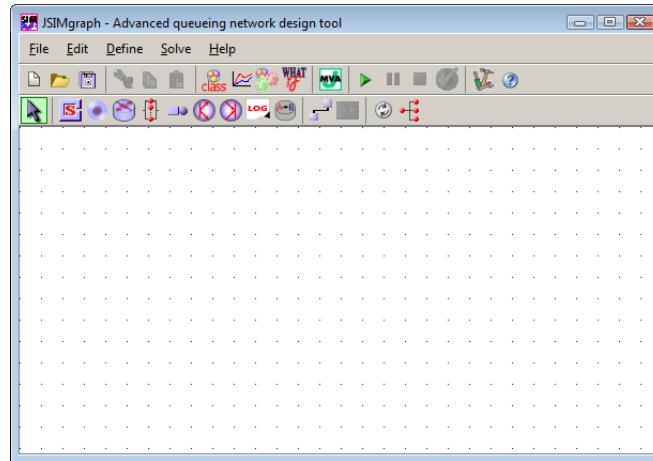


Figure 3.1: The home window of JSIMgraph

home window has a *menu bar* and *two toolbars*. The menu bar has 5 menus: File, Edit, Define, Solve, Help.

The *first toolbar* has the following icons:

- Create a new model
- Open a previously saved model
- Save the current model
- Cut
- Copy
- Paste
- Define customer classes
- Define the performance indices to be evaluated and plotted



Define current simulation parameters



Define What-if analysis parameters



Export the current model to JMVA



Start simulation model



Pause simulation



Stop simulation

-  Show simulation results window
-  Define new default values of model parameters

The **second toolbar** has the following icons:

-  Select
-  Insert a source station
-  Insert a sink station
-  Insert a routing station
-  Insert a delay station
-  Insert a queueing station
-  Insert a fork node
-  Insert a join node
-  Insert a logger station
-  Insert a class switch station
-  Connect two elements
-  Add selected stations to a new Finite Capacity Region
-  Rotate the component
-  Optimize the graph

3.3 Working with the graphical interface

3.3.1 Defining a new model

To define a new model the following steps have to be performed.

1. Draw the network (click and drop)
2. Define *Customer Classes* and select the *Reference Station* for each class
3. Set the parameters for each object
4. Select the performance indices to be collected and evaluated
5. If needed, insert one or more *Finite Capacity Regions* (FCR)
6. Choose or change the simulation parameters
7. Enable *What-If Analysis* and set its parameters, if required
8. Start the simulation
9. If diagnostic errors are detected, click on them and the related window that allows immediately to fix them will be shown.

Step 1: Create the new model

To draw a new network, select  or choose **New** from **File** menu. A white area in which the model should be drawn will be shown. Utilize the pre-defined objects like queueing station, delay, source, sink, logger, connection, routing station and fork/join.

Step 2: Define customer classes

In all the networks implemented, one or more *Customer Classes* must be defined. To describe them, see subsection 4.2.1 - "Defining Customers Classes" and parameterize the classes to use.

For each class of customers, a *Reference Station* should be set. This station is used to compute the *system throughput* for each class (i.e., the number of customers of that class that flow through the system in a time unit, and, in this case, that flow through the station selected as reference). It is a *required parameter* in order to compute correctly the simulation results. If a simulation is started without its prior definition, an error message will appear. Very often, the user station (usually a delay station) is selected as reference station. But this is not true on all the models. Thus, to provide the maximum of freedom to the users we ask this parameter as input for each model. Let us remark that the residence time of the reference station is accounted for the computation of the *system response time*.

Step 3: Define station parameters

All the stations have default parameters. The proper parameters of the objects should be defined: either the numeric values or the qualitative parameters such as routing strategy, queueing policy, maximum number of customers in a FCR region, etc. See section 3.10 - "Defining Network Topology" for details.

Step 4: Define performance indices

The performance indices that will be evaluated during the simulation should be selected. Select the indices and set the class and the station which each index refers to. See section 3.6 - "Performance Indices" for details.

Step 5: Define a Finite Capacity Region

A *Finite Capacity Region* (FCR) is a section of the model, that may consists of one or more stations, in which the number of customers is limited. Several FCRs can be defined in a network, provided that they *do not overlap*. See section 3.9 "Finite Capacity Region (FCR)" to learn how to set this type of region. **Step 6: Setting simulation parameters**

The parameters that control the simulation and the initial state of the network should be defined. See section 3.11 "Modification of the parameters" for details.

Step 7: Enabling a What-If Analysis

If you decide to set up a What-If Analysis read section 3.8.

Step 8: Start the simulation

Press ► or select **Simulate** from the **Solve** menu to start the simulation. Before starting the simulation, a check if the defined network is correct is performed, and the errors detected (fatal or warning) are shown. The results of a simulation are described in section 3.13.

Step 9: Fatal Errors and Warning Messages

The detected errors and warning messages are shown in section 3.12.

3.4 Classes of customers

The workload intensity is described by one of the following parameters:

- λ the arrival rate (for open models)
- N the population size (for closed models).

In *open* models the workload intensity is specified by the parameter λ , i.e., the rate at which requests (customers) arrive at the system. In these type of models there is an infinite stream of arriving customers and the customer population, i.e., the number of customers in execution, varies over time. Customers that have completed their execution leave the system (and reach a *sink station*). The class of customers of an open model is also referred to as *Open Class*.

In *closed* models the workload intensity is specified by a parameter N, indicating the average number of jobs (customers) in execution. In these models the population is fixed, i.e., N is kept constant. Customers that have completed their service are considered as if they left the model and have been replaced immediately by a new customer. The class of customers in execution in a closed model is also referred as *Closed Class*. Multiple class models consist of N customer classes, each of which has its own workload intensity and its own service demand at each center. Within each class, the customers are indistinguishable, i.e., statistically equal. Models, in which the customers belong to both of the two types of classes, open and closed, are referred to as Mixed models. The parameters defining the two types of classes are given below.

- **Open Classes parameters:** priority, interarrival time distribution, reference station, service time distributions of the stations
- **Closed Classes parameters:** priority, population value, reference station, service time distributions of the stations.

The classes of customers identify different customer behavior and characteristics, such as the type (closed or open), the size of the customer population (for closed classes) or the interarrival time distribution (for open classes), the path among the resources, the service time required.

They can be set from the **Define** menu by choosing **Customer Classes**. The following panel will be shown.

Classes must be explicitly added to the model, either one at a time by clicking the **Add Class** button, or by selecting directly the desired final number of classes from the **Classes** counter. The newly added classes will be listed with default parameters.

Double click on the default name (i.e., Class0, Class1, etc.) to change it. Each new class has a priority in the system. A smaller number indicates a lower priority. Default value is 0, it can be changed by double clicking on the corresponding area. In this panel you can insert either one or multiple customer classes.

Defining Open Classes

After adding a class and set its name and priority, you must select the type of the class. Classes are created *Closed by default*, so if you want an *Open* class, select the type *Open* from the **Type** menu.

Now the class characteristics should look like Figure 3.4.

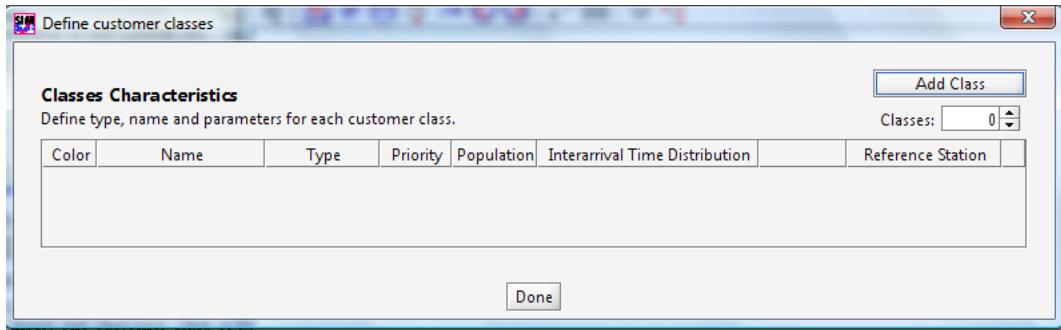


Figure 3.2: Window for the definition of the classes of customers



Figure 3.3: Selection of the type of the class

Open classes describe customer populations that vary over time. They are characterized by the probability distribution of the interarrival time of customers arriving at the system. The *default* Interarrival Time Distribution is *exp(1)* (Exponential Distribution with $\lambda = 1$). To change the Interarrival Time Distribution, click the **Edit** button.

The following window will appear:

Click on the **Selected Distribution** drop down menu to choose one of the following distributions:

Burst (General)
Burst (MMPP2)
Constant
Erlang
Exponential
Gamma
Hyperexponential
Normal
Pareto
Poisson
Replayer
StudentT
Uniform.

For each distribution the correct values of the parameters should be described, *default* values can eventually be used. Parameters that are related each others are automatically updated when one of them is modified. For example, for an *Erlang* distribution, when you set the (α, r) pair, the $(mean, c)$ pair is automatically set to the correct values. The *Replayer* distribution allows the user to use trace of data collected from real experiments. Click **OK** to return to **Class parameters** definition.

The final step of a class definition is the identification of the *Reference Station*, i.e., the station of the model used to compute the system throughput and response time of a class. It can be selected from the **Reference Station** menu (Figure 3.7). For *Open Classes*, *only* one of the stations of **Source** type can be selected as *Reference Station*.

Defining Closed Classes

By *default* Classes are created as *Closed*. Priority can be changed as in the case of Open class (the default value is 0, the minimum). The population size (also referred to as N) is the parameter that characterizes a closed class. For a closed class N is constant and does not change during the execution of the simulation. Its *default* value is 1 and it may be changed by clicking on the corresponding area in the class properties matrix. A Reference Station for the class *must* be selected from the **Reference Station** menu. With a closed class all the type of stations can be selected but neither a *Source* nor a *Sink*. The *Reference Station* is used to compute

Color	Name	Type	Priority	Population	Arrival Time Distribution	Reference Station
Blue	Class0	Open	2	1	exp(1)	Edit Source

Figure 3.4: Class characteristics window

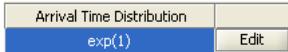


Figure 3.5: Definition of the interarrival time distribution and its parameters (Edit button)

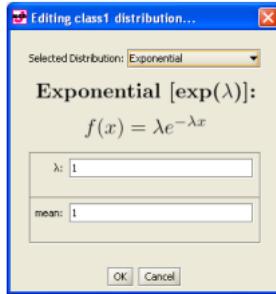


Figure 3.6: Window for the editing of the distribution of interarrival times



Figure 3.7: Selection of the Reference Station for an open class of customers

the system throughput and response time for the class considered.

3.5 Distributions

Open class models are workloads where the number of requests in the system fluctuates over time and new requests arrive at the system as if generated by an infinite source. The arrival pattern can be described by a probability distribution simple or very complex. It is often used the distribution of the *inter-arrival* times of consecutive requests, or customers.

A probability distribution $f(x)$ can be characterized by:

Mean (if it exists):

$$E[X] = \int_{-\infty}^{\infty} x f(x) dx$$

Variance (if it exists):

$$Var[X] = \int_{-\infty}^{\infty} (x - E[X])^2 f(x) dx = E[X^2] - E[X]^2$$

Coefficient of variation c (when mean and variance exist and mean is not 0):

$$c = \frac{\sqrt{variance}}{mean}$$

The following probability distributions are currently supported.

Burst (General) distribution

The Burst (General) distribution is a complex distribution obtained combining two different distributions. It allows the simulation of complex patterns of arrivals and may be suitable for simulating the load generated by web 2.0 applications. A Burst (General) distribution consists of two different types of intervals (A and B) independent among each other. For both the interval types the following parameters have to be specified:

- the *probability of occurrence* of that type of interval in the generated stream
- the *length distribution* for that type of intervals
- the distribution of the *values* generated into each interval.

The Burst (General) distribution behaves as follows. As soon as the simulation starts, an interval is chosen based on the specified probability of occurrence. If, for example, interval type A has probability of occurrence of 0.7 and interval B has 0.3, then an interval of type A is chosen with 70% probability. In order to determine the duration of an interval, an event from the interval-length distribution is obtained. The distribution of the events of an interval is then used to compute the arrival time of customers or the service time of a station,

Color	Name	Type	Priority	Population	Arrival Time Distribution	Reference Station
■ Class1	■ Closed	▼	0	4	▼	Server0 □

Figure 3.8: Closed class definition parameters

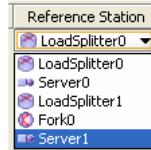


Figure 3.9: Selection of a Reference Station for a closed class of customers

depending on where the Burst (General) distribution is used. As soon as the interval ends, a new interval is chosen based on the given probability as before.

Figure 3.10 shows the concept idea of the Burst (General) distribution, clarifying the role of the occurrence probability and the role of the interval length.

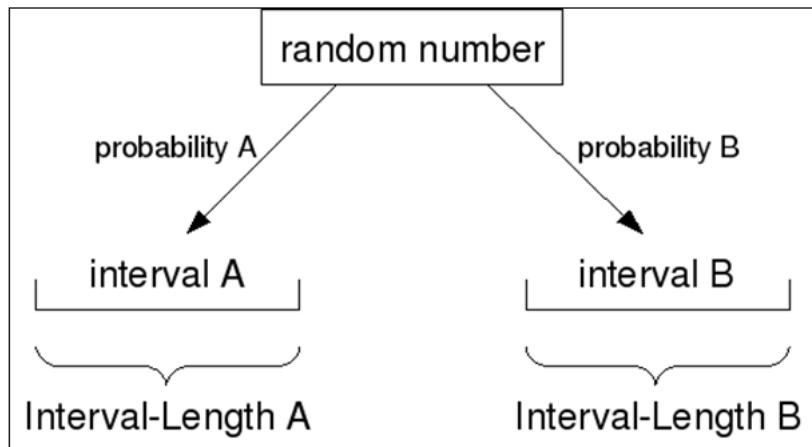


Figure 3.10: Main structure of the *Burst (General)* distribution consisting of two type of intervals with independent statistical characteristics

Burst (MMPP2) ($\text{mmpp2}(\sigma_0, \sigma_1, \lambda_0, \lambda_1)$) distribution

A MMPP(2) is a continuous-time Markov chain that jumps between two states and the active state determines the current rate of service. For example, one state may be associated with slow inter-arrival times (state 0), the other may have fast inter-arrival times (state 1). As time passes, the MMPP(2) jumps several times between the slow state 0 and the fast state 1. In JMT, the MMPP(2) is parameterized by four rates: σ_0 , σ_1 , λ_0 , and λ_1 (see Figure 3.11). While in state 0, the MMPP(2) generates arrivals with rate λ_0 or jumps to state 1 with rate σ_0 ; in state 1 the arrival and jump rates are λ_1 and σ_1 , respectively. This can be equivalently stated as follows: in state 0 a random number with exponential distribution having rate $\lambda_0 + \sigma_0$ is drawn, then with probability $\lambda_0 / (\lambda_0 + \sigma_0)$ is the arrival of a new job (or equivalently the completion of its service if the MMPP(2) is used as a service process), while with probability $\sigma_0 / (\lambda_0 + \sigma_0)$ without any job arrival or service completion; the case of state 1 is similar.

A MMPP(2) can be parameterized to have a predefined mean, c^2 , skewness, decay rate of the autocorrelation. Given these four parameters, there are closed-form formulas to obtain the corresponding values of σ_0 , σ_1 , λ_0 , and λ_1 . For example the mean is related to the rates of the MMPP(2) by

$$\text{mean} = \frac{\sigma_0 + \sigma_1}{\lambda_0 \sigma_1 + \sigma_0 \lambda_1}$$

while the decay rate of the autocorrelation that controls the burstiness is

$$\text{decay rate} = \frac{\lambda_0 \lambda_1}{\lambda_0 \lambda_1 + \lambda_0 \sigma_1 + \sigma_0 \lambda_1}.$$

In particular, a large decay rate (> 0.9) creates large bursts of arrivals/service completions. The reader could find additional details on how to fit a MMPP(2) for example in [CZS07] and references therein.

example 1) $\lambda_0 = \lambda_1 = 5$ is an exponential distribution for all choices of σ_0 and σ_1

example 2) $\lambda_0 = 1.4346$, $\lambda_1 = 0$, $\sigma_0 = 0.0139$, $\sigma_1 = 0.0319$ is an hyperexponential with mean= 1, $c^2 = 20$, $p = 0.99$. since the hyperexponential has no burstiness, here the autocorrelation coefficients are equal to zero.

example 3) $\lambda_0 = 12$, $\lambda_1 = 0.0879$, $\sigma_0 = 0.0010$, $\sigma_1 = 0.0001$ is a MMPP(2) with burstiness. The mean is 1, $c^2=20$, skewness= 7.31, lag-1 autocorrelation coefficient is 0.4745. Since for a MMPP(2) the autocorrelation is always less than 0.5, this is an example of a process with very large burstiness.

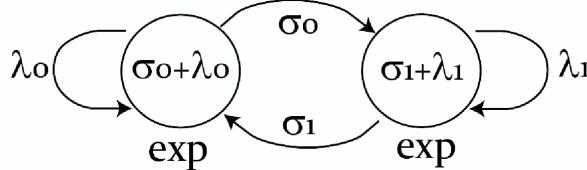


Figure 3.11: Main structure of the *Burst (MMPP2)* distribution

Deterministic (det(k)) distribution

This distribution describes a deterministic (constant) flow of customers, arriving exactly every k time units. The probability density function is:

$$f(x) = \begin{cases} 1 & x = k \\ 0 & x \neq k \end{cases}$$

The only parameter that should be specified is the *mean*, equal to k .

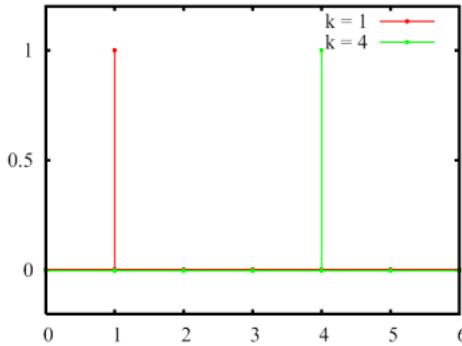


Figure 3.12: *Deterministic* distributions for two different mean values

Erlang (erl(α, r)) distribution

The *Erlang* distribution is a continuous distribution, with two parameters: the *shape* r , an integer value, and the *rate* α , a real value. It is a special case of a Gamma distribution with integer shape parameter. The probability density function is:

$$f(x) = \frac{\alpha^r}{\Gamma(r)} x^{r-1} e^{-\alpha x}$$

$\Gamma(r)$ is called Eulero function and when r is a non null positive integer, as in the case of the Erlang distribution, the Eulero function reduces to $\Gamma(r) = (r - 1)!$.

A random variable with Erlang distribution of order r can be obtained as a sum of r exponentially distributed random variables with mean $1/\alpha$ (see Figure 3.13). When the values of α and r are changed, the system

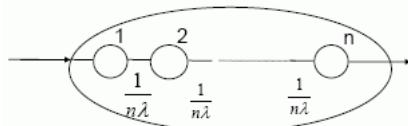


Figure 3.13: Simulation of an Erlang distribution with a sequence of exponential stages

will automatically recompute the mean = r/α and the variance $Var = r/\alpha^2$. A family of probability density functions that illustrate the impact of various (α , r) pairs is shown in Figure 3.14.

Exponential (exp(λ)) distribution

This is a continuous probability distribution where $\lambda > 0$ is the distribution parameter, often called the *rate*

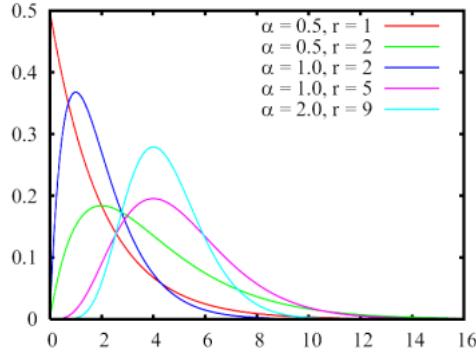


Figure 3.14: A family of Erlang distributions with different values of the parameters (α, r)

parameter; the distribution is defined in the interval $[0, \infty)$. The probability density function is:

$$f(x) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

The exponential distribution is used to model Poisson processes. The time interval between two consecutive events generated by a Poisson process can be described by an exponential random variable with parameter λ . The parameter λ is a real number, the mean value is given by $1/\lambda$, the variance is given by $1/\lambda^2$.

A family of exponential density functions with different values of λ is shown in Figure 3.15.

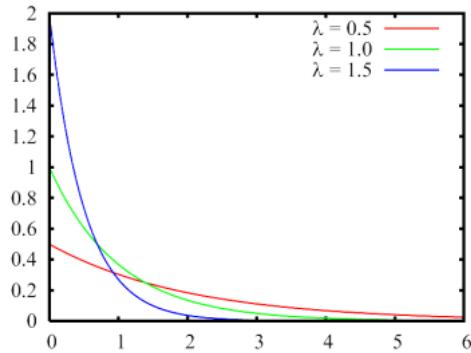


Figure 3.15: Exponential density functions with different mean $(1/\lambda)$ values

Gamma ($\text{gam}(\alpha, \lambda)$) distribution

The *Gamma* is a continuous probability distribution with two parameters: the shape α and the scale λ , both real numbers. The probability density function is:

$$f(x) = \frac{x^{\alpha-1}}{\Gamma(\alpha)\lambda^\alpha} e^{-x/\lambda}$$

where $\Gamma(t)$ is the Euler function. When the Gamma distribution is selected, the user can either provide α and λ or the distribution mean equal to $\alpha\lambda$ and the variance $\alpha\lambda^2$. A family of probability density functions is shown in Figure 3.16, for a set of α and λ values.

Hyperexponential ($\text{hyp}(p, \lambda_1, \lambda_2)$) distribution

A hyperexponential distribution describes a random variable characterized by a variability higher with respect to an exponential one with the same mean. It is the result of a weighted sum of two independent exponentially distributed random variables, with parameters λ_1 and λ_2 respectively. The weight p is the probability that the random variable behaves like the exponential variable with parameter λ_1 and $1-p$ that it behaves like the exponential variable with parameter λ_2 . The probability density function is:

$$f(x) = p \lambda_1 e^{-\lambda_1 x} + (1-p) \lambda_2 e^{-\lambda_2 x}$$

When this distribution is used to model customer interarrival time or a station service time, with probability p the next interval before a new arrival (or the next service time) is distributed like the upper server in Figure 3.17 the figure above while with probability $1-p$ it will be distributed like the lower server.

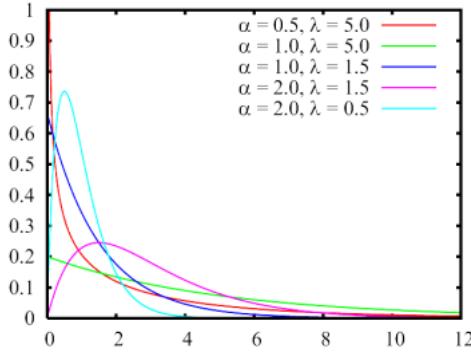


Figure 3.16: *Gamma* density functions for different values of α and λ

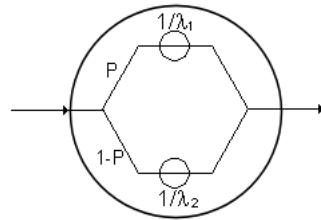


Figure 3.17: Generation of the values of an hyperexponential function through two exponential stages in parallel

A family of hyperexponential density functions is shown in Figure 3.18. Note that when $\lambda_1 = \lambda_2$, the hyperexponential reduces to a simple exponential.

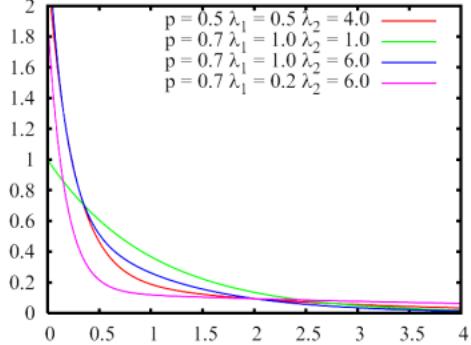


Figure 3.18: Family of hyperexponential density functions

Normal ($\text{norm}(\mu, \sigma)$) distribution

The *Normal* distribution is also called Gaussian since its probability density function is the Gaussian function. It is well known for its bell-shaped density function.

The two parameters are μ = location (real number, it is the *mean* of the distribution), and σ = scale (real number, it is the *standard deviation* of the distribution, i.e., the square root of the variance). The density is symmetrical around the mean and the variance. The probability density function is:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

The *standard normal distribution* is the normal distribution with $\mu = 0$ (mean equal 0) and $\sigma = 1$ (variance and standard deviation equal 1). A family of normal density functions is shown in Figure 3.19.

Note: it may be that the sequence generated is *not* perfectly normal since negative values are *discarded*.

Pareto ($\text{par}(\alpha, k)$) distribution

This distribution is usually utilized to describe the behavior of social and economical phenomena (e.g., the distribution of wealth, where a small portion of the people owns the larger part of the wealth). It is characterized

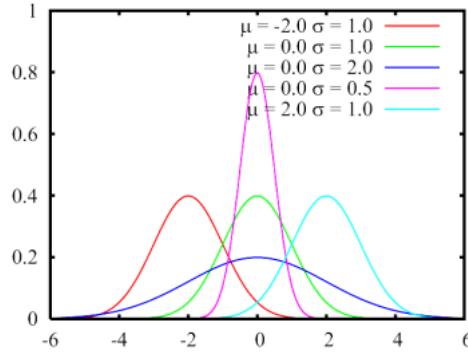


Figure 3.19: Family of normal density functions. The standard normal density is the green colored.

by the parameters $k > 0$, *location* (real), and $\alpha > 0$, *shape* (real). The probability density function is:

$$f(x) = \alpha k^\alpha x^{-(\alpha+1)}$$

If k and α are provided as input parameters, the simulator compute the mean $ka/(\alpha - 1)$ for $k > 1$ and the variance

$$\frac{\alpha^2 x}{(x-1)^2(x-2)}$$

A family of Pareto density functions is shown in Figure 3.20.

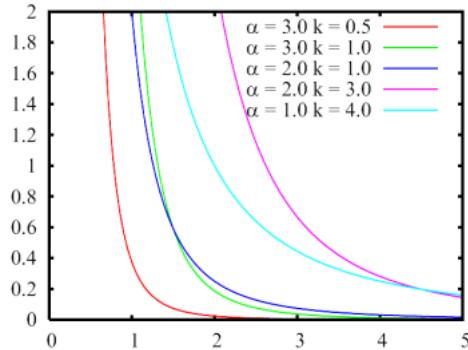


Figure 3.20: Family of Pareto density functions.

Poisson (poisson(λ)) distribution

The Poisson distribution describes the number of events occurring in a time interval, when such events are independent of the amount of time elapsed and they occur at a fix rate. It is a discrete probability distribution characterized by a single parameter, λ , a positive real number, which is the average number of events in a time interval and its variance. The probability of having an arrival in a time interval $(t, t+\Delta t)$ is $\lambda\Delta t + o(\Delta t)^2$, while the probability of more than one arrival in the same interval is $o(\Delta t)$.

For large time intervals T , the distribution is near the mean value, thus the number n of arrivals over the interval is given by $n = \lambda T$. The time intervals between two consecutive events having a Poisson distribution are exponentially distributed with average value equal to $1/\lambda$. The probability mass function is:

$$f(x) = \frac{\lambda^x}{x!} e^{-\lambda}$$

A family of Poisson probability mass functions is shown in Figure 3.21.

Replayer (replayer("filename")) distribution

When *Replayer* is chosen, a trace of data provided by the user can be reused as interarrival times or service times. The file format should be text/binary with values separated by CR (Carriage Return) or SPACE. The format of the values is DIGITS [POINT DIGITS], malformed elements will be ignored. In order to use this user-supplied file of data, the user should provide in the input window the absolute path name of the file. If the file does not exist or does not contain any valid value, JSIMGRAPH will use a default file (a file with all values set to zero).

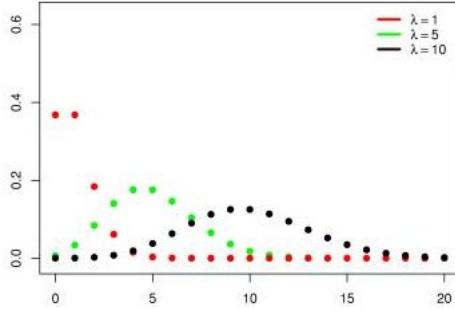


Figure 3.21: Family of Poisson probability mass functions.

Warning: be careful when using models generated in other computers that the path must be recognized also from the actual one.

Student-T (studT(ν)) distribution

The T -distribution, or StudentT distribution, is a continuous distribution characterized by the single parameter ν , a real positive number. It is used when the mean of a normally distributed population must be estimate using only a small sample size. It is the basis of the Student- t 's test that is used to evaluate the statistical significance of the difference between two sample means and for the difference between two population means. It is a special case of the generalized hyperbolic distribution. The mean is 0 for $\nu > 1$ and the variance is $\nu/(\nu - 2)$ for $\nu > 2$ (infinite otherwise). The probability density function is:

$$f(x) = \frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi}} \frac{1}{\Gamma(\frac{\nu}{2})} (1 + \frac{x^2}{\nu})^{\frac{\nu+1}{2}}$$

where $\Gamma(t)$ is the Eulero function. A family of probability density functions for a set of ν values is shown in Figure 3.22.

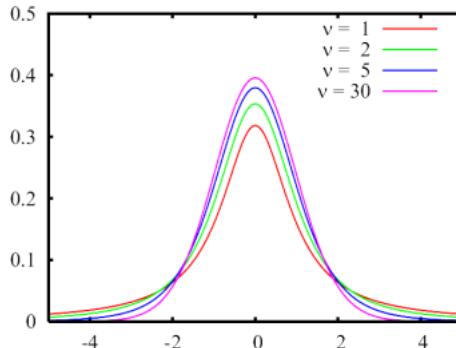


Figure 3.22: Family of Student-T density functions.

Uniform (U(min,max)) distribution

The *Uniform* distribution, also referred to as Rectangular distribution due the shape of its density function, describes a random variable that may assume all the values in the range (min, max) with the *constant* probability $1/(max - min)$. The probability is 0 outside the considered range.

The user can either provide the pair (min, max) or the *mean* $m = (max + min)/2$ and *variance* $c = (max - min)^2/12$. Two uniform density functions are plotted in Figure 3.23.

3.6 Performance indices

The following list include the performance indices that can be obtained from a simulation run.

- **Number of Customers (of a station):** number of customers N at a station, both waiting *and* receiving service.
- **Queue Time (of a station):** average time spent by the customers waiting in a station *queue*. It does not include the Service Time.

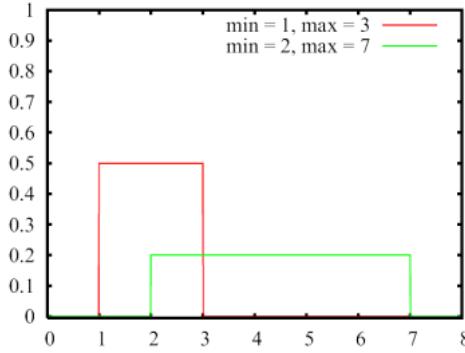


Figure 3.23: *Uniform* density functions with different range of values.

- **Residence Time (of a station):** total time spent at a station by a customer, both queueing and receiving service, considering *all* the visits at the station performed during its complete execution.
- **Response Time (of a station):** average time spent in a station by a customer for a *single* visit (sum of Queue time and Service time).
- **Response Time per Sink :** average time spent in system by a customer before dropping at the selected sink.
- **Utilization (of a station):** percentage of time a station is used (i.e., *busy*) evaluated over all the simulation run. It ranges from 0 (0%), when the station is always *idle*, to a maximum of 1 (100%), when the station is constantly *busy* servicing customers for the entire simulation run. *Queueing stations* may have more than one server, their number is a parameter to be specified (*default* is 1). It is important to point out that the *utilization U* of a queueing station with a *single server* is given by $U = \lambda S$, and in a station with *m servers* the utilization of *any* individual server is given by $U = \lambda S/m$. In *delay stations*, for consistency with Little's law, the *utilization* is computed as the *average number of customers* in the station, and thus it may be *greater than 1*.
- **Throughput (of a station):** rate at which customers departs from a station, i.e., the number of requests completed in a time unit.
- **Throughput per Sink :** rate at which customers departs from the system with respect to the selected sink, i.e., the number of requests completed in a time unit that reach a given sink.
- **System Throughput [X] (of the entire system):** rate at which customers departs from the system.
- **System Response Time [R](of the entire system):** average time a customer spends in the system in order to receive service from the various stations it visits. It corresponds to the intuitive notion of response time, as the interval between the submission of a request and the reception of the response. It may be obtained summing the *Residence Times* of all the resources.
- **System Number of Customers (of the entire system):** average number of customers in the system. If the index is associated with a closed class, then it is equal to the number of customers in the class (constant).
- **System Power (at system and per-class levels):** The optimal operational point of a system is the point corresponding to the maximum System Throughput X with the minimum System Response time R, i.e., the value of the ratio X/R is maximized in this point. This ratio is known as **System Power**. Typically is computed at the level of the entire system. The **System Power** may be computed also for each class of customers considering the throughput and the response time of the class (in this case is referred to as **Per-class System Power**).

Any subset of indices from the above list can be plotted as model output. Each index is associated with a class and a station and will be computed within the given Confidence Interval and Maximum Relative Error, both defined on the (0-1) range, by performing the following steps:

1. Select the index you want to add to the model from this menu:
2. Select **Add Selected Index** and the index will be added to the panel. Then the index must be set.
3. Select from the **Class** menu a **Single class**, or **All Classes**, for which the index must be computed.
4. Select the **Station** for which the index must be computed from **Station** menu. In case of system wide indices, namely, System Throughput and System Response Time, this option is not available.
5. Double click to modify the default values for the *Confidence Interval* size of the solution and for the *Max Relative Error* of the greatest sample error, if you want more/less accurate results.
6. Repeat these steps for all the indices you want to include in the model output.

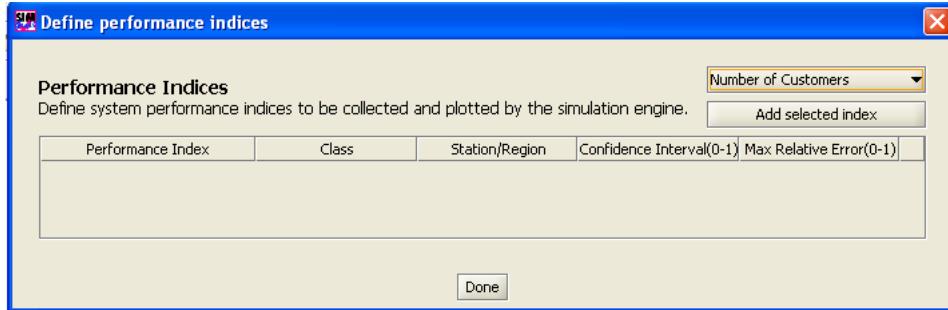


Figure 3.24: The window for the selection of the *performance indices*.

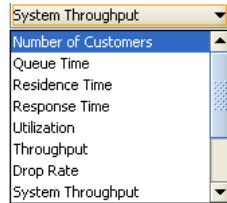


Figure 3.25: The drop-down list for the selection of the *performance indices*.

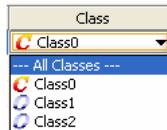


Figure 3.26: The drop-down list for the selection of the *Class*.



Figure 3.27: The drop-down list for the selection of the *Station*.

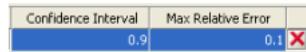


Figure 3.28: Definition of the *Confidence Interval* and *Max.Relative Error*.

NOTE: Users must be informed that the value of *System Power* computed by JSIMgraph and JSIMwiz is approximate and not the exact X/R where System Throughput X and System Response Time R are obtained from the simulator. This is mainly due to the implementation limitations and the reduction of the computational complexity.

NOTE: Errors in parameter settings will be detected only when the simulation is started, raising a warning or an error message.

3.6.1 Confidence Intervals

The confidence interval shown at the end of a simulation run contains the true value of the estimated index with the selected probability $(1-\alpha)$ or, equivalently, if an experiment is repeated many times, in $(1-\alpha)*100\%$ of cases. Various difficulties in meeting theoretical assumptions can cause that the real percentage of the confidence intervals containing the true parameter differs significantly from $(1-\alpha)$. The robustness of the above methods of data collection and analysis is usually measured by the coverage of confidence intervals, defined as the frequency with which the intervals $(X(n)-\Delta x, X(n)+\Delta x)$ contain the true parameter value μ_x , at a given confidence level $(1-\alpha)$, $0 < \alpha < 1$. The coverage analysis can be applied only to systems with a theoretical well-known behavior, since the value of μ_x has to be known. Any analyzed method must be applied in a statistically significant number of repeated simulation experiments, usually 200 or more replications, to determine the fraction of experiments producing the final confidence intervals covering the true mean value of the estimated parameter.

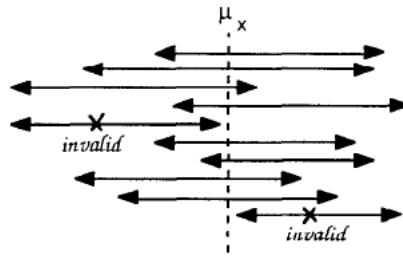


Figure 3.29: *Confidence intervals* for the correct parameter value μ_x evaluated in 10 runs. The coverage is 80% since two of them do not include the correct value.

3.6.2 Max Relative Error

Let x be the true value of a quantity and x_i be the measured or inferred value. The relative error is defined by:

$$\frac{|\bar{X}(n) - \mu_x|}{|\mu_x|} \quad \text{where} \quad \bar{X}(n) = \sum_{i=1}^n \frac{x_i}{n}$$

where μ_x is the mean value. The relative error is the sum of the deviations between the sample values and the mean value, divided for the mean value.

3.7 Simulation Parameters

The **Define Simulation Parameters** window (see Figure 3.30) can be reached either by selecting **Simulation Parameters** from the **Define** menu or by clicking the **Define Simulation Parameters** icon  from the toolbar.

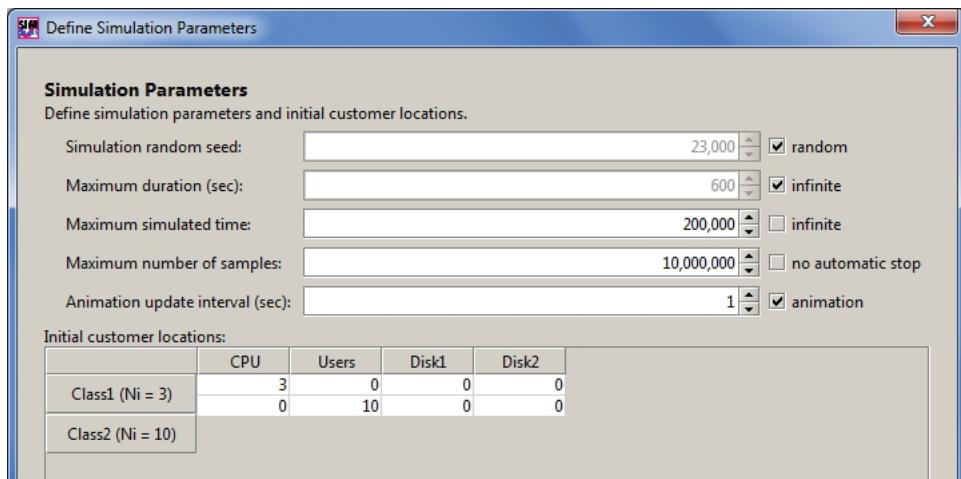


Figure 3.30: Window for the definition of the **Simulation Parameters**

The parameters that can be used to control the simulation are:

- **Simulation Seed:** is the number used by the simulation engine to generate pseudo-random numbers. If you change the seed, you will obtain a different sequence of pseudo-random numbers. You may select **random**, which indicates that the simulator will use a seed randomly generated, or you may type the number that you want to be used as seed. When a simulation is repeated using the *same seed*, the same sequence of pseudo-random numbers will be generated, thus leading to *identical results*. The default value is **custom** simulation the one which has been set in the **Simulation parameters** section of the **Editing Default Values**. In the figure it is required the generation of a random seed.
- **Maximum duration (wall time, sec):** It represents the maximum amount of time, in seconds, that the simulation will run, i.e., the *wall time* value. If the simulation ends before the maximum duration time (due to the automatic stop controls), this parameter is ignored. The *default* value is **infinite**, deselect it and specify the maximum time value if you do not want the simulation to run for a possibly very long

time. In this case, the simulation stops when the time limit is reached, although a reliable solution may not be available yet.

- **Maximum simulated time:** It is the maximum simulated time allowed for the current simulation run. The simulation will stop when this time is reached (if other stopping criteria eventually activated are not reached). In the example of Figure 3.30 the simulation time is set to 200,000 time units.
- **Maximum number of samples:** It is the maximum number of samples (data) for each index that JSIMgraph collects before ending the simulation. The default value for the **maximum number of samples** is 1,000,000; you may increase it (for a more accurate simulation) or decrease it (for a faster simulation).
- **Animation Update Interval (sec):** This is the granularity at which results are plotted on the screen, i.e., the time interval (we will refer to the *wall time* and not to the simulated time) between the plot of two consecutive values of the graphs, as the simulation proceeds. An **animation** checkbox is used to enable or disable plot animation during the simulation run.

A simulation run is *stopped* in case of:

- *Success*, if the values of the considered index have reached the required **Confidence Interval** with an error less than the **Max Relative Error**
- *Failure*, if the simulation has analyzed the **Maximum number of samples** but has not reached the required **Confidence Interval** or the error is greater than the **Max Relative Error**
- *Failure*, if the **Maximum duration time (wall time)** has been reached before the *Success* criterion
- *Failure*, if the **Maximum simulated time** has been reached before the *Success* criterion.

Initial state of a simulation

The *Initial state* is the model state at time 0, typically described by the number of customers in each station at the beginning of the simulation.

For closed customer classes, all customers are allocated by *default* to their *reference stations*. You can modify this allocation, as long as the total number of customers remains the one defined in the **Classes** tab. For open customer classes, it is possible to initialize each station with any desired number of customers. In Figure 3.30 the *initial state* of a model with four stations and two closed classes (*Class1* with 3 customers in the *CPU* station and *Class2* with 10 customers in the *Users* station) is shown. The selection of a **Initial customers location** is very important since, as a function of the model complexity, it may influence the time required for convergence of some indexes.

3.8 What-If Analysis

A What-If Analysis consists of a series of simulations in which one or more *control* parameters are varied over a specified range. This allows the observation of system behavior under a spectrum of conditions, unlike the single simulation run where the system is observed under a fixed set of parameters. By default the What-If Analysis is not enabled. It must be activated explicitly and its parameters should be defined.

Activating the What-If Analysis

After completing the definition of the model and selecting the **What-If Analysis** tab, check the **Enable what-if analysis** checkbox to activate it.

Selecting the What-If Analysis

After enabling the What-If Analysis, it is possible to select the parameter to control the sequence of simulation runs using the menu of Figure 3.32. When you select a What-If Analysis parameter, the bottom section of the window of Figure 3.31 will change depending upon the parameter. In the right portion a **Description** is provided of the selected parameter and of the impact of its variation. In the left portion the details of the parameter range (**From** and **To** fields) and the number of executions (**Steps**) on the range are provided. The set of modifiable parameters depends upon the number and type of classes in the model: in a *single class* model, you simply select the parameters you want to change during simulation while in a *multiclass* model, you must select the parameter and specify whether you want to apply the variation to all the classes or just to one specific class.

The parameters that may be used to *control the sequence of executions* in a What-If Analysis are:

- **Number of Customers:** (only for models with **closed** classes)

JSIM repeats the simulation changing the number of customers in each run, starting from the number inserted in the **From N** field, to the value inserted in the **To N** field. The simulation is repeated **Steps(n.of exec.)** number of times. In Figure 3.33 a What-If Analysis is planned on a single closed class model. The option **Increase number of jobs of one closed class** has been selected. The initial value of the

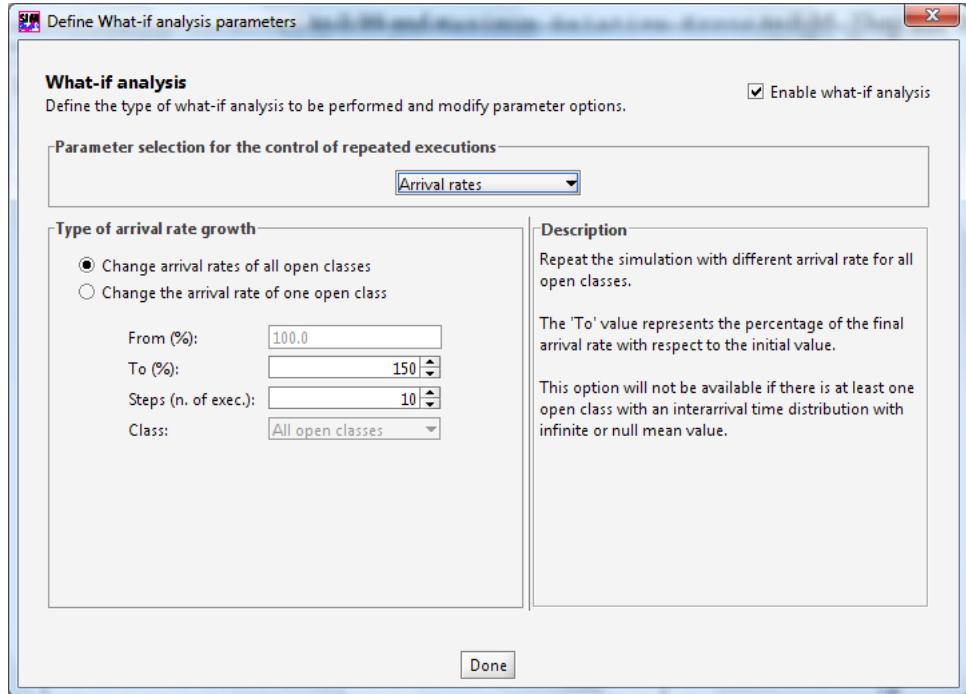


Figure 3.31: The window for What-If Analysis definition.



Figure 3.32: Selection of the parameter for the control of a What-If Analysis.

number of customers is not modifiable from this window, as it is part of the **Classes** tab. The final value should be specified in the field **To N**. In this case, with a final value of 20 and 6 Steps, simulations are run for 10, 12, 14, 16, 18 and 20 customers, respectively. Only the customer number in the class selected in the **Class** (*ClosedClass*, in the picture) will be changed. The remaining classes (if they are present) will keep their initial number of customers. The simulator control that the sum of the *percentages of jobs* of the various classes (represented by the components β_i of vector β) evaluated over the global population N of the model add up to 1, as shown in the **Population mix** table on the bottom of the window of Figure 3.33 in the simple case of a single class model.

If the **Increase number of jobs of all closed classes** option is selected, the overall population is increased keeping constant the relative proportion of jobs in the various classes, i.e., the values β_i (also referred to as *population mix*). Because in the JSIM the number of customers in each class can only be integer numbers, only the population vectors with all integer components can be considered. Therefore, the actual number of executions may be smaller than the one specified.

The population mix describes the way the global population is subdivided between the classes, i.e., the percentage of customers in each class (β_i values) over the total population. The population mix can be modified extensively selecting the way we want to change it with the increasing of the global population of customers: all classes increase proportionally or only one class increases keeping constant the jobs of the other classes (select the option **Increase number of jobs of one closed class** in this case). Mixed models can be analyzed too. Remember that only models with closed classes (at least one) will be considered in this What-If Analysis.

- **Arrival Rate:** (only if there are **open** classes)

Arrival rate is the frequency at which jobs arrive at a station during a period of time. Similarly to the number of customers, the arrival rate can be changed for one specific open class or for all the open classes in the model.

If the option **Change the arrival rate of one open class** is selected, the final arrival rate and the number of steps must be specified.

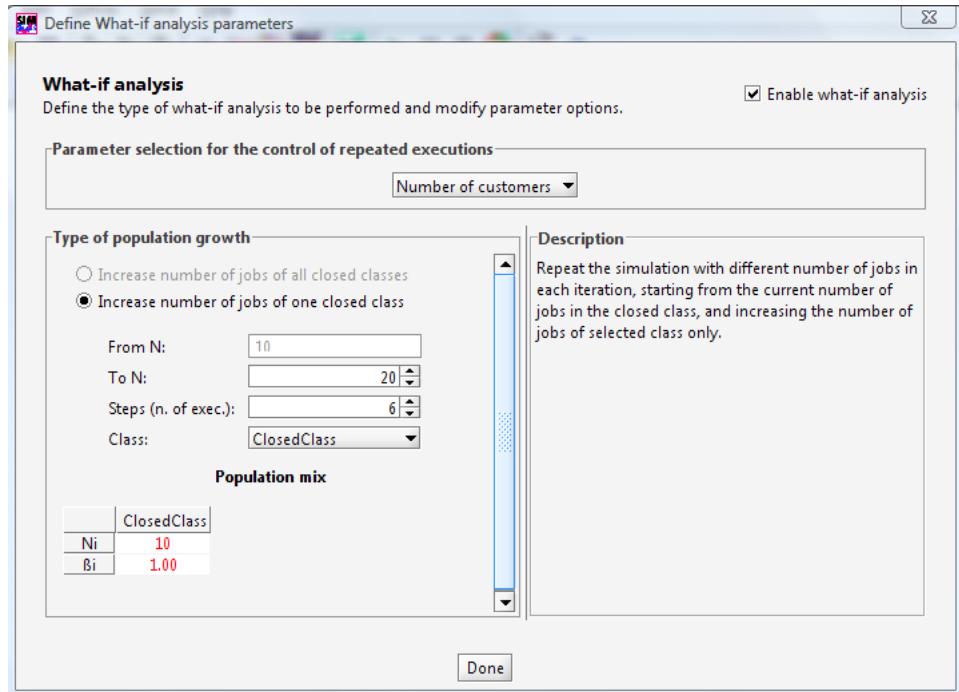


Figure 3.33: Selection of the Type of population growth in a What-If Analysis.

The initial arrival rate is specified in the **Arrival Rate** section of the **Classes** tab and it is not modifiable here.

If the option **Change arrival rates for all open classes** is selected, the final value is expressed as a percentage of increase with respect to the actual value that is applied to the arrival rates of all the classes. Figure 3.31 shows the settings for a What-If Analysis of the arrival rate of all the open classes. The **To** field is set to 150%, which means that for each class the final arrival rate will be 1.5 times greater than the initial value. 10 runs will be executed with equally spaced (in percentage) intermediate values of arrival rates.

- **Service time:** (for all types of classes) Service Time is the time required by a customer at each visit of a station. In this case, besides the final value and the number of runs to be executed, the station and the customer's class (or all the classes) whose service time will be varied must be specified. Figure 3.34 shows

From (s):	0.2
To (s):	0.4
Steps (n. of exec.):	10
Station:	Server1
Class:	Class1

Figure 3.34: Selection of the final value of service time in a What-If Analysis.

the settings for a What-If Analysis of the service time of class *Class1* at station *Server1*. The service time distribution will not change. Only its average will be modified to span the range defined by the initial value (specified in the **Station Parameters** tab) and the final value specified here in the **To** field.

If the **Change service time of all classes** option is selected, the range of service time to explore is expressed in percentage, starting from the initial value specified at model definition (which is considered as 100%). The station whose service time should be modified must be specified.

- **Seed:** (for all types of classes)

Unlike the previous cases, where the analysis is performed for a range of values of one of the model parameters in order to investigate the system behavior under a variety of conditions, a What-If Analysis on the seed aims at evaluating the sensitivity of the simulation engine to numerical conditions, in particular to the numerical value used by the pseudo-random number algorithm to generate the sequence of numbers, i.e., the seed. The simulation engine uses a pseudo-random number generator to generate the sequence

Steps (n. of exec.):	10
----------------------	----

Figure 3.35: Selection of the number of repeated executions with different seeds in a What-if analysis.

of values used in each execution. By changing the seed, a different sequence of values is produced, thus leading to different numerical results. The first seed is the one defined in the **Simulation Parameters** tab. The number of executions is specified in the panel of Figure 3.35 and the simulation engine generates as many pseudo-random seeds to be used (one for each execution).

3.9 Finite Capacity Region (FCR)

A Finite Capacity Region is a region of the model where the number of customers is controlled. It is possible to define two types of FC region capacity constraints:

- *Shared*: an upper bound for the number of customers that are in the region, regardless of the classes they belongs to.
- *Dedicated*: an upper bound for the number of jobs for a specific customer class in the region

During the simulation the most restrictive constraint is applied. For example consider a multiclass model with two classes (*Class1* and *Class2*) with a shared constraint of 100 customers, a dedicated constraint of 30 customers for *Class1* and no dedicated constraint for *Class2*. If during the simulation the queue contains 30 customers belonging to *Class1* and 60 customers belonging to *Class2*, an incoming job of *Class1* will be rejected (as it's dedicated constraint is violated) while an incoming job of *Class2* will be accepted (as it will not exceed the shared constraint). If the initial state was 20 jobs of *Class1* and 80 jobs of *Class2* an incoming job will always be rejected, despite of its class, as it would violate the shared constraint.

The **utilization** of an FCR is set to 0 since, as a function of the stations allocated inside the region, it may have no meaning.

How to define a FCR:

1. Select the stations to include in the region with the mouse: left-click with the mouse and hold it pressed until all the elements are included. The selected stations are framed with green dashed lines, as shown in Figure 3.36.

2. Select the icon  and the Finite Capacity Region will appear with a blue background, see Figure 3.37.

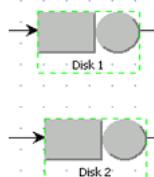


Figure 3.36: Selection of the stations to be included in a FCR.

3. Double click on **FCRegion** to set the properties. The properties panel will appear, Figure 3.38. **Global**

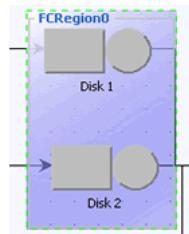


Figure 3.37: The area with the blue background is the FRC.

Properties

Region Name: the name of the region created

Region Capacity: max number of customers that can be in the region. Enable Infinite if you don't want a bound.

Class Specific Properties

In the bottom part of the panel the class specific properties can be defined. Here you can define each class capacity as infinite or as defined, in same way stated above for FCR capacity, and choose the dropping property of the class. **Capacity**: maximum number of customers of that class into the FCR.

Drop: when the FCR is busy, and Drop is "false", the incoming jobs are not dropped but are put into a temporary queue, until the FCR can accept them, otherwise they are dropped from the network.

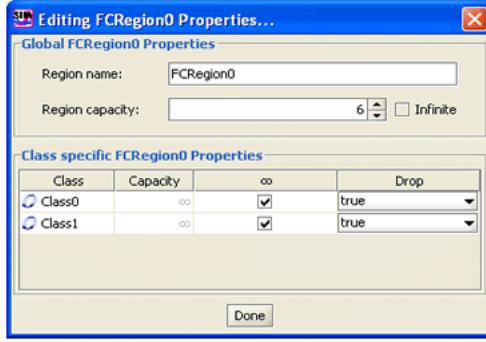


Figure 3.38: Window for the definition of the FCRegion properties.

3.10 Type of Stations

To define a new model select **New** from **File** menu or click the icon and draw the network topology.

Selecting the stations

From the second toolbar (Figure 3.39), select a station and click on the model panel to insert it (drag and drop). The available stations are:



Figure 3.39: The toolbar for the selection of the stations to be inserted in the network.

- Insert a source station
- Insert a sink station
- Insert a routing station
- Insert a delay station
- Insert a queueing station
- Insert a fork node
- Insert a join node
- Insert a logger station
- Insert a class switch station
- Add selected stations to a new Finite Capacity Region

To rotate a component press the button. To optimize the final layout of the network press the button.

Connecting two elements

To link two stations of the model:

1. Select the icon
2. Select and hold the mouse pressed from one station to the other station to which you want to connect to.

3.10.1 Source Station

Setting station properties

Open classes are characterized by an infinite stream of jobs that can enter the system. Source stations are used to generate customers in the model. The interarrival time of the customers of each class should be defined as a parameter of the class. The routing strategy defines the first station a newly created customer will visit. Only open class customers can be routed from source stations. Note that the **Load Dependent routing** cannot be selected in a **Source** station since it has no meaning for this type of station. It is listed among the policies of the **Source** station only for convenience and completeness of the list of the routing policies.

Setting or changing the properties

Double click on the station icon to open the properties panel of Figure 3.40. There is only one section: **Routing Section**.

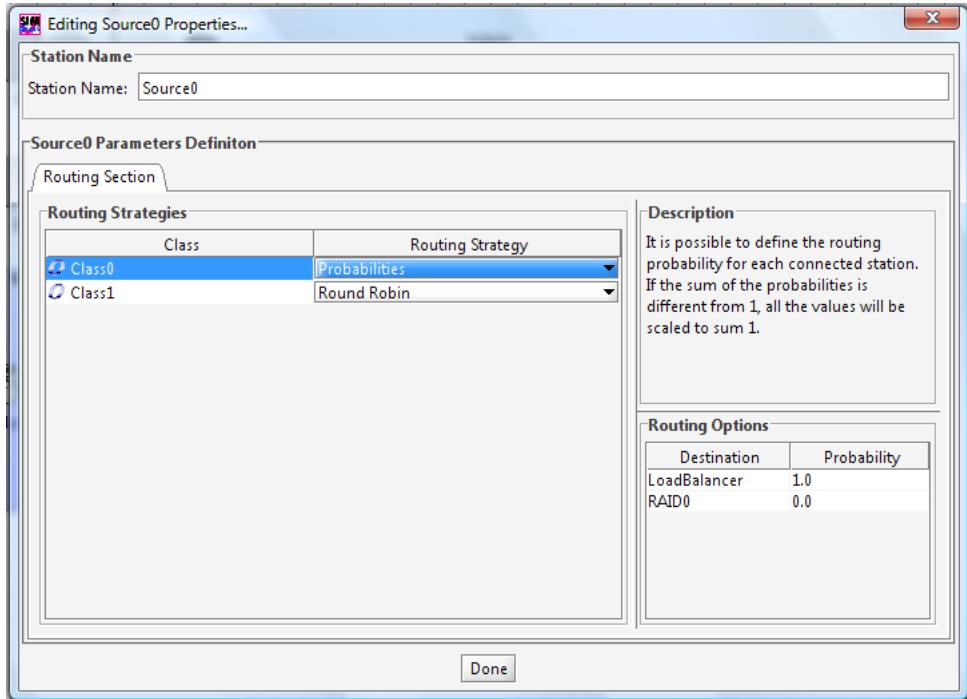


Figure 3.40: Window for the Editing of the properties of a Source station.

Routing Section

In the routing section, for each class, the generated customers are routed to the devices connected to the analyzed station according to various routing strategies. The following algorithms are available :

- **Random:** Customers are routed randomly to one of the stations connected in output to the considered station. The outgoing links are selected with the same probability. Figure 3.41 illustrates the routing strategy with 3 output links. For each link the probability to be selected is $1/3$.

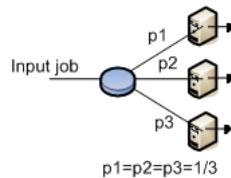


Figure 3.41: Routing with *Random* algorithm.

- **Round Robin:** Customers are cyclically routed to the outgoing links according to a circular routing. As shown in Figure 3.42, the first customer is sent to the top station, the second customer is sent to the central station, and the third customers is sent to the bottom station. The next customers would be sent to the top station again, and so on.

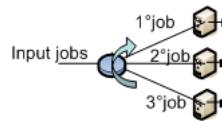


Figure 3.42: Routing with *Round Robin* algorithm.

- **Probabilities:** The routing probability for each outgoing link must be defined. The sum of all probabilities must be equal 1 (Figure 3.43 and Figure 3.44). If the values provided do not satisfy the constraint, JSIM automatically normalizes the values before the simulation starts. The probability for each output link may be set in the panel on the bottom right of the window shown in Figure 3.40.
- **Join the Shortest Queue, JSQ:** (sometimes referred to as *Shortest Queue Length*) Each customer is routed to the station connected in output that has the *smallest* number of customers either in queue and in service at the time the customer leaves the routing station. Figure 3.45 shows a case where the number

Routing Options	
Destination	Probability
Server2	0.2
Server3	0.4
Server4	0.4

Figure 3.43: Definition of the probability of the outgoing links.

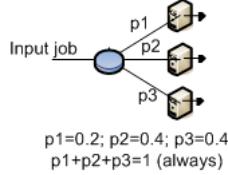


Figure 3.44: Routing according to the *Probability* algorithm.

of customers (in queue and in service) at the devices are 3, 2, and 1 job, respectively, from top to bottom. The exiting customer will be routed to the bottom station, since its queue is the shortest (1 customer).

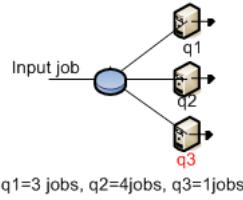
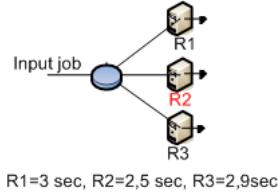
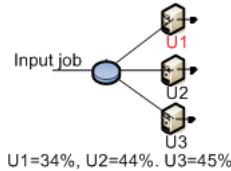


Figure 3.45: Routing according to the *Join the Shortest Queue* algorithm.

- **Shortest Response time:** Customers are sent to the station where the average response time for the job's class is the smallest at the moment a customer leaves the routing station. Figure 3.46 shows that at the time of routing, the middle station has the smallest average response time, R, so the customer will be sent to it.
- **Least Utilization:** The destination station is chosen as the one with the smallest average utilization at the time routing is performed. In the example, shown in Figure 3.47 depicted in the picture, the top station is the least utilized, so it will receive the next customer to leave the blue station.
- **Fastest Service:** A customer is routed to the device with the smallest average service time, S, for the job's class. In Figure 3.48 the exiting customer will be routed to the top station since its service time is the minimum among the three.
- **Load Dependent Routing (cannot be selected in a Source station):** The customers are sent to the destination station according to both the *probabilities* defined by users *and* the *load* of the source station (i.e., the station that we are considering). The routing decisions are made independently for each class. The *load dependent* routing probabilities must be described for *all the classes* by the users. Fig.3.49 shows the selection of the Load Dependent Routing policy for the *Class1* customers. The definition of the routing probabilities of the station *Queue 1* for *Class1* customers is shown in Fig.3.50. When the number N_{Q1} of *Class1* customers in station *Queue1* is $1 \leq N_{Q1} \leq 4$ the *Class1* customers are routed to station *Queue 2* with probability 0.1 and to station *Queue 3* with probability 0.9. When the number N_{Q1} of *Class1* customers in station *Queue1* is $5 \leq N_{Q1} \leq 9$ they are routed with the same probability 0.5 to *Queue2* and *Queue3*. When their number in station *Queue1* is $N_{Q1} \geq 10$ they are routed to station *Queue 2* with probability 0.8 and to station *Queue 3* with probability 0.2.

3.10.2 Sink Station

Open class customers leave the system once they have received all the services they need. Sink stations are used to model customers leaving the system, as they enter the sink station but do not ever leave it. Sink stations have no parameters, only incoming connections from one or more stations, depending upon the model.

Figure 3.46: Routing according to the *Shortest Response Time* algorithm.Figure 3.47: Routing according to the *Least Utilization* algorithm.

3.10.3 Queueing Station

The *Queueing Station* is one of the most important components in a queueing network model. A queueing station consists of two main components: a *queue* and a *server* (one or more) to execute the requests. If all the servers of the station are busy when a new customer arrives at the station, the arriving customer joins the queue and waits its turn to receive service from the first idle server. The queueing discipline determine which customer is served next when a server becomes free. The response time at queueing stations includes service time and queueing time. Queueing stations may have more than one server, their number is a parameter to be specified (*default* is 1). It is important to point out that the *utilization* U of a queueing station with a *single server* (i.e., the fraction of time in which the server is busy) is given by $U = \lambda S$, and in a station with m servers the utilization of *any* individual server is given by $U = \lambda S/m$.

Set or change of the properties

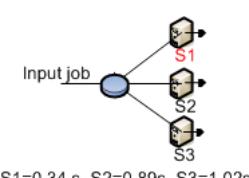
Double click on the Queueing Station icon and the **Editing Server Properties** window will open (see Figure 3.52).

Station name is the name of the station that the user like to assign. There are three tabs: **Queue Section**, **Service Section** and **Routing Section**.

Queue Section

The Queue section allows the specification of the queue *capacity* (finite or infinite) and scheduling *policy*. Different classes of customers may have different scheduling policies associated with them.

- **Capacity:** a station can accept any customer number and let them wait in queue, in which case its capacity is considered infinite, or it can only accept a finite number of customers. In this case its capacity is finite, the max number of customers is to be specified in the field **length**.
- **Queue policy:** it is the algorithm used to decide which customer to serve next. A variety of factors can contribute to the order in which customers are served, such as arrival order, priorities associated with a class, the amount of service already provided to customers, etc. The scheduling disciplines are grouped into three categories: **Non-preemptive**, **Non-preemptive with Priority**, and **Processor Sharing**. The **Non-preemptive** disciplines available are (see Figure 3.52):
 - **FCFS:** Customers are served with the same sequence in which they arrive at the station. If the model is exported to MVA, the following constraint is enforced in the exported model because the MVA analytical algorithm (see the BCMP theorem in [BCMP75]) requires in a multiple class environment

Figure 3.48: Routing according to the *Fastest Service* algorithm.

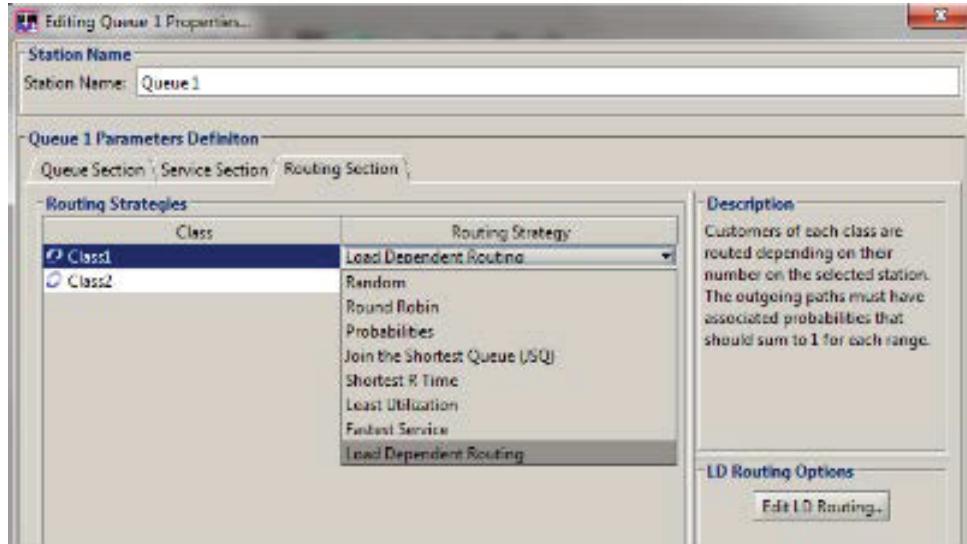


Figure 3.49: Selection of the Load Dependent Routing for *Class1* customers.

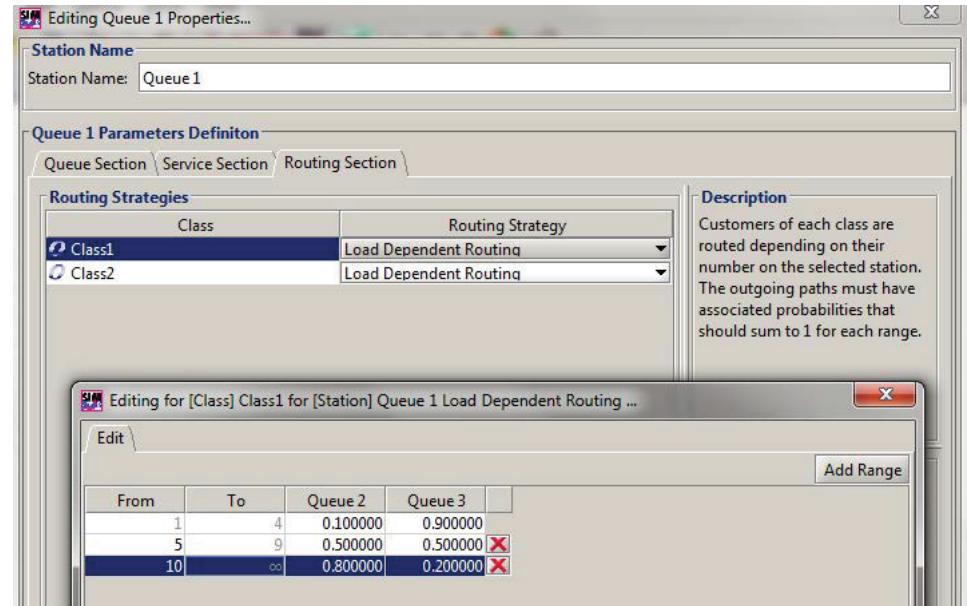


Figure 3.50: LD Routing: definition of the routing probabilities for *Class1* customers.

the customers of all the classes must have the same average service time $S_{c,k}$ at a FCFS queue station. In order to take care of the differences among the service requirements of the different classes, the total number of visits to the station per each class $V_{c,k}$ is adjusted in order to obtain the correct values of service demands $D_{c,k}$. If a user is interested only in simulation (with JSIMgraph or JSIMwiz) no constraint is imposed on the parameters regarding service times, visits, and service demands.

- **FCFS(Priority):** Customers are ordered according to their arrival time but customers with higher priority jump ahead of customers with lower priority (a *small* priority number means low priority). Customers with the same priority are served FCFS.
- **LCFS:** An arriving job jumps ahead of the queue and will be served first. The LCFS discipline implemented in JSIM is not of the preemptive-resume type.

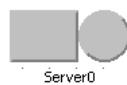


Figure 3.51: The Queueing Station icon.

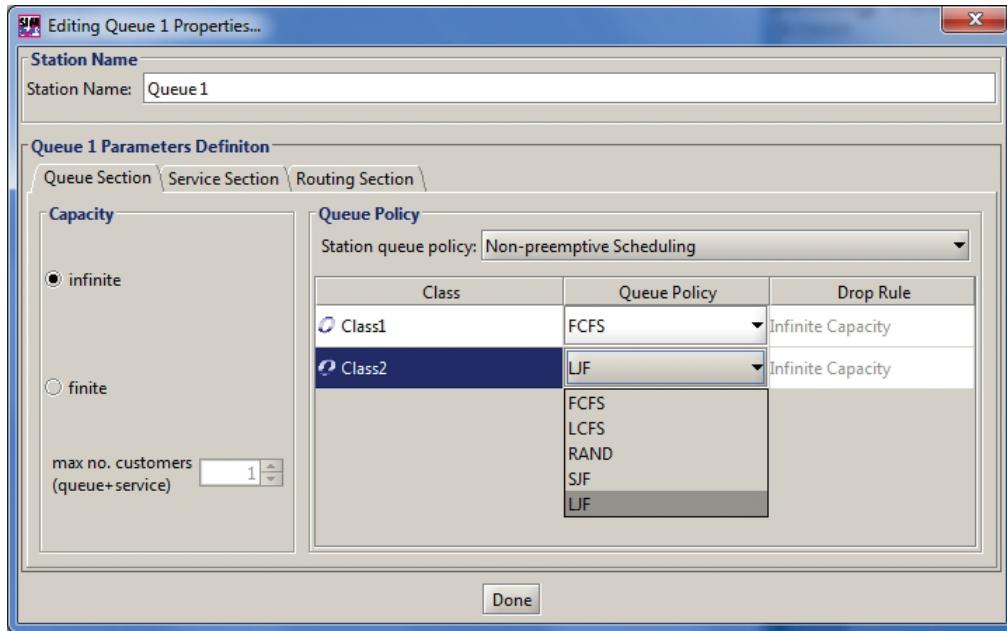


Figure 3.52: Window for editing the Queueing Station properties.



Figure 3.53: Window for the editing of the Fork properties.

- **LCFS(Priority):** The next customer to be served is one with the highest priority (conventionally a *small* priority number means low priority), so an arriving customer can only jump ahead of the queue of the other customers with equal or smaller priority. Customers with the same priority are served LCFS.
- **RAND:** An arriving customer join the queue the queue in a random position and will be served in a random order (*with or without priority* among classes of jobs).
- **SJF (Shortest Job First):** The customer in queue with the *smallest* service time is the first to be executed (*with or without priority* among classes of jobs).
- **LJF (Longest Job First):** The customer in queue with the *longest* service time is the first to be executed (*with or without priority* among classes of jobs).

The Processor Sharing discipline operates as follows:

- **Processor Sharing (PS):** the server works as all the customers in the station are processed simultaneously, but devotes to each of them a fraction of its total capacity that is *inversely* proportional to the number of customers. It can be seen as a RR scheduling with a *quantum size* zero so that the control of the server circulates infinitely rapidly among all the customers. If the station has *multiple servers* (greater than 1), when there are more customers in execution than servers, each

server splits its capacity equally across the customers. In the other case, the capacity of a server is completely allocated to the customer it has to execute, so its service time is the same as with FCFS, for example. Thus, it will never happen that a customer is executed with a service time less than the time it requires as if it is alone in the station.

Service Section

The service time distribution and the number of servers (*default* is 1) should be defined. The load *dependent*, *independent* or *zero service time* characteristic of the service times must be specified for each class of customers through the menus of Figure 3.54 and Figure 3.55.

Please refer to *Service Section* of subsection 3.10.4 *Delay Station*.

Routing Section

In the routing section, for each class of customers, you can decide the path followed by the completed jobs are routed to the devices connected to station for which the routing strategy is defined. For each class, the user should select the algorithm you want to use in order to determine the outgoing connection followed by a customer. The following algorithms are available:

- Random
- Round Robin
- Probabilities
- Join the Shortest Queue - JSQ
- Shortest Response Time
- Least Utilization
- Fastest Service
- Load Dependent routing.

To know details about these algorithms, please refer to the *Routing Section* of subsection 3.10.1-*Source Station*.

3.10.4 Delay Station

Customers that arrive at this station are delayed for the amount of time that defines the station service time. They do not experience any queuing, since a delay station is modelled as a station with an infinite number of servers with the same service time. Thus response time of delay stations is equal to the service time, $R_i = S_i$. Furthermore, the queue length corresponds in this case to the number of customers receiving service since there is no waiting: $N_i = R_i X_i = S_i X_i = U_i$. In *delay stations*, for consistency with Little's law, the *utilization* is computed as the *average number of customers* in the station, and thus it may be *greater than 1*!

Delay stations are used when it is necessary to produce some known average delay. Application of delay stations may be to model transmission time (download, upload, ...) of large amounts of data over a network (Internet, lans, ...) or to model users think time at the browsers.

Setting or changing the properties

Double click on the icon representing the delay station to see the property panel.

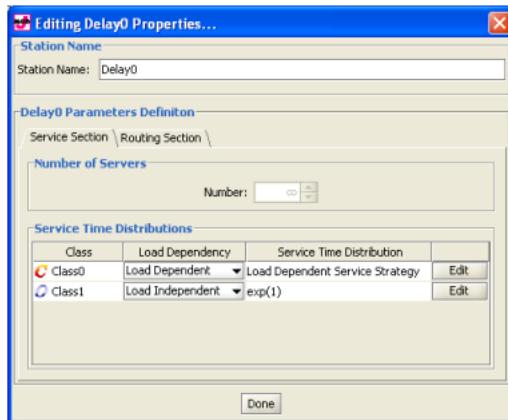


Figure 3.54: Windows for the editing of *delay properties*.

Service Section

Delay stations are infinite servers with the same service time characteristics; the service time distribution should be defined. The infinite numbers of servers provide the same average response time for all jobs, as no job waits in queue for service. The load *dependent* or *independent* characteristic of the service time must be specified for each class of customers through the menus of Figure 3.54 and Figure 3.55.



Figure 3.55: Selecting load dependency.

- **Load Independent:** A load independent service indicates that, regardless of the number of customers that are in the station, the system will serve all the customers following a fixed policy modelled by the chosen statistical distribution. To choose the Distribution press the **Edit** button and insert all the parameters from the window of Figure 3.56.

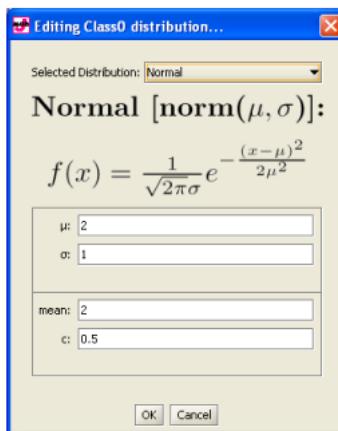


Figure 3.56: Editing of the parameters of a distribution.

The following service time distributions (see section 3.5) are supported: *Burst (General)*, *Constant*, *Erlang*, *Exponential*, *Gamma*, *Hyperexponential*, *Normal*, *Pareto*, *Poisson*, *Student-T*, *Uniform*.

- **Load Dependent:** A load dependent service time indicates that the amount of time the server spends with each customer depends upon the current number of customers in the station. A set of intervals for the number of jobs in the station is specified, either by adding one range at a time via the **Add Range** button or by specifying the total number at once. For each range its lower (**From** button) value must be specified. Automatically its upper value (**To** field) is computed. Each range of values can be associated with different service times, distribution, mean and coefficient of variation, or a subset of them. To set the parameters of a Load Dependent service time, click the **Edit** button to edit the Service Time Distribution. The panel of Figure 3.57 appears, then specify the parameters for each range.

For each range of the number of customers the following parameters must be described:

- * **Distribution:** you can choose among *Burst (General)*, *Burst (MMPP2)*, *Pareto*, *Erlang*, *Exponential*, *Hyperexponential*, *Poisson*, *Uniform*, *Constant*, *Gamma* and *Normal* distribution.
- * **Mean:** the mean value of each distribution is specified in the "Mean" form by double clicking on it. Insert a number or an arithmetic expression that will be evaluated with JFEP - Java Fast Expression Parser. For a complete list of the command supported by JFEP you can read the **Help** tab or see the JFEP web site at <http://jfep.sourceforge.net/>
- * **c:** The coefficient of variation of each distribution (when *c* exists) can be specified by double clicking on the *c* form. For example, in Figure 3.57 two distributions are defined: when there is only one customer in the station the service times are generated according to an Erlang distribution with *mean=1* and *c=0.5*. For any number of customers greater than 1 in the station, the service times are generated according to an Hyperexponential distribution with *mean=1* and *c = 1.19*.

To delete a range click on the *delete* icon at the end of the correspondent row.

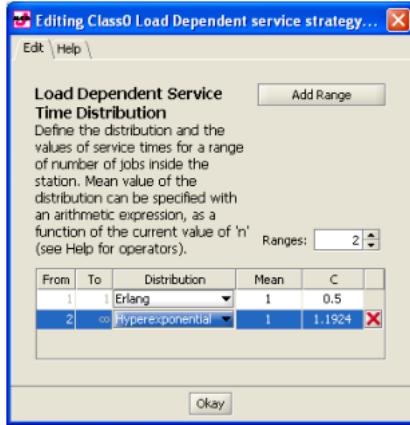


Figure 3.57: Window for editing a load dependent service strategy.

- **Zero Service Time:** A Zero Service Time strategy is used to model stations having negligible (or null) service time. A station with zero service time may have a queue if the output customers are routed to a station with a BAS blocking scheduler.

Routing Section

In the routing section, for every class defined, you can decide how the completed jobs are routed to the other devices connected to station for which the routing strategy is defined. For each class, the user should



Figure 3.58: Selecting the Routing Strategy.

select the algorithm you want to use for outgoing connections. The following algorithms are available:

- Random
- Round Robin
- Probabilities
- Join the Shortest Queue
- Shortest Response time
- Least Utilization
- Fastest Service
- Load Dependent routing.

To know details about these algorithms, please refer to subsection 3.10.1 of *Source Station*.

3.10.5 Fork Station

A Fork station is a station where jobs are split into tasks. No service is provided; therefore there is no service time specification. Tasks are then routed along the Fork station outgoing links (see Figure 3.59).

Unlike classical queueing theory fork-join queues, a JSIM Fork station is not associated with a join

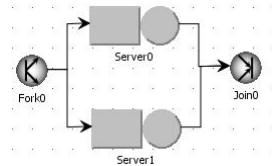


Figure 3.59: The Fork and Join stations.

station automatically. Any combination of queueing stations, Finite Capacity Regions, fork-join, routing stations, loggers, etc., is possible after a Fork station. This feature allows the modelling of very general parallel behaviors, of which the traditional Fork-Join one is a special case. In JSIM the classical queueing theory fork-join queue behavior is obtained by connecting the Fork station to as many queueing stations as the degree of parallelism requested, with one task per outgoing link. Each queueing station is then

connected to a Join station, where the job is recomposed.

A Fork station is characterized by the *forking degree*, i.e., the number of tasks routed on each one of its outgoing links, and the *capacity*, i.e., the maximum number of jobs that can be served by the station simultaneously. Therefore, the number of *sibling tasks* a job is split into is given by the product of the number of outgoing links from the Fork station times the forking degree. Note that a finite station capacity makes sense only when there is a Join station downstream from the Fork station that can recompose the split jobs. Otherwise, inconsistencies in the model and subsequent simulation error, such as out-of-memory, may occur. No automatic checks to identify such critical conditions have been implemented since it may happen that users are required to simulate special conditions purposely. Both the forking degree and the capacity are section parameters to be specified in the model. As an example, a Fork station with forking degree 1, connected to three queueing stations, would split a job into 3 sibling tasks (this is a traditional Fork-Join like behavior). If no Join station is connected to any of the three Servers, a warning message is displayed since the model could quickly saturate due to the extra load (3 more customers) created in addition to each job entering the Fork station.

Set or change of properties

The station has two sections: **Fork Section** and **Queue Section**.

Fork Section: In this section the user can define the station *forking degree*, i.e., the number of tasks created for each job arriving at the fork station, and its *capacity*, i.e., the maximum number of jobs that can be in a fork-join section (when a join is present):

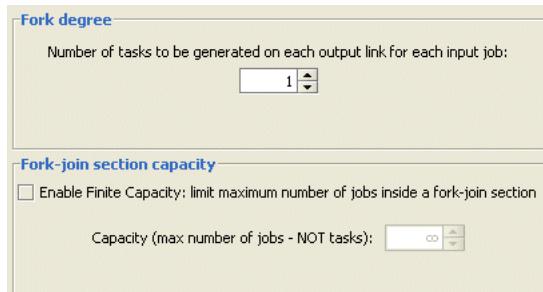


Figure 3.60: Setting of the Fork degree and the Fork capacity.

- **Forking degree:** It is the number of tasks that are routed on each outgoing link of the fork station. Therefore, each customer is split into $(\text{forking degree}) \times (\text{number of outgoing links})$ tasks. By default the forking degree is 1, it can be modified as shown in Figure 3.60.
- **Capacity:** It is the maximum number of customers (jobs) that can be served by a Fork-Join section simultaneously. It makes sense only if there is a Join station matching the Fork one. It can be *finite*, in this case when the limit is reached the jobs wait in the queue of the Fork station. A job is removed from the queue and serviced (i.e., split into tasks) when a job is recomposed at the matching Join station and leaves it. Capacity is defined using the form shown in Figure 3.53, after checking the **Finite capacity...** box.

Queue Section

Please refer to *Queue Section* of subsection 3.10.3 *Queueing Station*

- **Drop Rule:** it is not active when infinite capacity is selected. For each class you can select a rule to apply when a customer cannot enter a station since the max number of customers allowed is reached.

3.10.6 Join Station

Join stations are complementary to fork stations (see Figure 3.59). In classical queueing network theory, a task arrives at a join station from the corresponding Fork station.

In JSIM, a Join station may have incoming links from stations other than the corresponding Fork one. A *Join* station has *no service time*, as it is only used to recombine the tasks a job had been previously split into and then route the job to some other station(s). When a task arrives at a join station, it waits until all its sibling tasks have arrived. At this time, the original job is recomposed and routed to the next station. If a job arrives from a station other than the corresponding Fork, i.e., a job that was not split, it is simply routed to

the next station. In this case the Join station operates as a routing station

Set or change of properties

It has only the Routing section.

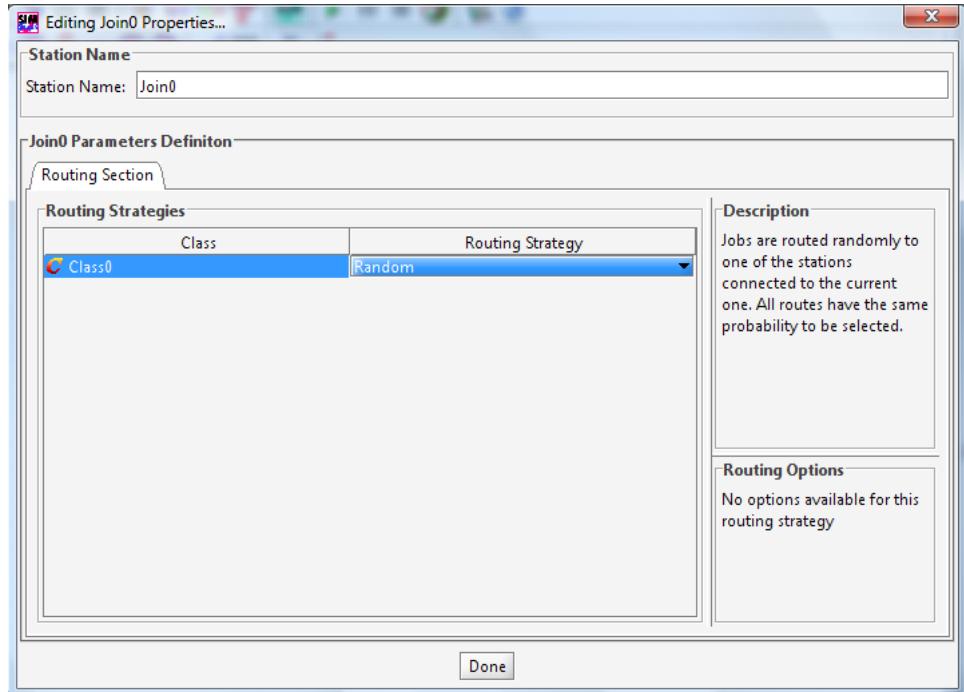


Figure 3.61: Editing of the Routing Strategy.

Routing Section:

In the routing section, for each class defined, you can decide how the completed jobs are routed to the other devices connected to the station for which the routing strategy is defined. For each class, the user should select the algorithm applied to determine the path followed by the outgoing customers. The following algorithms are available:

- Random
- Round Robin
- Probabilities
- Join the Shortest Queue JSQ
- Shortest Response time
- Least Utilization
- Fastest Service
- Load dependent routing.

To know details about these algorithms, please refer to the subsection 3.10.1 *Source Station*.

3.10.7 Routing Station

A *routing* station is a dummy station, with service time equal 0, which is used to create more sophisticated routing strategies by sending customers through one or more such stations. For example, if we want that two thirds of the incoming traffic at station Z to be randomly routed to either station A or B or the remaining third to go either to station C or D, depending on the shortest queue at the two stations, we could implement the following. Add a routing station, Y, to the output of Z station and define random routing for the three stations connected in output (namely, A, B, Y). Then connect Y to C and D and define shortest queue routing JSQ for C and D.

Set or change of properties

With a double click on the routing station icon, the Editing Routing Station Properties window is shown (see Figure 3.61). It has only one tab Routing Section.



Figure 3.62: The Routing Station.

Routing Section:

In the routing section, for each class, you can decide how the completed jobs are routed to the other devices connected to the considered station. For each class, the user should select the algorithm applied to determine the path followed by the outgoing customers. The following algorithms are available:

- Random
- Round Robin
- Probabilities
- Join the Shortest Queue JSQ
- Shortest Response time
- Least Utilization
- Fastest Service
- Load Dependent routing.

To know details about these algorithms, please refer to the subsection 3.10.1 *Source Station*.

3.10.8 Logger station

A logging station (i.e., *logger*) reads information flowing through it and writes it to a file. In the simplest way, it is a tool to understand and debug the traffic flow moving through the interesting part(s) of the model. Place the logger station into the model, choose the parameters, and trace the data as it passes through the model.

Set or change of the properties

Double click on the Logger Station icon  to open the Editing Logger Properties station's configuration dialog (see Figure 4.3). There are two sections: **Logger Section** and **Routing Section**.

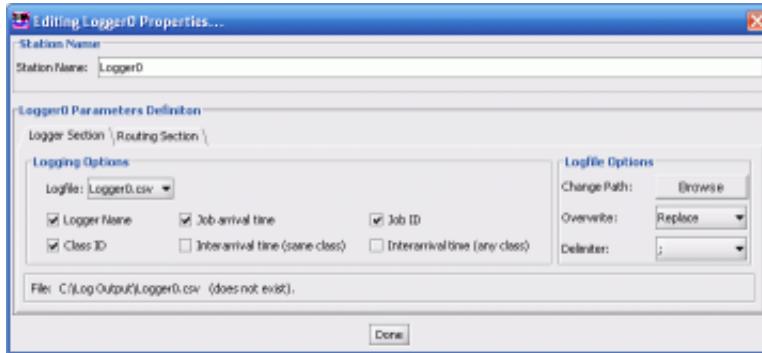


Figure 3.63: Window for the Logger Station configuration.

Logger Section

The configuration properties of the **Logger Section** are:

- **Logging Options:**

- The Logfile's name to use, either individual or merged (Logger0.csv or global.csv, respectively).
- The information to log (fields): Logger Name, Job Arrival Time (simulation units), unique Job ID, defined Class ID, Interarrival time of same class, Interarrival time of any class. These fields are found in the next section.

- **LogFile Options:**

- Browse button: allows changing the directory where logfiles are stored.
- Overwrite method to use when the logfile exists, and a new simulation needs to overwrite the file. Replace overwrites the file, append adds data to the end of the file.

- Delimiter chooses the character to separate between.
- **Status** displays the path and file-status of the logfile that is going to be written.

As messages flow through the Logger from one station to another, the following information can be logged:

- **Logger Name**, the name of the logger where the message occurred (e.g., *Logger0*)
- **Job arrival time**, this timestamp marks the current simulation time from start of simulation (not seconds)
- **Job ID**, the auto-generated unique sequence number of the message (e.g. 1,2,3...).
- **Class ID**, the name of *customer class* of message (e.g., *Class0*)
- **Interarrival time (same class)**, is a time difference between customer of the same class that passes through the logger
- **Interarrival time (any class)**, is a time difference between customers of any class that passes through the logger.

Once a *Logger* is configured, running a simulation produces a logfile with the chosen fields. An example of logfile output is:

```
LOGGERNAME;TIMESTAMP;JOBID;JOBCLASS;TIMEELAPSED_SAMECLASS; TIMEELAPSED_ANYCLASS
Logger0;0.199;1;Class0;0.000;0.199
Logger0;0.559;2;Class0;0.341;0.341
```

Routing Section

For each class of customers, the user should select the algorithm that want to apply in order to determine the outgoing connection (i.e., the routing strategy) followed by a customer that completed its service in the current station. The following algorithms are available:

- Random
- Round Robin
- Probabilities
- Join the Shortest Queue - JSQ
- Shortest Response Time
- Least Utilization
- Fastest Service
- Load Dependent routing.

To know details about these algorithms, please refer to the **Routing Section** of subsection 3.10.1-*Source Station*.

3.10.9 Class-switch station

A **Class Switch** station allows the definition of models where jobs may change *class*, i.e., *service requests*, during their execution. The switch of the jobs between the classes is defined by the *class-switch probability matrix*, referred to as **C**. Let $R = (1, \dots, r)$ be the set of the classes of the model, then **C** is a $r \times r$ square matrix. The element $c_{i,j}$, $i, j \leq r$, is the probability that a job entering the **Class Switch** station in class i exit the station in class j .

In Fig. 3.64 it is shown an example of a open model with a three-class workload (A,B,C), two **Class Switch** stations, and three **Delay** stations. Jobs are generated by **Source 1** in *class A* and receive service from station **Delay1**. Then, after being served, it changes class from *A* to *B* in **Class Switch A->B** station (see the matrix of Fig. 3.66) and receive service in **Delay2** station. Then, after being served, it changes again class from *B* to *C* in **Class Switch B->C** station and exit the model in *class C*.

Let us remark that when this type of station is included in a model, a **new** class of jobs may be *generated* not only from a **Source** station (or in the initial population vector in the case of a closed model) but **also** in a **Class Switch** station. This is the case of *classes B* and *C* of the example. For this type of classes, a **Class Switch** station *must be selected* as **Reference Station** and it is *not allowed* to define their generation process since it depends on the arrival patterns from the other stations (see Fig. 3.65). In the model of Fig. 3.64, the throughput of the system consists *only* of *Class C* jobs in spite that *only Class A* jobs are arriving at the model generated from **Source1**.

In the last section (*Definition of the context and Implementation issues*) the topic of *class switch* is addressed in more detail by analyzing some problems of context definition and some implementation issues.

Set or change the class-switch parameters

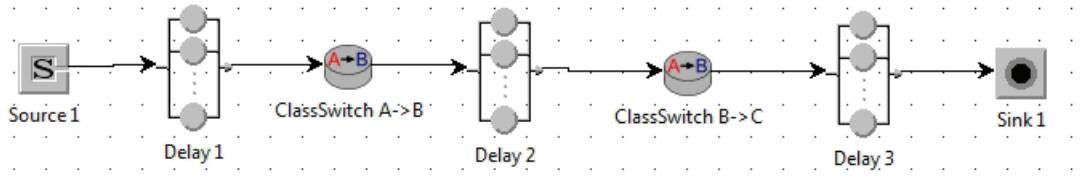


Figure 3.64: Example of an open model with two Class Switch stations.

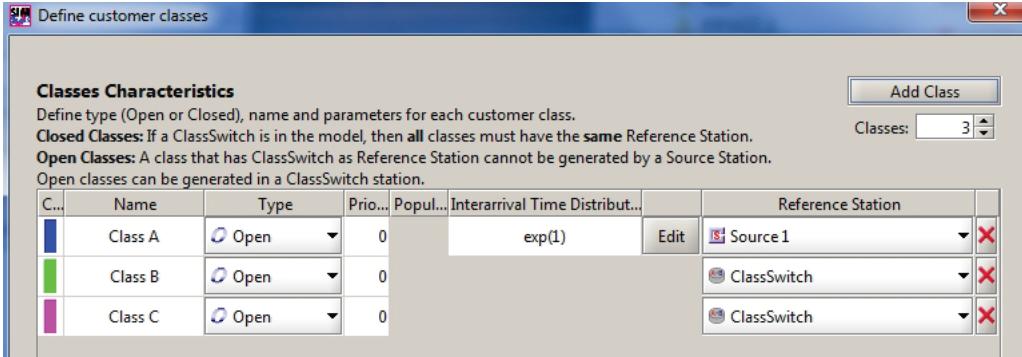


Figure 3.65: Example of the definition of the three-class workload of Fig.3.64, with one class (Class A) arriving from Source 1 station and two classes, Class B and Class C, generated by Class Switch stations.

Double click on the Class-switch icon to open the **Editing Class-Switch Properties** station's configuration dialog (see Fig. 3.66). There are two tabs: **Class-Switch Matrix** and **Routing Section**.

Class-Switch Matrix

In this section the probabilities of class-switch of the jobs must be described in matrix **C**. Each element of the matrix represents either normalized or absolute values (e.g., number of visits), the sum of each row is constrained to be greater or equal than 1. A *warning* message is given when the sum of the values is greater than 1. An *error* message is prompted when the sum is less than 1, and the simulation does not start (see Fig. 3.67).

Routing Section

For each class of customers, the user should select the algorithm that want to apply in order to determine the outgoing connection (i.e., the routing strategy) followed by a customer that completed its service in the current station. The following algorithms are available:

- Random
- Round Robin
- Probabilities
- Join the Shortest Queue - JSQ
- Shortest Response Time
- Least Utilization
- Fastest Service
- Load Dependent routing.

To know details about these algorithms, please refer to the **Routing Section** of subsection 3.10.1-*Source Station*.

Limitations when using Class-Switch

Several *restrictions* are introduced in the models that comprise one or more Class Switch stations.

- **per class System Throughput:** this index is NOT computed since it may be that one or more classes never exit a model due to the combined actions of the Class Switch stations and the Routing policies (see the classes A and B of Fig. 3.64). Also, it may happens that in a model at the equilibrium the mix of classes in input to the system is not the same as the one in output;

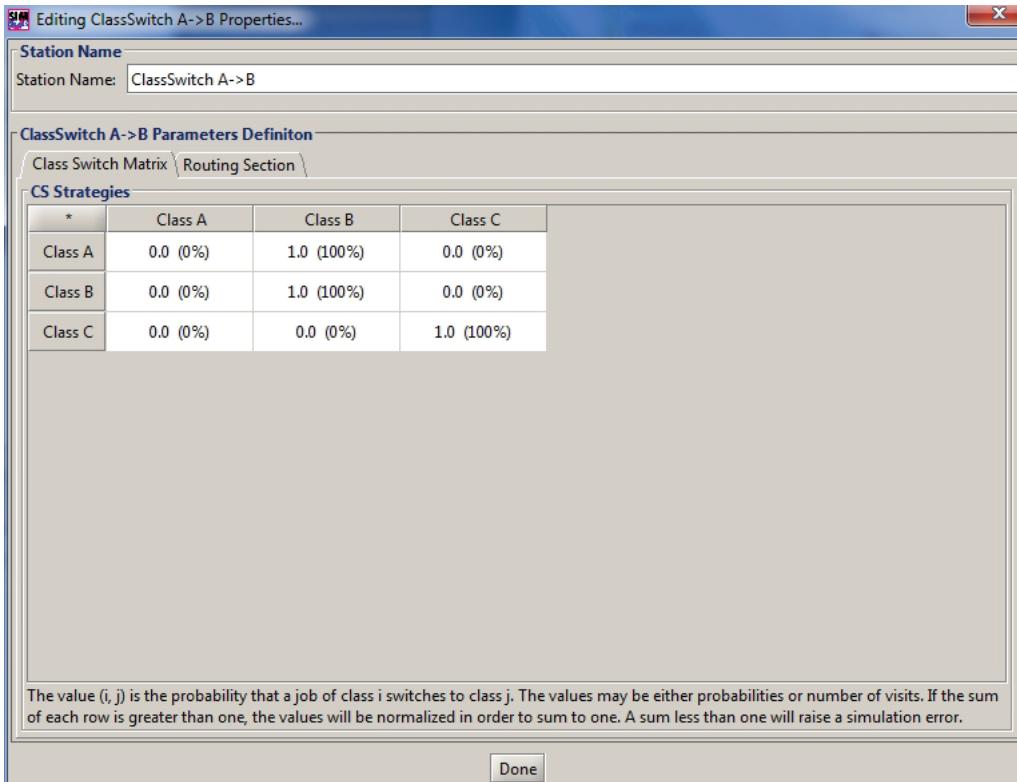


Figure 3.66: Window of the **Class-switch A->B** station for the definition of the transition matrix elements, i.e., of the probabilities of switch between classes, of the model of Fig.3.64.

- a *new class* may be generated ALSO in a **Class Switch** station. In this case, a **Class Switch** station must be defined as **Reference Station** and IT IS NOT *allowed* to define an *interarrival* process for its jobs;
- it is NOT POSSIBLE to have a switch of jobs between an *open class* and a *closed class*, and viceversa;
- FOR THE RELEASE 0.9.2: it is not possible to have models with **Class Switch** and **Fork/Join** or **Finite Capacity Region** stations. Sorry!

Definition of the context and Implementation issues of the Class-switch

Models with class switch are very powerful in terms of representativeness, but it must be used very carefully because of the new problems that arise over the traditional models that we are used to.

In what follows we will consider only open models as for them the effects of class switch can be described more intuitively than for the closed ones. However, the validity of the concepts introduced can be easily extended to closed models also. In this case, it is simply required to replace the **Source** station with the **Reference** station and the **arrival process** with the **initial population mix** of the model.

First of all, the *concept of equilibrium* in models with class switch is valid only at the *system level*, and not at the class level. In other words, Little law can be applied only to the level of the *overall system* and not to single

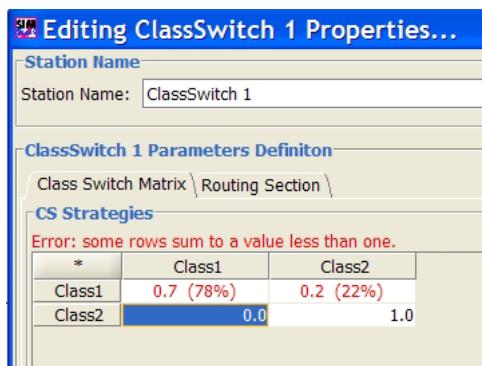


Figure 3.67: Error message prompted by the control of the switching probabilities of **Class1** that sum to a value < 1.

class level. Indeed, the population mix of the jobs in the various classes may vary after a class switch station where jobs change class, new classes may be generated or existing classes may disappear. Thus, it may happens that the classes that exit the model are different from the ones that arrive to the model (see e.g., Fig.3.64) violating the basic concept of equilibrium.

Let us remind the difference between the **Service Times** S and the total **Service Demands** D of a job, since they have a direct impact on the difference between **Response Times** (Rp) and **Residence Times** (Rd) of jobs. The **Service time** S_r is the average time that resource r requires to execute a request (i.e., is the mean service time required by *one visit* to that resource). The **Service Demand** D_r of a job at resource r is the *total* service time required to that resource during its complete execution. D_r is given by $V_r S_r$ where V_r is the mean number of visits that a job makes to that resource, also referred to as *visit count*, during its complete execution.

In *single class* models, the **Response Time** Rp_r of a resource r is the mean time required from (*one*) visit to resource r (queue time + execution time). The **Residence Time** Rd_r of a job at resource r is the *global time* spent by the job on that resource during its complete execution. While the metric **Response Time** Rp_r is *local* to a resource (i.e., it may be computed considering *only* variables related to the resource considered: queue time and service time), to derive the **Residence Time** Rd_r of a resource it is necessary to know the behavior of a job through *all* the resources during its complete execution (i.e., the *visit ratio* or *visit count*, to all resources). In *multiclass* models also the **Response Time** Rp_r of a resource r becomes a *global* metric. Indeed, with a workload consisting of C *classes* of jobs, the Rp_r is given by:

$$Rp_r = \sum_{c=1}^C Rp_r^c \frac{X_c^{Sys}}{X_{tot}^{Sys}} \quad (3.1)$$

where Rp_r^c is the **Response Time** of the resource r for the jobs of class c , X_c^{Sys} is the throughput of the system of jobs of class c , and X_{tot}^{Sys} is the global **System Throughput**.

The dependence of Rp_r from the per-class throughput makes it unfeasible to apply eq.3.1 for its computation since with class switch the *per-class* system throughput *cannot be defined precisely*.

IMPLEMENTATION ISSUES

Three COUNTERS are used by JSIM to measure the **System Response Time**, the **System Throughput**, and the **per-class System Response Time**.

The global **System Response Time** Rp^{Sys} is obtained accumulating in a counter the time that all jobs spent in the system during a complete execution and dividing this value by the number of jobs completed (independently from their class). The value obtained is *correct* and is independent of the class of the jobs since the execution time is collected for *all* the jobs completed.

Similarly, the global **System Throughput** is obtained by collecting the global number of jobs executed (that exit the model) and dividing its value by the global simulation time. As already pointed out, the **per-class Throughput** cannot be computed in the same way since a job may change class during its execution.

To avoid an excessive overload of the memory and of the processing time, 64 bits are associated to the internal data structure of each job. One bit is associated to each class assumed by a job during its execution (thus, 64 is the max number of classes that a job can assume during a complete execution). For each job we keep track *only* of the classes assumed during its complete execution, but NOT of the *sequence* of the classes assumed. This decision has some *positive* aspects related to the size of the memory required to store the traces of the executed jobs (that can be even several millions), and some *negative* aspects due to the limitations of the metrics that can be measured. For each class there is a *counter* that keeps track of the number of jobs that assumed that class during their execution. So, for the same *single* job it may be that *several* counters will be incremented, as a function of all the classes assumed during its execution. For this motivation, these counters are used *only* to compute the **per-class System Response Time** and NOT the throughput.

To count the jobs in the model, for each class there are *two counters*: one in the **Reference Station** (in open models the **Source** is assumed as **Reference Station**, in closed models any station can be a **Reference Station**) and one in the **Class switch** stations. The sum of the jobs of a class that flow out by these two station types represents the *global number of jobs* that *entered* an open model, or that *are* in a closed model. In eq.3.2 we will refer to these jobs as *Generated*.

To compute the **System Response Time** of class A jobs, i.e., the total time spent in the system by a *class A* job during its complete execution (mean value), we need to sum the **Residence Times** of class A jobs for each resource. And, to compute the latter index we need to know the number of times that class A jobs visit each station. Let us remark again that with **ClassSwitch**, a job may be generated *inside* the model and thus it may not visit the *same set* of stations that jobs of the same class have already visited.

To compute the correct number of *visits* that a class A job perform to station r we will compute for each station

the following *Visit Ratio*:

$$\text{Visit Ratio}_A^r = \frac{V_A^r}{\text{Generated } A} \quad (3.2)$$

where V_A^r is the total number of visits of class A jobs (*all* the class A jobs!) that have gone through station r (collected in a counter) and *Generated A* is the total number of class A that have been generated in the model according to the above definition (by Source + Class Switch stations). Then, the **Residence Time** of *class A* at station r will be given by:

$$\text{Residence Time}_A^r = \text{Response Time}_A^r * \text{Visit Ratio}_A^r \quad (3.3)$$

where the **Response Time** $_A^r$ is the mean time required by one visit from a class A job to station r . The sum of the values given by eq.3.3 for *all* the classes and *all* the stations is the **System Response Time**:

$$\text{System Response Time} = \sum_{r \in \text{stations}} \sum_{A \in \text{classes}} \text{Residence Time}_A^r \quad (3.4)$$

This value must coincide with the one measured by JSIM summing in a counter the **system response time** of all the jobs executed and dividing the result by their number.

3.11 Modification of the Parameters

3.11.1 Modifying Simulation Parameters

To modify the simulation or initial state parameters , the user has to select **Simulation Parameters** (icon ) from the **Define** menu and change the values. From **Simulation Parameters** the user can:

1. change the *Initial state*, i.e., the location of the customers at the beginning of the simulation
2. change or confirm the *seed* of the random number algorithm in order to have different run of the simulation
3. change the maximum number of *samples*
4. change the time interval used in the graphical representation of the indices
5. change or confirm the maximum *duration* of the simulation.

For more details about these parameters see the Section **Simulation Parameters** of subsection 3.11.3.

3.11.2 Modifying station parameters

To modify the parameters of a station select the icon  and double click on the station to modify. The properties panel of a station will be opened and the modifications could be applied.

To see a complete list of properties of each station see section 3.10 *Defining Network Topology*.

3.11.3 Modifying the default values of parameters

The simulator default settings for *Class*, *Station*, *Simulation*, and *Finite Capacity Region* parameters can be changed from the **Define** menu in the menu bar. At first the user need to select **Default parameters** from the **Define** menu. Alternatively, the user can select the  (Define default values of model parameters) button. In JSIMgraph all the parameters have default values. Such values can be changed to suit the user's most common modelling activities. The default values of *Class*, *Station*, *Simulation*, *Finite Capacity Region* (*FCR*) and their possible modifications are described in the following sections.

Class Parameters

These settings define the default values of class parameters assigned to a new class (see Figure 3.69).

- **Name:** The default name for each newly created class of customers is "Class", followed by a progressive integer, starting from 1, indicating how many classes you have created so far. It can be set to any alphanumerical string, which automatically will be followed by the same numbering scheme.
- **Type:** The default class type is "Closed". If open classes are used more often, you may want to change to Open as default, so as to minimize the type changes in the class definition section.
- **Priority:** The default class priority is 0. Higher numbers correspond to higher priority.

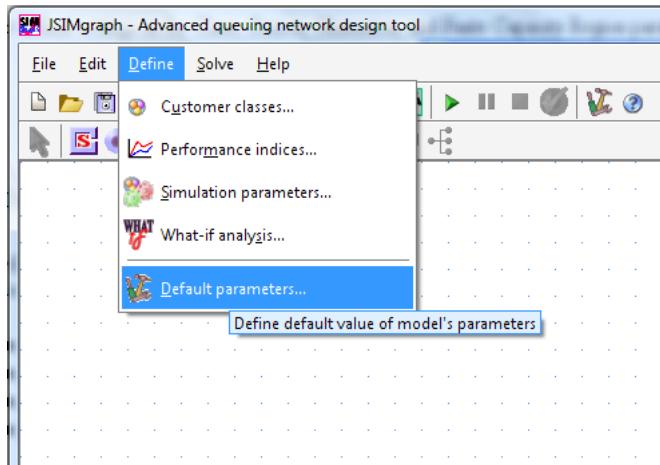


Figure 3.68: Selection of the Default parameters from the Define menu.

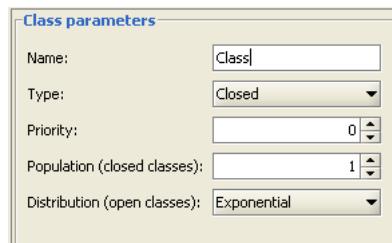


Figure 3.69: The Class parameters modification window of default values.

- *Population*: This parameter applies *only* to closed classes; the default value is 1, i.e., all closed classes are created with 1 customer each. Change the value if you want larger populations by default in each closed class.
- *Distribution*: This parameter applies *only* to open classes; the default value is Exponential since it is the most popular distribution that characterizes customer interarrival times at a system. Change it to any of the distributions available if most of your customer interarrival times follow a non-exponential pattern.

Station Parameters

These settings are general parameters for any type of station (see Figure 3.70).

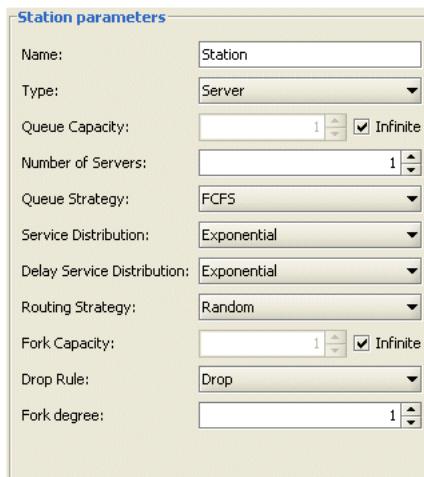


Figure 3.70: Station parameters modification window of default values.

- *Name*: the default name of each newly created station is "Station", followed by a progressive integer, starting from 1, indicating how many classes you have created so far. It can be set to any alphanumerical string, which will be followed by the same numbering scheme.
- *Type*: the default station type is "Queueing" (sometimes referred to as Server), since this is the most popular type of station in performance models. Alternative types are Fork, Join, Routing, Delay, Logger.

- *Queue Capacity*: this parameter applies only to Queueing and Fork station types; the default value is *infinite*, i.e., an infinite number of customers can queue at such stations. It can be set to finite, with a finite value specified, by checking out the **Infinite** checkbox.
- *Number of Servers*: this parameter applies only to Queueing stations; the default value is 1, as most devices are single server. It can be changed to any finite value.
- *Queue Strategy*: this parameter applies only to Queue and Fork station types; the default value is FCFS and can be changed to LCFS. In both cases, a priority version of the discipline is also available.
- *Service Distribution*: this parameter applies only to Queueing Stations; the default value is Exponential. It can be changed to any of the available distributions if most of the devices modelled are non-exponential.
- *Delay Service Distribution*: this parameter applies only to Delay stations; the default value is Exponential but it can be changed to any of the distributions available.
- *Routing Strategy*: this parameter applies only to Delay, Queueing, Join, and Routing stations; the default value is *Random* and it can be changed to any of the available routing strategies, namely Random, Round robin, Probabilities, Join the Shortest Queue, Shortest Response time, Least utilization, Fastest service, and Load Dependent routing.
- *Drop Rule*: this parameter applies only to *Fork stations*. When a finite capacity is defined, the default value of the Drop Rule is *Drop*, i.e., all customers exceeding the station capacity are discarded. Two other policies are possible. When the capacity is infinite, the Drop Rule is disabled by default.
- *Fork Capacity*: this parameter applies only to *Fork stations*; the default value is infinite, i.e., no limit on the number of customers entering a Fork station exists. It can be changed to finite, by checking the blocking checkbox and a finite number must then be specified.
- *Forking Degree*: this parameter applies only to *Fork stations*; the default value is 1, i.e., one task is generated for each outgoing link of the Fork station. It can be changed to any finite value, thus increasing the degree of parallelism a job has (and the number of tasks it is split into).

Simulation Parameters

These parameters define the simulation run from a statistical point of view. More details on *Confidence Interval* and *Max Relative Error* are reported in subsection 3.6.1 and subsection 3.6.2.

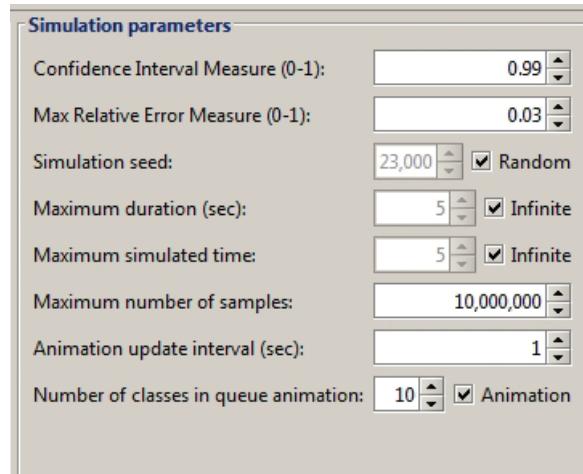


Figure 3.71: Parameters for the control of the simulation.

- **Confidence Interval Measure**: This parameter is set by default at 99%, a commonly used value as it provides a good trade-off between results accuracy and simulation time. Larger values will lead to more accurate results at the expenses of an increase in the time the simulation takes to complete, smaller values will achieve the opposite effect.
- **Max Relative Error Measure**: This parameter is set by default at 3%; smaller values will increase results accuracy while bigger values allow for larger errors in the samples.
- **Simulation Seed**: this parameter is used to initialize the pseudo-random number generator; the generated sequence of pseudo-random numbers is correlated with the seed used. A *Random* value is selected by default (typically related to the clock time), or a user may define its own value.

- **Maximum Duration:** this parameter is set to infinite by default, so that even lengthy simulations can complete and satisfy even narrow confidence intervals; finite values (in seconds) may force termination before the end of the simulation.
- **Maximum Simulated time:** this parameter is set to **Infinite** by default, this is the time simulated during the simulation run. As a function of the objective of the study, a user may want to stop the simulation at a given time. In this case, the user may uncheck the **Infinite** check box and type the desired value of the simulated time.
- **Maximum Number of Samples:** this parameter is set by default to 10,000,000. With a smaller number of samples it may not be possible to achieve the requested confidence interval, a larger number may not necessarily increase the results accuracy and simply extend the simulation time. It should be tuned depending on the objectives of the simulation study performed.
- **Animation Update Interval:** this parameter indicates the time interval between consecutive graph updates on the screen; the default value is 1 sec, as it provides for a smooth progression of the graphs on the screen. Larger values will make the evolution of the simulation appear jerky.
- **Number of classes in queue animation:** this parameter controls the number of classes for which graphs will be plotted for the selected performance indices. By setting the default value to 10, all classes are represented in most models. Graph animation is enabled by default but can be disabled.

Finite Capacity Region (FCR) Parameters

The default values for newly created Finite Capacity Regions follows.

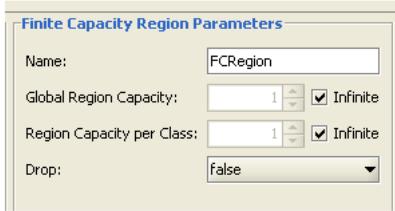


Figure 3.72: Parameters of a Finite Capacity Region.

- **Name:** the default name of each newly created Finite Capacity Region is **FCRegion**, followed by a progressive integer, starting from 1, indicating how many classes you have created so far. It can be reset to any alphanumerical string, which will be followed by the same numbering scheme.
- **Global Region Capacity:** the default value of this parameter is infinite, i.e., there is no upper limit to the total number of customers allowed in the region; the value can be changed to finite, and a number must be specified.
- **Region Capacity per Class:** the default value of this parameter is infinite, i.e., there is no upper limit to the per class total number of customers allowed in the region; the value can be changed to finite and a number must be specified.
- **Drop:** the default value of this parameter is **False**, i.e., no customer is ever discarded when arriving at the region; it can be changed to **True**, in which case customers in excess of the region capacity are discarded.

Reset to Default Parameters

If you have modified the default parameter and you want to restore the original values press the **Reset** button at the bottom of the panel.

3.12 Error and Warning Messages

JSIMgraph analyzes the network before starting the simulation. If errors or warnings are found, a window reporting the description of the errors, like the one of Figure 3.73, is shown.

Click on an error or warning message to open the panel where you can fix it (modifying the wrong parameters or changing the network).

In the following table the *diagnostic messages* of the most common errors and the suggested actions to fix them are shown.

<i>Station X is not forward linked</i>	Error	This error occurs when the station (source or join) has not outgoing, or forward, links to any other station in the model. Only Sink stations do not have forward links.
<i>Station X is not backward linked</i>	Error	Each station must have at least an incoming, or backward, link from other stations, for open class jobs to be able to leave the system. Only the Source station does not have a backward link.
<i>No reference station defined for Class X</i>	Error	For each class you must define a Reference Station that is used to estimate system throughput and response time. Click on this error to open and set the missing reference station.
<i>No performance indices defined</i>	Error	This error occurs when you try to start the simulation but no performance index is defined.
<i>Fork found but no join</i>	Warning	Fork and Join stations should be inserted together in the model. If you have inserted only one of the two stations, when the simulation is run JSIM will show a diagnostic message. Having a Fork without a Join is possible, although it may lead the system to saturate quickly.
<i>Join without fork</i>	Error	Having a Join without a Fork is a mistake, hence the Error message. The missing station must be added with the corresponding links.
<i>Source X without open classes associated</i>	Error	Insert in the network a Source only if you have an open class. If you have only a closed class, the source cannot be defined. But if you have open and closed classes you have to define a Source and a Sink in the network. This error appears when you have built a model with a source but without open customer classes.
<i>No classes defined</i>	Error	The definition of at least one class of customers is required in order to solve a model. Customer classes are a mandatory parameter of any model.
<i>A performance index is defined more than once</i>	Error	In the definition of the model output, the same index has been added more than once for the same station and class. Multiple occurrences must be removed.
<i>Closed class Class X routed to a station linked only to sink</i>	Error	Customers of closed classes keep circulating in the system. They may not visit a Sink station or a station that is connected on the outgoing link only to the Sink, since this would cause them to leave the system. The station connections must be changed.
<i>Undefined station in performance index</i>	Error	When a new performance index is defined, a connected station should also be selected. Click on Performance Index from Define menu and select the correct station.
<i>No station defined</i>	Error	You have to insert at least one station in the model.
<i>Open class found but no source defined</i>	Error	When an open customer class is defined, a Source and a Sink must be added to the network (to generate and collect the jobs). Add a source to the network.
<i>Closed class ClassX at station Server0 is routed to a sink with p=1</i>	Error	In the routing section of station Server0, the routing probability of a closed class job to a sink is one. This is an error because jobs cannot leave a closed model. Add another link to connect the station with other components of the network and set the new routing probabilities.
<i>Open classes were found but no sink have been defined</i>	Error	When an open customer class is defined, a Source and a Sink must be added to the network (to generate and collect the jobs). Add a sink to the network.
<i>Sink without open classes</i>	Error	A sink is only used to collect customers of open classes. This means that a sink without any closed class is useless.
<i>More than one sink defined, measures may not be accurate</i>	Warning	The evaluation of System Throughput performance index may be inaccurate with multiple sinks. We recommend to use one sink only.
<i>What-if analysis model modified</i>	Warning	One What-if analysis has been defined but after the model has been modified adding a station. The analysis may not work properly. Redefine the What-if Analysis
<i>Finite Capacity Region RegionX is empty</i>	Error	You have defined a Finite Capacity Region that is empty. A Finite Capacity Region must contain least one station.
<i>Preloading of stations inside a finite capacity region is not supported</i>	Error	This error appears because you have defined some initial states for the stations in the Finite Capacity Region. All Stations in a FCR must have initial state equal to 0 otherwise this error will appear. Preloading is not supported in FCR.
<i>Response Time per Sink and Throughput per sink should not be used if there is no Sink defined in the model.</i>	Error	This error appears because you have selected Response Time per Sink or Throughput per Sink performance Index but there no sink is defined in the model.
<i>Response Time per Sink and Throughput per sink should not be used for closed class.</i>	Error	This error appears because you have selected Response Time per Sink or Throughput per Sink performance Index with respect to closed class. Closed class models jobs cannot leave the model and hence no jobs can be routed to sink.
<i>Error: some rows sum to a value less than one.</i>	Error	This error appears because the sum of the probabilities of switch of a class is less than one (in a class-switch station).



Figure 3.73: Window with some diagnostic errors found by the simulator.

When you try to Export model defined with JSIM to JMVA some additional errors can appear due to the assumptions that must hold in order to apply the MVA algorithm.

<i>XXX routing strategy in ClassX for Source is not allowed. This was considered as RandomRouting</i>	Warning	A few constraints apply as for the admissible routing strategies. Round Robin routing is not implemented in JMVA, so it will be automatically transformed into Random, if you click the "Continue" button. Otherwise, you can change it following the link.
<i>A state dependent routing strategy was found</i>	Warning	You have defined a Routing strategy that doesn't match the one of the BCMP theorem. Click on the warning message and choose if you want to convert all non state independent routing strategies to Random routing or change the routing strategy manually.
<i>ServerX with non valid service time distribution</i>	Warning	You have defined a service time distribution not accepted by MVA. Modify the service time distribution to an exponential one. If "Continue" button is pressed, this distribution is considered as an Exponential with the same mean value of the original one.
<i>What-If Analysis (WIA)not available</i>	Warning	When you have defined a WIA and you want to export the model in JMVA, this error appears because the JMVA can't support WIA. If "Continue" button is pressed, WIA is ignored.
<i>Different per-class queueing strategy found at StationX</i>	Warning	This error appears during the export in JMVA because you have defined, for the stationX, a queue strategy different for the various classes. To export in JMVA, all queue strategies must be equal for all the classes. If "Continue" button is pressed, each queue strategy is considered as "Processor Sharing"
<i>Non uniform service strategy inside FCFS station StationX</i>	Warning	A few constraints apply as for the admissible service time distributions. A FCFS station must have exponentially distributed service time with the same mean for all the classes of customers that visit the station. If you click the "Continue" button, this issue is ignored.
<i>Non exponential service time inside FCFS station StationX</i>	Warning	A few constraints apply as for the admissible service time distributions. A FCFS station must have exponentially distributed service time with the same mean for all the classes of customers that visit the station. If you click the "Continue" button, this issue is ignored.
<i>In StationX, rows must sum to a value equal or greater than one.</i>	Error	This error appears because some rows of the class switch matrix of StationX do not sum to a value equal or greater than one.
<i>StationX is followed by a queue with BAS strategy scheduling.</i>	Error	This error appears when StationX is a class switch station and it is directly connected with a queue implementing a BAS strategy scheduling. This topology should make performance indices computation inconsistent, thus it is forbidden.
<i>StationX between fork/join. This topology is not allowed..</i>	Error	This error appears when StationX is a class switch station and is placed into a path that connects a fork and a join station. In this scenario is hard to define which is the class of the jobs at the exit of the join station, thus this topology is forbidden.

3.13 Simulation results

The results generated are function of the type of simulation performed: a *single* simulation run or a *What-If Analysis* run. Many factors affect the simulation results obtained with a model. Among them are: transient length, confidence intervals and max error requested, max number of samples, seed selected. The automatic *transient detection* algorithms implemented in JSIM are described in Sect.3.13.4.

3.13.1 Results from a single simulation run

At the end of a simulation, a panel with several tabs corresponding to the performance indices previously selected is shown. If there are several indexes of the same type, for example if the Response Time is referred

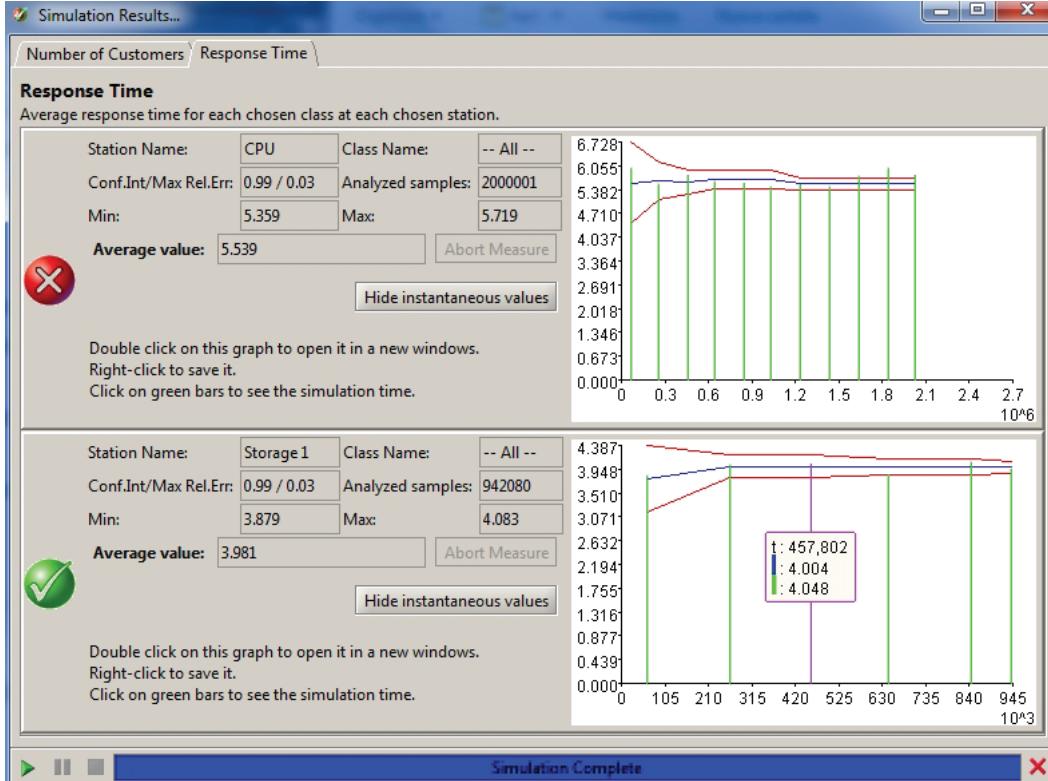


Figure 3.74: Results of a simulation run.

by two or more stations or different classes, you will see the graphs under the same tab (see Figure 3.74).

In each window, results for all the stations for which the performance index is specified are listed. Numerical values and graphs are given. Successful results, i.e., when the confidence interval for the index has been computed with the precision set by the user, are indicated by the check-mark green symbol (see Figure 3.74). In all the other cases, the red symbol indicates that the results obtained are *not* within the requested confidence interval.

In case of a syntactically correct network with some connections that make no sense from a modeling point of view, e.g., a station that is never visited by any customer, a yellow question mark indicates that the simulator could not compute the index for lack of measurements.

Values are available for the following parameters:

- **Station Name:** This is the name of the station for which the index is computed
- **Class Name:** This is the name of the class for which the index is computed at the station (it could be "All", to mean All Classes)
- **Conf.In / Max Rel.Err.:** This is the Confidence Interval and Maximum Relative Error of the computed index
- **Analyzed Samples:** This is the number of samples (the collected data) used to compute the performance index
- **Min.:** This is the minimum value observed for the index
- **Max.:** This is the maximum value observed for the index
- **Average Value:** This is the computed average value of the index, usually the value of greater interest.

Double-click on a graph (Figure 3.74) to magnify it. The x -axis represents the simulation time, i.e., the time considered by the simulator, that is event-driven. Every fixed number of detected values (a value set internally by default, see Sect.3.13.4), i.e., a *sample interval*, the simulator compute:

— the mean values of the index, connected with a *blue line*, computed on a number of measurements which increases with the progress of the simulation. All the collected values are considered at each computation except

the ones discarded when detected as transients.

- the Confidence Intervals, *red lines*, of the values detected in the last set of values considered by the simulator,
 - a *green bar* representing the mean value of the index computed with the measurements of the last interval.
- Clicking on a green bar a popup will appear showing the corresponding simulation time (t), the mean value (blue), and the instantaneous value (green).



The values are plotted in the graph when an *animation interval* expires (to set click on the icon from the toolbar, see Figure 3.30). Since the animation intervals, the intervals used to plot the values on the graphs, are based on the wall time while the sample intervals (computation intervals) are based on the simulation time (that is event-driven) the interval between consecutive bar charts may be irregular.

3.13.2 Result of What-If Analysis simulation run

At the end of a *What-If Analysis* simulation run, a panel showing the statistical values of the indexes, a plot of the indices behavior with respect to the control variable of the What-If Analysis and a table are shown. The panel shows a number of tabs corresponding to the number of indices inserted.

For each tab, i.e., each performance index, the results are grouped into three parts:

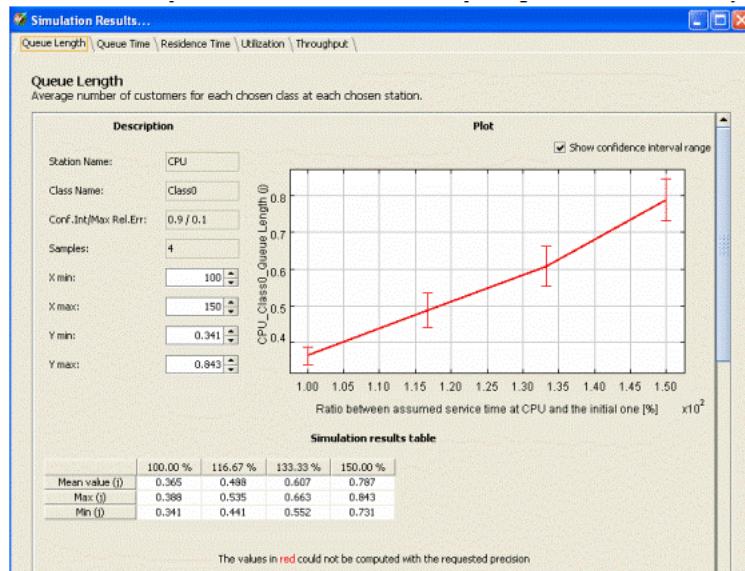


Figure 3.75: Results of a What-If-Analysis.

- The first part consists of the names of the index, of the station, and of the Class, the number of samples executed, the confidence interval and the maximum relative error, and the minimum and maximum values of the index.
- The second part is represented by a graph with a grid to facilitate the reading and the X and Y axes with their measure unit and scale. By default, on the graph are plotted the confidence interval range for all the executions with different values of the What-if analysis control variable, that can be disabled through the check box.
- The third part consists of a table showing the results of each simulation run. The number of columns of the table corresponds to the number of steps executed. When the simulation engine cannot compute the confidence interval or the max relative error with the required probabilities, the values are written in red.

The size of each plot can be magnified double-clicking on it.

3.13.3 Export to JMVA

A simulation model created with JSIMgraph can be exported to the analytic solver component of the JMT suite, namely JMVA. In the Action menu, click **Export to MVA**.

If there are errors or conditions not allowed in models to be solved by analytical techniques, a dialog window with information about such errors appears. If you want to continue with the analytical solution, you must correct the errors.

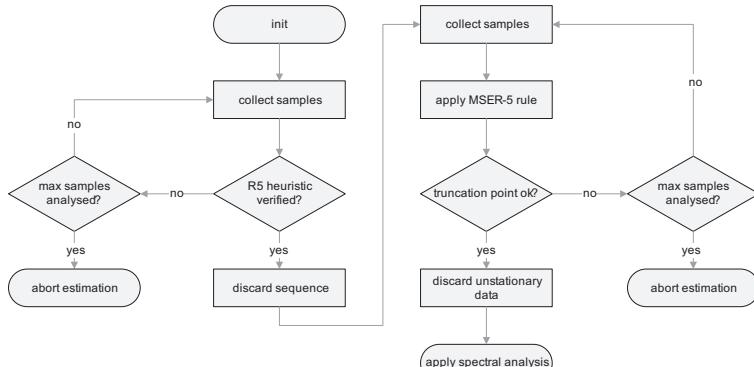


Figure 3.76: JSIM: transient detection and removal flowchart.

Refer to JMVA user's guide for specific help on JMVA functionalities.

3.13.4 Transient detection

Simulation results are analyzed using transient detection and confidence interval estimation algorithms. These techniques are executed online, and can stop the simulation if all accuracy requirements are met. Confidence intervals are generated using the spectral method presented in [HW81]. The effectiveness of this technique depends on the stationarity of the sample distribution. If the series of samples shows trends or pronounced non-stationary behaviors, the estimate of its power spectrum can be unreliable, and this degrades the quality of the confidence intervals generated by the spectral method which works in the frequency domain. Therefore, techniques for discriminating if a group of samples is stationary are important to maximize accuracy, since detecting and removing non-stationary data can greatly improve the quality of power spectrum estimates. For this purpose, we have implemented transient detection using the R5 heuristic [Fis73] and the MSER-5 stationarity rule [Spr98]. The related transient detection and removal flowchart is shown in Figure 3.76. During the execution of the simulation, the statistical analyzer is fed with samples of each performance measure. First the R5 heuristic is evaluated until it indicates the termination of the transient. Afterwards, the MSER-5 is run to double-check the indication of the R5 heuristic. When also the MSER-5 test indicates stationarity, the data is sent to the statistical analyzer for the final generation of confidence interval using the spectral method of [HW81]. A transient period is characterized in the simulation graph of a performance index by the absence of the red lines delimiting the confidence interval. In Fig.3.77 it is possible to see the transient period (from 0 to about 260 sec of clock time) for the index *System Response Time of class C1*.

We now review the R5, MSER-5 and spectral methods and outline their implementation in the JMT simulator.

The R5 heuristic control

The R5 heuristic [Fis73] detects the initial transient period by checking if the time series of samples crosses its mean value more than k times, where k is a user-specified parameter. We implemented this rule using the indications of Pawlikowski [Paw90]. In order to limit time and space requirements, we periodically check transient termination using a period of 500 samples. If the new samples do not satisfy the crossing condition, 500 new samples are collected before a new check is performed. After matching the stopping criteria, the R5 heuristic is complete and the simulator performs a second transient detection using the MSER-5 rule. This is done because we noted that applying several rules empirically reduces the number of wrong detections.

Concerning the choice of the k parameter, Gafarian et al. [GAM78] recommend $k = 25$ for $M/M/1/\infty$ models, while Wilson and Prisker [WP78] recommend $k = 7$ for $M/M/1/15$ models. We inspected more than 50 single workload simulation models with randomly generated networks including up to 4 load-independent and load-dependent queues, and checked the behavior of utilization, throughput, queue-length and response time metrics. We observed that the values proposed in the literature did not correctly identify transients on some of the instances. In particular, there exist cases in which $k = 7$ gives an early detection during an unfinished initial transient ramp. Conversely, with the $k = 25$ value, the transient of the utilization metric tends to be very slow, and in some cases even hundreds of thousands of samples are discarded before moving to the MSER-5 rule. Since the last problem is less severe than a wrong generation of results, we have chosen a value $k = 19$ to maintain the general properties of the recommendation in [GAM78], while reducing the number of cases where the transient is excessively slow.

The MSER-5 Rule control

MSER-5 rule is an identification method for the best truncation-point in a data sequence, first presented in [Spr98]. Initially, we used Schruben's test for this purpose [Sch82], but the results were not always satisfactory, as observed also in [WCS00]. Since the MSER-5 rule is not generally meant for online analyses, but instead works on a fixed data set, we adopted the approach of Robinson [Rob05] which consists in getting online new samples unless the truncation point is detected before the half of the analyzed sample set. Our implementation uses circular lists of 5000 batches (25000 samples), and has constant access and computation times. We observed that using structures with increased size had no benefit on accuracy, but imposed additional computational overheads. In the simulator, the MSER-5 rule is reapplied periodically until the detection of the optimal truncation-point. We set the period equal to the number of samples discarded by the R5 heuristic.

The spectral analysis

The spectral analysis of Heidelberger and Welch [HW81] is a stable and computationally efficient method for computing simulation confidence intervals using variable batch sizes and a fixed amount of memory. In the JMT simulator, the method is run on the stationary part of the sequence of samples. The spectral analysis is periodically run until the required confidence intervals are found. Nonetheless, it happens quite often that the portion of data immediately available after the MSER-5 rule is already sufficient to compute the required confidence intervals.

The spectral analysis proceeds as follows. Given a covariance-stationary sequence of samples $X(1), \dots, X(N)$ of the performance measure X , the spectral analysis obtains an estimate of the power spectrum $p(f)$ at the frequency $f = 0$. The value $p(0)/N$ is an unbiased estimator of the sample variance, and therefore can be used to generate confidence intervals on X also if the sequence of sample is correlated. The advantage of the technique with respect to the standard variance estimator

$$\text{Var}(X) \sim \frac{1}{N-1} \sum_{j=1}^N (X(j) - \bar{X})^2$$

is that the latter does not hold if the samples are correlated. It is known from long-time that performance metrics in queueing network models are correlated, see, e.g., [BKK84] for correlations in response times of product-form models, and this motivates the use of spectral analysis methods in the JMT simulator.

The spectral analysis requires to first compute the sample period gram $I(n/N)$, $0 < n < N/2$, and then generate the function $J(n) = \log(0.5(I((2n-1)/N) + I(2n/N)))$ which is the logarithm of the mean period gram over consecutive values of $I(n/N)$. The most important property of $J(n)$ is that its functional shape is linear in a neighborhood of the zero frequency, thus the value of $I(0)$ (which gives the power $p(0)$) can be estimated by regression of $J(n)$.

We implemented the regression technique using singular value decomposition, and fitting the data to a polynomial of order two. This implementation is consistent with the graphs in [HW81] which show that for batch sizes of 4-8 samples $J(n)$ is approximately linear or quadratic in a neighborhood of zero.

3.13.5 Dead performance index

In JSIM there is a control for detecting if no (or very few) values are detected for a performance index. This event may happens in models not well parameterized. For example, after an initial transient it may be that there are paths in which do not transit customers for a long time (because their routing probability is very low or other peculiarities of the routing policy selected), and hence the resources linked to them do not detect new values for the corresponding performance indices. We will refer to these indices as "dead indices".

The implemented test controls that, for each index, the number of samples received every 240000 increments of the simulation clock is different from zero. If it is zero, the collection of sample for that index is stopped and a *Orange question mark* is shown. In Fig.3.77 it is shown a dead index (System Response Time for class C2) detected. Note that the number of samples collected for this index is not zero (they are 3052), but clearly they were detected all in the transient phase since the average value shown is zero (the samples collected in a transient phase are not considered for the computation of the index value). If the average value of a dead index is different from zero means that the sample collection has been stopped after the end of the transient phase, that has been detected. The average value refers to the small number of samples detected.

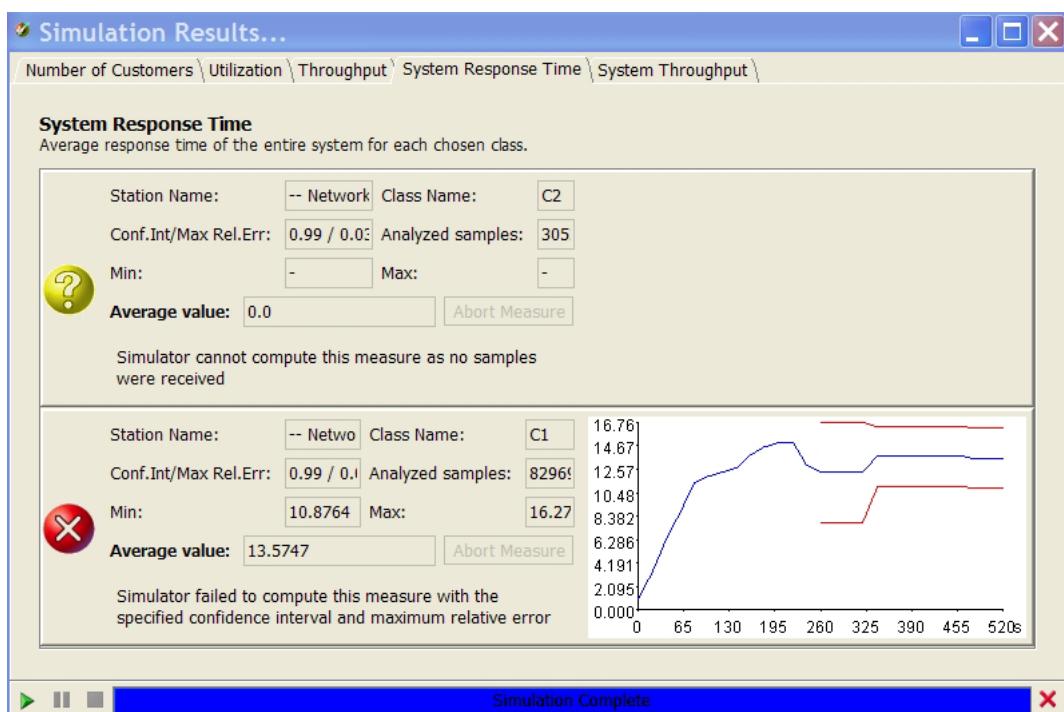


Figure 3.77: Detection of a *dead index*: System Response Time for class C2.

3.14 Statistics on performance indexes

In this section we will describe how the statistical values of the performance indexes generated as output of a simulation run can be obtained and how their values are computed.

3.14.1 How to obtain Statistics and Graphs of the simulation results

For each performance index selected it is possible to obtain several statistical values and graphs. To obtain the statistical values of an index you should check the box **Stat.Res.** (*Statistical Results*) in the corresponding line of the **Define performance indices** window. For example, in Fig.3.78 the statistical values of the **Response Time** and of the **Utilization** have been required.

A CSV file with the data needed for the statistical computations is generated for *each* index selected. The default path of these files is `C:\Users\user name\JMT\` and the default *names* are `Station name.index name.csv`, e.g., `Station 1_Response Time.csv`. You may change the path in the window shown in Fig.3.78. The structure of the files and the meaning of the data stored are described in Sect.3.14.2.

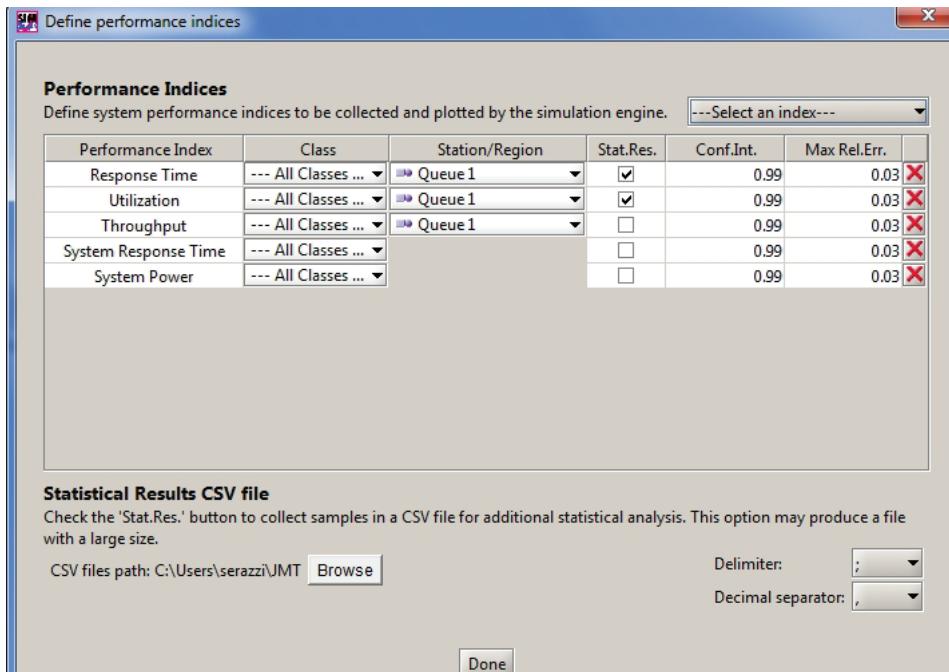


Figure 3.78: Selection of the **Response Time** and **Utilization** indexes for the collection of their values and the computation of their statistical metrics (see the **Stat.Res.** check boxes).

At the end of the simulation run the **Statistical Results** button in the **Simulation Results** window of the index selected will be activated. By pressing on it, the window with the statistical values of the corresponding index (**Response Time** in this case) will be shown (see Fig.3.79).

The values considered can be filtered by the *number of the samples* collected (**First Sample** and **Last Sample**) or by the *simulation time* (**Initial Simulation Time** and **Final Simulation Time**) in the **Filter analyzed samples** boxes. A user may also filter the values considered in the graphs selecting the min and the max values in the boxes of the **Graph Drawing Options** section. The **Number of intervals** in which the values are grouped to draw the graphs can also be selected. Three types of graphs are available and can be selected in the **Graph Drawing Options** section of the window: **density line**, **histogram**, **distribution**. In Fig.3.80 the **Histogram** of the **Response Time** values is shown. The values computed for generating the graphs can be saved in CSV files.

When the **Distribution** type graph is selected, the values are sorted in increasing order. The *quartiles* divide the set of observations in 4 equal parts, and the *percentiles* in 100 equal parts. To plot the quartiles or the percentiles it is sufficient to set the graph type to **Distribution** and the **Number of intervals** to 4 or 100 respectively.

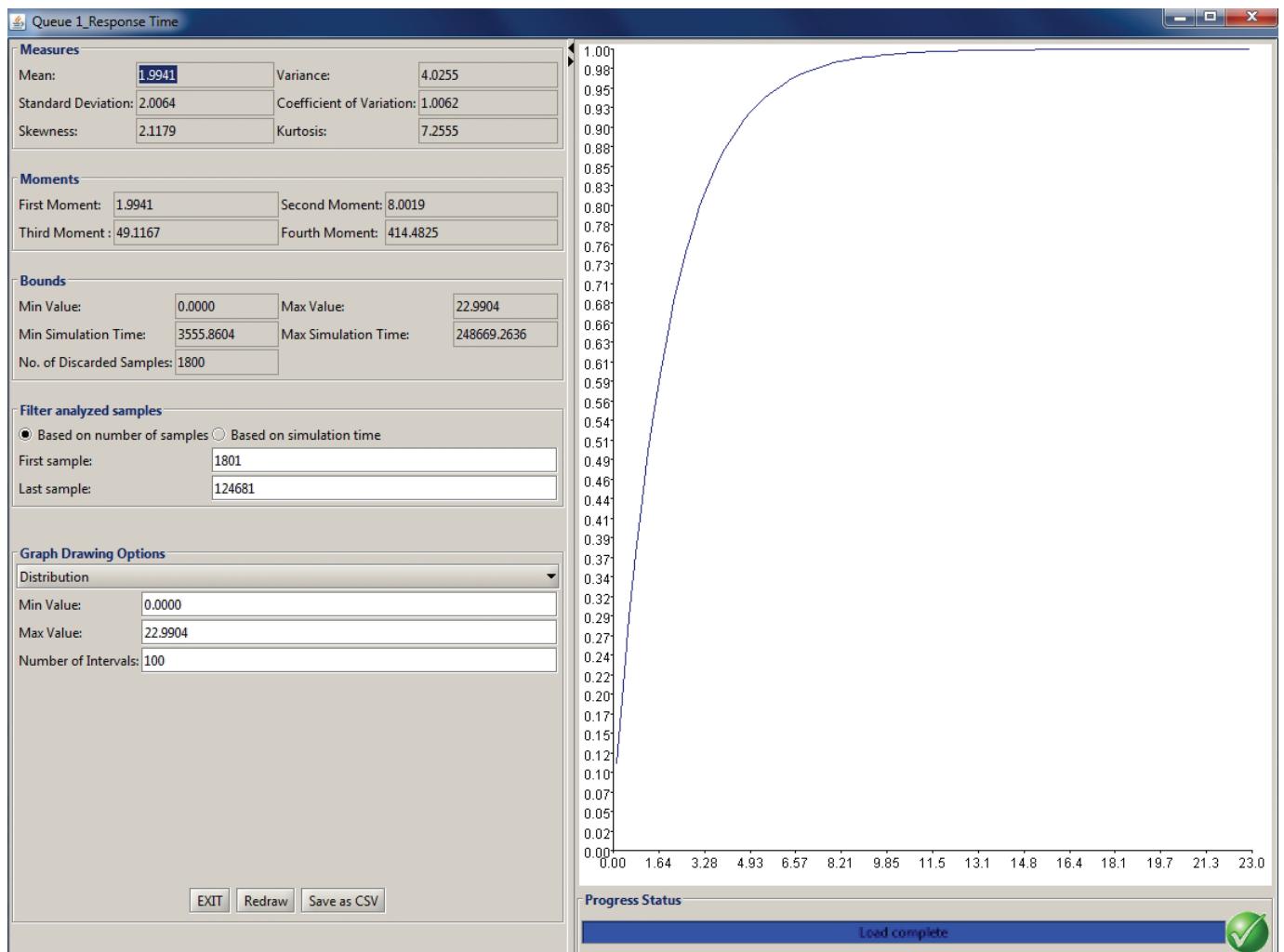


Figure 3.79: Statistical values of the Response Time, the graph selected is the *distribution*.

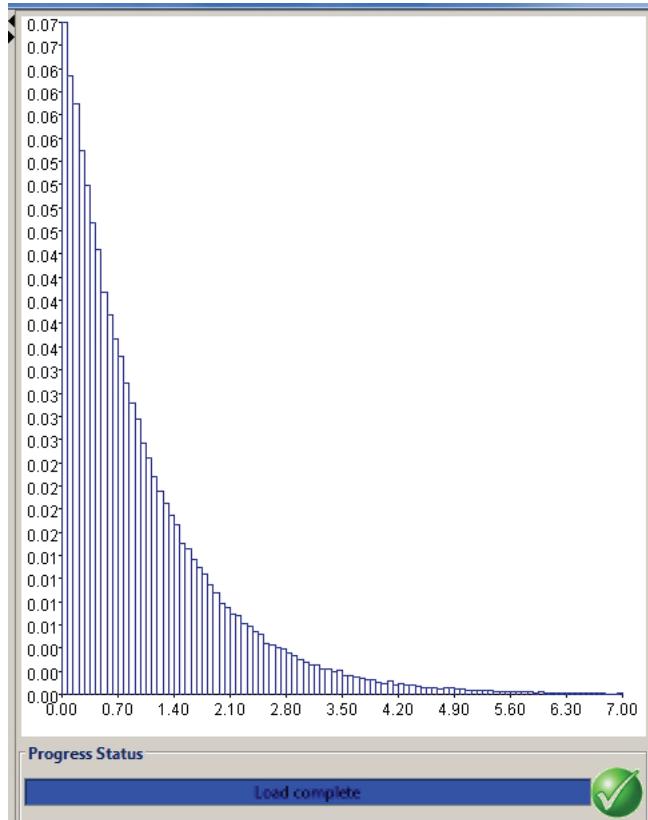


Figure 3.80: Histogram of the **Response Time** obtained grouping the values in 100 intervals (selection of the **Number of Intervals** parameter to 100) in the graph. The values represented are the *percentiles*.

3.14.2 Computation of the statistical values

The computations required to obtain the statistical values of the various indexes are different as a function of the index considered. A *Statistical Results* file CSV is generated for *each* index selected, whose default path is C:\Users\user name\JMT\ and whose default name is **Station name_index name.csv**, e.g., **Station 1_Response Time.csv**.

In Table 3.1 a synthetic description of the variables collected for each metric is shown.

The metrics can be subdivided into *two groups* as a function of the values of WEIGHT field used to compute the mean value of the sample collected. A *first group* is the one with WEIGHT=1.

Let us consider, for example, the **System Response Time** index of a simulation run in which n jobs were executed. When job i exits the model, a row of the *Statistical Results csv file* shown in Fig.3.81 is written. For this index, the values of data fields are:

- (1) **TIMESTAMP**: simulation time at which job i exits the model,
- (2) **SAMPLE**: the **Response Time** R_i of the job i computed as the difference from the execution start time and its completion time,
- (3) **WEIGHT**: a weight value W_i that will be used for the computation of the mean value of the index considered. For the indexes having the weight values W_i equal to 1 each line of the file corresponds to a single job and thus each element has the same weight for the computation of the mean value. Typically, the mean **System Response Time** of n jobs is obtained as:

$$R = \frac{\sum_{i=1}^n R_i}{n} \quad (3.5)$$

A *second group* of indexes is that for which the WEIGHTS are no longer constants but assume the values of *time-intervals* between consecutive events. Let us consider, for example, the index **mean Number of customers** of a station. When the request i enters/exits the station, a row of the *Statistical Results CSV file* shown in Fig.3.82 is written. The meanings of the data fields are:

- (1) **TIMESTAMP**: simulation time at which request i enters/exits the station,
- (2) **SAMPLE**: is the number m of requests that are in the station (in queue and in service) when request i exits the station,
- (3) **WEIGHT**: a weight value W_i that will be used for the computation of the mean value of the number of

Performance Index	TIMESTAMP (event detected)	SAMPLE	WEIGHT
Response time (station) [s]	exit from station	time spent in a visit (queue + service)	1 (req)
System Response Time [s] (referred to as R)	exit from system (from Ref.Station)	time in the system (queue + service)	1 (job)
Residence time (stat.) [s]	exit from system (from Ref.Station)	time spent in station (for a complete exec)	1 (job)
Queue time (station) [s]	exit from queue (enter service)	time in queue (waiting for service)	1(req)
Throughput (station)[req/s]	exit from station	inter-departure time	1 (req)
System Throughput [j/s] (referred to as X)	exit from system (from Ref.Station)	inter-departure time	1 (job)
Drop rate (station) [req/s]	exit from queue (dropped)	time between drops	1(req)
System Drop rate [j/s]	exit from system (dropped)	time between drops	1(req)
System power [X/R]	exit from system (from Ref.Station)	X/R	1 (job)
No.customers (stat.) [req]	arrival/exit (to/from station)	no. of req. in station (before the event)	elapsed time from this event and the previous one
System No.of custom. [j]	arrival/exit (to/from system)	no. of req. in system (before the event)	elapsed time from this event and the previous one
Utilization (station) [%]	exit from queue (the server is idle)	0	elapsed time from this event and the previous one
Utilization (station) [%]	exit from server (server was busy)	1	elapsed time from this event and the previous one

Table 3.1: Performance indexes and related data stored in the corresponding files for their statistical processing.

	A	B	C	D
1	TIMESTAMP	SAMPLE	WEIGHT	
2	1,481281719	0,28281	1	
3	2,112621364	0,584314	1	
4	2,760347034	0,534165	1	
5	3,142743561	0,786578	1	
6	3,37834445	0,963454	1	
7	3,682782122	1,211253	1	

Figure 3.81: Example of the Excel file Queue 1_Response Time.csv for the Response Time index of station Queue 1.

requests. Each value W_i represents the duration of the interval of time in which the m requests of the SAMPLE that are in the station when the event is detected have been there. For the request i , the W_i value is computed as the difference $[TimeStamp(i) - TimeStamp(i - 1)]$.

Let T_m be the time interval during which m requests were in the station, and max be the maximum number of requests that were in the station during the simulation run. The total simulation time T is given by $T = \sum_{m=0}^{max} T_m$. Typically, the mean number N of requests in the station for a simulation run of duration T is given by:

$$N = \sum_{m=1}^{max} \frac{mT_m}{\sum_{j=0}^{max} T_j} = \sum_{m=1}^{max} \frac{mT_m}{T} \quad (3.6)$$

JMT utilizes the following *single formula* to process all the indexes:

$$I = \frac{\sum_{i=1}^n S_i W_i}{\sum_{i=1}^n W_i} \quad (3.7)$$

where the W_i are the WEIGHTS values and the S_i are the SAMPLE values shown in Table 3.1.

When the mean value of a index with all the W_i equal to 1 is to be computed, e.g., the Response Time,

	A	B	C	D
1	TIMESTAMP	SAMPLE	WEIGHT	
2	1,198471466	0	1,198471	
3	1,481281719	1	0,28281	
4	1,528307117	0	0,047025	
5	2,112621364	1	0,584314	
6	2,226181647	0	0,11356	
7	2,356165391	1	0,129984	
8	2,414890076	2	0,058725	
9	2,471529278	3	0,056639	
10	2,760347034	4	0,288818	
11	2,885456167	3	0,125109	

Figure 3.82: Example of data stored in the Excel file Queue 1_Number of Customers.csv for the Number of Customers index of station Queue 1.

eq.3.7 becomes (in this case the S_i are equal to R_i):

$$I = \frac{\sum_{i=1}^n S_i W_i}{\sum_{i=1}^n W_i} = \frac{\sum_{i=1}^n R_i}{n} = R \quad (3.8)$$

providing the same result of eq.3.5.

Otherwise, when the mean of an index of the other type, e.g., the Number of customers, is to be computed, the W_i represent the time in which m requests were in the station, and the S_i values are the number of m requests in the station when the $i - th$ request leave the station. In this case eq.3.7 becomes:

$$I = \frac{\sum_{i=1}^n S_i W_i}{\sum_{i=1}^n W_i} = \frac{\sum_{i=1}^n S_i W_i}{\sum_{i=1}^n TimeStamp(i) - TimeStamp(i-1)} = \frac{\sum_{i=1}^{max} m T_m}{\sum_{i=0}^n T_n} = N \quad (3.9)$$

providing the same result of eq.3.6.

The indexes Throughput, System Throughput, Drop Rate, System Drop Rate obtained processing directly their values of SAMPLE and WEIGHT of the corresponding files are the inverse of the correct values. Indeed, the SAMPLE values are the inter-exit times of the requests/jobs. Thus, it became necessary to reverse the values obtained from their computations to show the correct statistics and graphs.

Let us remark that, as a function of the simulation condition, sometimes in the files of statistical values of some index (e.g., Utilization, System Number of Customers) it may appear a few lines with SAMPLE=WEIGHT=0 or only WEIGHT=0 and the same TIMESTAMP of the previous line. This is due to the working logic of simulator but of course do not affect the calculations of the statistical indexes.

3.15 Examples

Two simple examples of performance evaluation studies executed using JSIMgraph are shown. We believe that readers could benefit from their analysis by concentrating on the abstraction process and on the model design rather than on the actual quantitative results presented in the projects.

The first example is a single simulation run whereas the second one is a What-If Analysis.

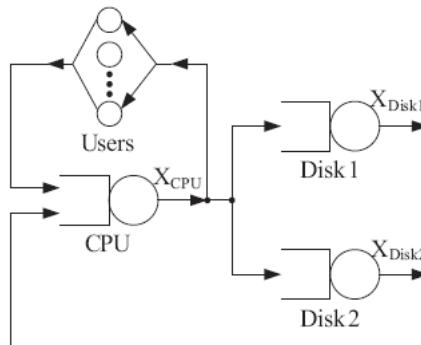


Figure 3.83: Layout of the system of Example 1.

	CPU	Disk1	Disk2	Users
Service time [sec]	0.006	0.038	0.030	16
Visits	101	60	40	1

Table 3.2: The parameters for the single class model of Example 1.

3.15.1 Example 1 - A model with single closed class

For teaching purposes we are considering here the same *Example 1* presented in the JMVA user manual. We will see that the results obtained with JSIMgraph include in their confidence intervals the correct values obtained with the exact solver JMVA.

The model

The digital infrastructure of a company consists of a computing server and a storage server equipped with two large disks arrays. The user requirements are homogeneous and the workload generated may be considered as a single class. The layout of the digital infrastructure is shown in Figure 3.83. The customer class, referred to as *ClosedClass*, has a population of $N = 3$ customers. There are four stations (*CPU*, *Disk1* and *Disk2*), three are of queueing type load independent and one is of delay type (*Users*). Users delay station represents user's think time ($Z = 16s$) between interaction with the system. Service times, distributed exponentially, and the visits at the stations are reported in Table 3.2.

Drawing the graph

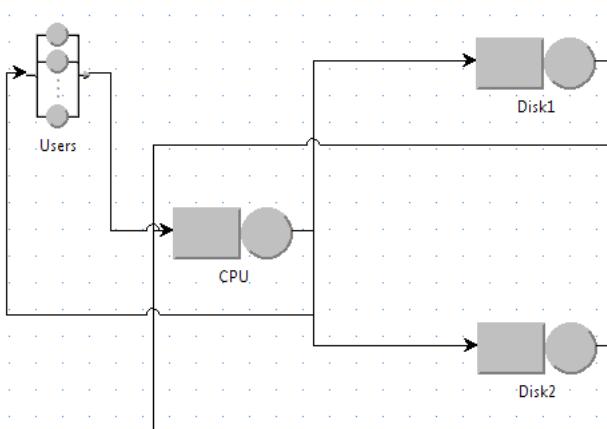


Figure 3.84: The system represented with JSIMgraph

- Select **File** → **New** or click on the icon from the first toolbar.
- Insert a **Queueing station** in the drawing window by at first clicking the icon and then clicking on the drawing window. Perform this task 3 times in order to add 3 stations.
- Double click on a **Queueing station**. You will find a textbox to modify **Station Name**. By clicking each of the queueing stations, rename **Station Names** as *CPU*, *Disk1*, and *Disk2*.
- Insert a **Delay Station** by selecting the icon from the toolbar. Double click on it and rename the **Station Name** as *Users*.
- By selecting the icon, connect the queueing stations and the delay station as given in the problem. The graph should look like Figure 3.84.

Now we have to describe the values of the parameters.

Defining customer class

- Select **Define** → **Customer Classes** from the menu bar or click on the .
- Click on **Add Class**. Set **Population** as 3 and **Reference Station** as *Users*. Note that that **reference station** is the station which initiates and completes the flow of customers in the network.
- Click **Done** on the window of Figure 3.86.

Setting the values of the parameters

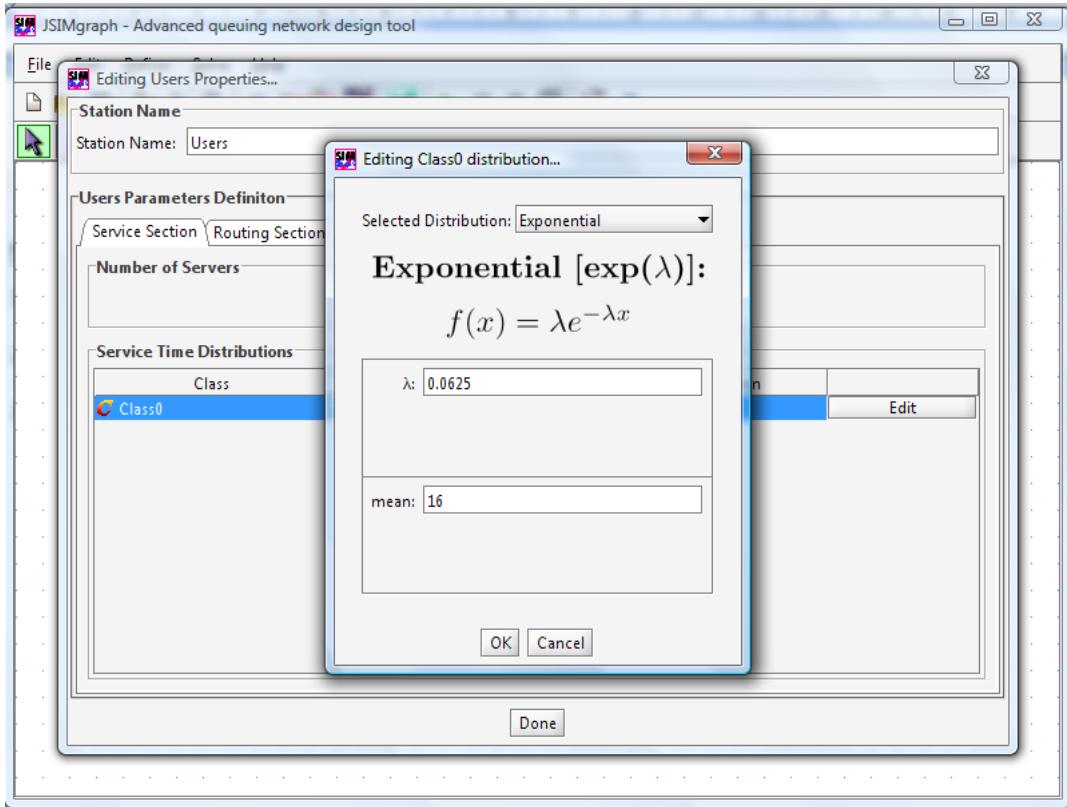


Figure 3.85: Setting the mean value of *Users Think time* for the delay station

- Double click on **Users** delay station.
- Click on **Edit**.
- The default **Selected Distribution** should be **Exponential** (see Fig.3.85). Set **Mean** value as 16 (recall that the Customer think time is Z=16s). Click **OK**. Note that the value of λ is automatically computed by the tool.
- Double click on **CPU**. Click on Service Section tab. Click on **Edit**.
- The default **Selected Distribution** should be **Exponential**. Set **Mean** value as 0.006. Click **OK**. Note that the value of λ is automatically computed by the tool.
- Click on the **Routing Section** tab. Set **Routing Strategies** as **Probabilities**. As there are 3 outgoing links from **CPU**, we have to set a job's probability to choose each of these paths. This is done by setting the probabilities of **Disk1**, **Disk2** and **Users** as 60, 40 and 1 respectively (see Figure 3.87). Click on **Done**. Note that the values of the **Probabilities** are automatically adjusted by the tool.
- Double click on **Disk1**. Click on Service Section tab. Click on **Edit**.
- The default **Selected Distribution** should be **Exponential**. Set **Mean** value as 0.038s. Click **OK**. The value λ is automatically computed by the tool.
- Click on the **Routing Section** tab. Choose **Routing Strategies** as **Probabilities**. Since there is only one outgoing link, which goes to the **CPU**, from **Disk1** so select the **Probability** of going to CPU (under the **Routing Options** subsection) as 1 (see Figure 3.88). Click on **Done**.
- Double click on **Disk2**. Click on Service Section tab. Click on **Edit**.
- The default **Selected Distribution** should be **Exponential**. Set **Mean** value as 0.030. Click **OK**. The value of λ is automatically computed by the tool.
- Click on the **Routing Section** tab. Choose **Routing Strategies** as **Probabilities**. Since there is only one outgoing link, which goes to **CPU** from **Disk2**, set the **Probability** of going to CPU (in the **Routing Options** subsection) to 1. Click on **Done**.

Defining the Performance Indices

Before start the simulation we must select the performance indices to analyze. In Example 1 we want to study the following indices:

- *Queue length [jobs]* (for CPU, Disk1, Disk2, Users and the global System)

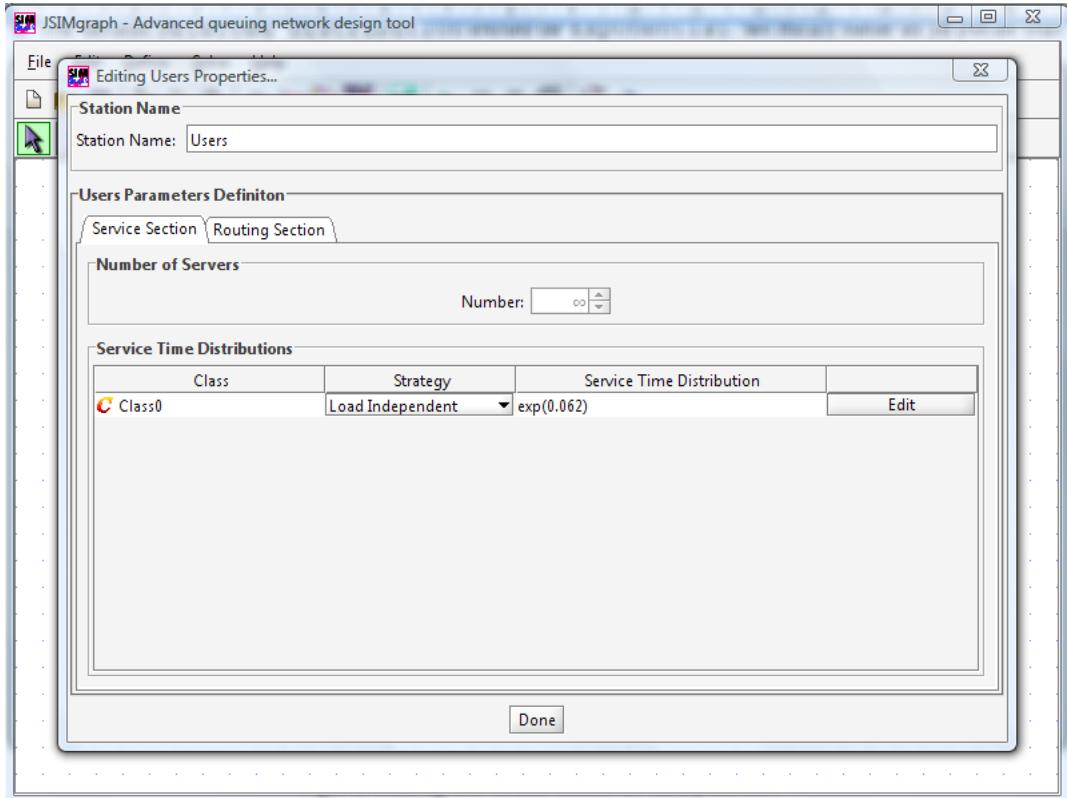


Figure 3.86: The Users properties window

- *Throughput [jobs/sec]* (for CPU, Disk1, Disk2, Users and the System)
- *Residence time [sec]* (for CPU, Disk1, Disk2, Users and the System)
- *Utilization* (for CPU, Disk1, Disk2 and Users)

The following actions should be done:

- From menu bar select **Define** → **Performance Indices** or select  from the toolbar.
- From the drop down menu at the right, select **Queue Length**. Click on **Add Selected Index** for four times. Change **State/Region** of these Indices to *CPU, Disk1, Disk2* and *Users*.
- From the drop down menu at the right, select **Throughput**. Click on **Add Selected Index** for four times. Change **State/Region** of these Indices to *CPU, Disk1, Disk2* and *Users*.
- From the drop down menu at the right, select **Residence Time**. Click on **Add Selected Index** for four times. Change **State/Region** of these Indices to *CPU, Disk1, Disk2* and *Users*.
- From the drop down menu at the right, select **Utilization**. Click on **Add Selected Index** for four times. Change **State/Region** of these Indices to *CPU, Disk1, Disk2* and *Users*.

The **Define Performance Indices** window should look like Figure 3.90. It should be noted that we can change the **Confidence Interval** and/or **Maximum Relative Error** for any performance index from this window. At the end click on **Done**.

Running the Simulation

To run the simulator - press **Alt+s** or select **Simulate** from the **Solve** menu or press  from the toolbar. Note that if you had run the simulation for the same program before, *JSIMgraph* asks for a confirmation whether you want to replace the previous simulation results or not. Choose **yes** to confirm. In the drawing window of the Simulator (Figure 3.91), the colored parts of a station represents the percentages of station busy time and of the queue length due to the customers of *Class0*. In the **Simulation Results** window, Figure 3.92, opened automatically when simulation starts, the progress of the average values of the selected performance indices and the extremes of the confidence intervals are shown.

Table 3.3 shows the average, min and max values of the indexes at the station level at the end of the simulation. Table 3.4 shows the average, min, and max values of Response Time, Throughput, and number of customers at the level of the global system.

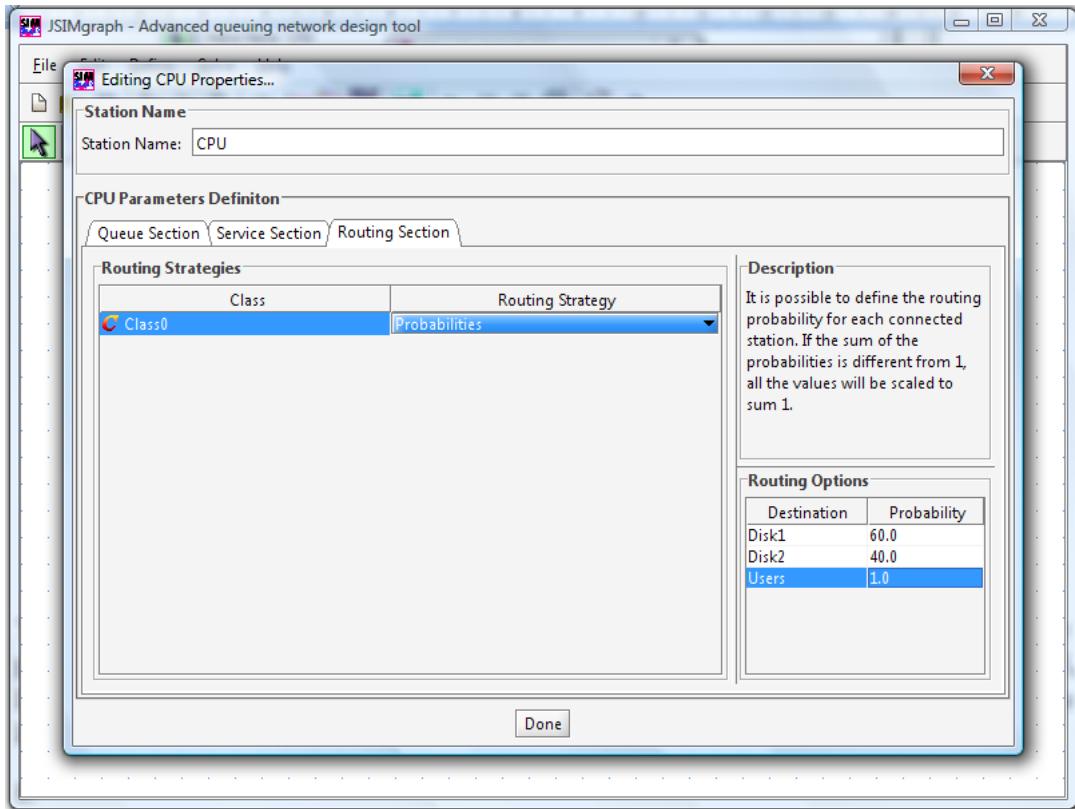


Figure 3.87: Setting the probabilities (or the visits) in output of *CPU* station

Note that the results of different simulation runs may slightly vary due to the differences in the sequence of random numbers generated with different seeds.

3.15.2 Example 2 - What-If analysis of a system with multiclass customers

The problem

Consider an intranet consisting of a storage server and an Apache server. The storage server consists of three disks used according to a RAID0 algorithm (striping). The web server consists of two independent systems that for performance issue can accept globally a limited number of customers in concurrent execution, i.e., they are allocated in a Finite Capacity Region with the maximum number of customers $MaxClients = 100$. A *load balancer* split the requests among them according to policies described later.

The customers are subdivided into two *open* classes, *Class0* and *Class1*: the first class access only the Apache

		Queue length [jobs]	Residence time [sec]	Utilization [%]	Throughput [jobs/sec]
CPU	min	0.080	0.882	0.076	13.067
	max	0.096	1.019	0.089	15.014
	avg	0.088	0.950	0.082	13.973
Users (delay)	min	2.157	15.681	2.157	7.496
	max	2.463	17.302	2.463	8.606
	avg	2.310	16.492	2.310	8.013
Disk1	min	0.373	2.836	0.276	4.996
	max	0.434	3.327	0.318	5.713
	avg	0.403	3.082	0.297	5.331
Disk2	min	0.181	1.326	0.159	0.135
	max	0.216	1.495	0.185	0.149
	avg	0.199	1.410	0.172	0.141

Table 3.3: The results of the simulation at the stations level.

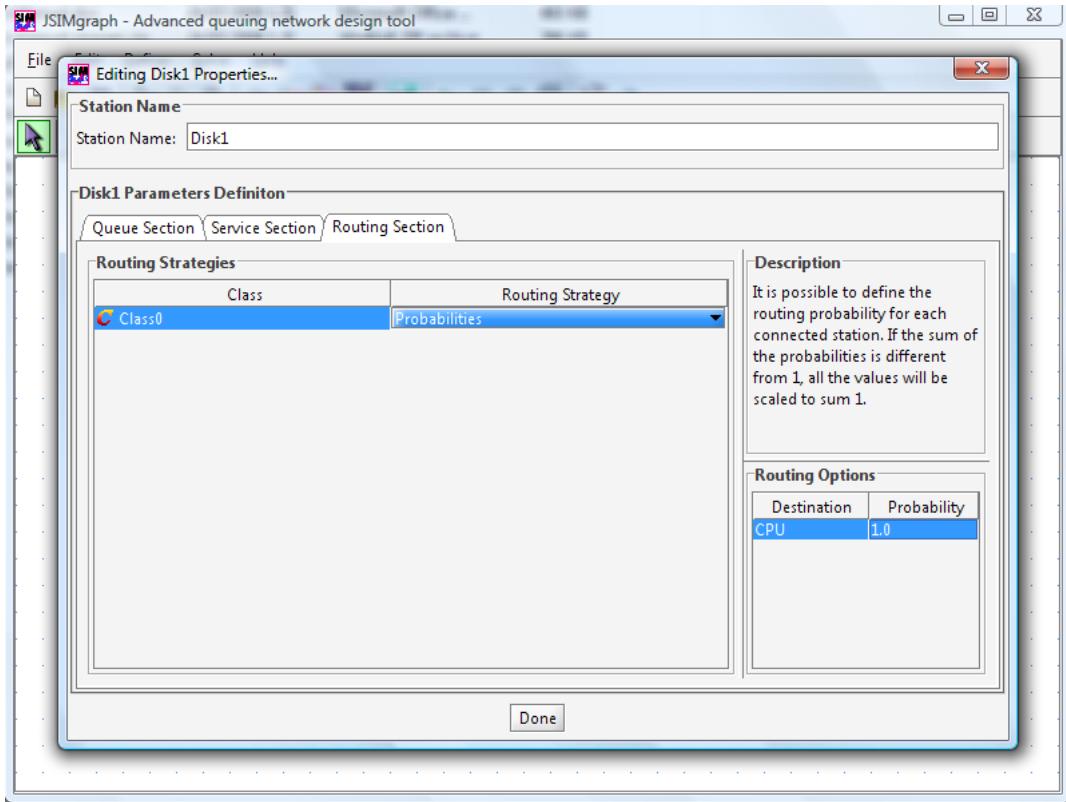


Figure 3.88: Setting the routing probabilities (or the visits) in output of *Disk1* station

	System Response Time [sec]	System Throughput [job/sec]	Customers number [jobs]
Min	20.510	0.134	2.952
Max	21.413	0.149	3.047
Avg	20.961	0.141	3.000

Table 3.4: The results of the simulation at the system level.

server while the customers of the second class visit either the storage or the Apache server according to a probabilistic algorithm. All *Class0* customers go to the *Load Balancer* and their interarrival times are hyperexponentially distributed with parameters $(p, \lambda_1, \lambda_2) = (0.291, 0.182, 0.442)$, see Figure 3.94, resulting in a mean value equal to 3.2 sec and coefficient of variation equal to 1.192.

The interarrival times of *Class1* customers are exponentially distributed with mean 5 sec. In order to model the RAID0 striping algorithm a Fork station is used. When a request arrive at the Fork station *RAID0* it is splitted in three requests sent in parallel to all the disks of the storage server. Fork degree at *RAID0* station is 3, that is, for each incoming request three requests are generated in each outgoing link. Service times for all the disks - *Disk1*, *Disk2* and *Disk3* are 5 for *Class0* and 0.5 for *Class1* customers respectively. An FCR is used in order to model the Apache server, which contains two web servers - *Web Server 1* and *Web Server 2*, that accept a maximum number of requests equal to 100. The *load balancer* station in this FCR split the load among the two web servers with the following algorithms: *Class0* customers with *Join the Shortest Queue* and *Class1* customers with *Shortest Response Time*. The service times for both Web Servers are 1 sec for both the classes.

According to some enterprise objectives, we need to study the behavior of this system when the *Service Times for all classes* of *WebServer1* increase from current values to 150%. Particularly, we want to forecast the *System Response Time* for both *Class0* and *Class1* customers at *Confidence Interval* 0.99 and *Maximum Relative Error* 0.05. We want also to know the global *throughput* of *WebServer1* at *Confidence Interval* 0.90 and *Maximum Relative Error* 0.10. Thus, the control parameter that should be selected in the What-If Analysis is the *Service Times for all classes*.

Defining the model

- Insert *Source*, *Fork*, *Join*, *Routing*, *Queueing Stations* and *Sink* as required in the problem considered.

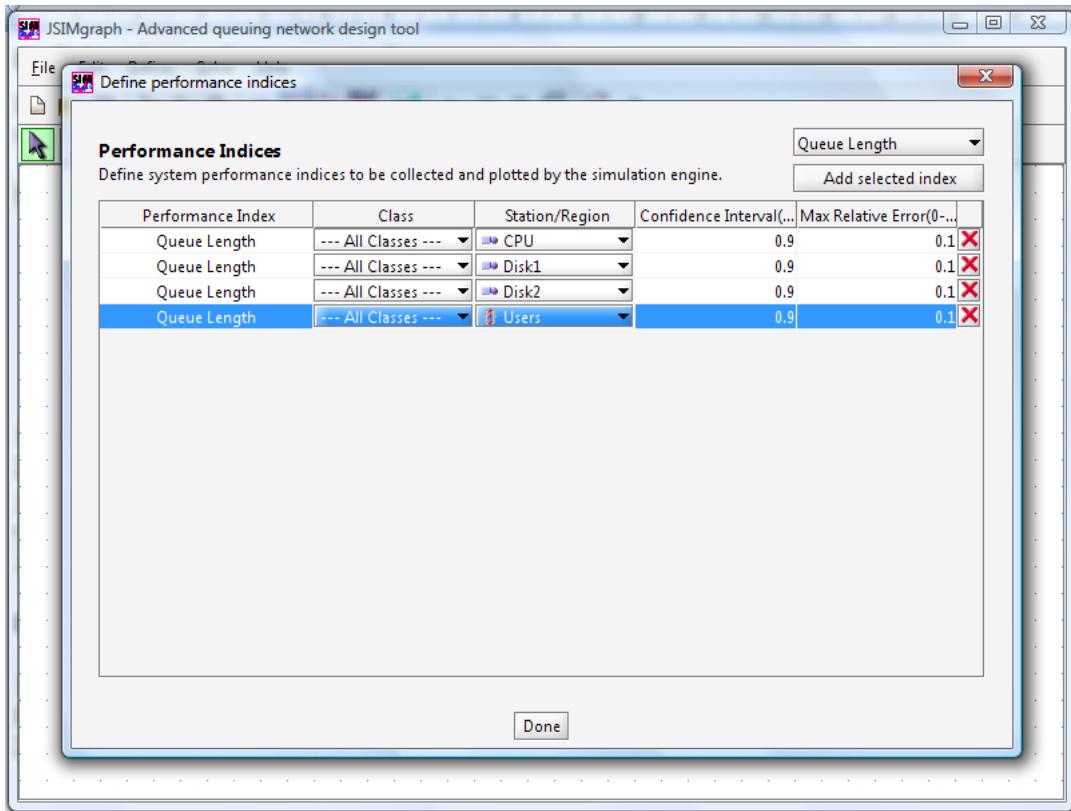


Figure 3.89: Setting the Queue length performance index

Then connect them according to the specifications.

- Double click on the added resource, rename each of them as given in the problem.
- Hold Ctrl key on the keyboard and select **Load Balancer**, **Web Server 1** and **Web Server 2**. Then click on the icon. It will create a new Finite Capacity Region consisting of those three elements.
- Double click on the finite capacity region, rename it as Apache, uncheck the infinite checkbox and set Region Capacity as 100. Click Done.
- From the menu bar choose **Define** → **Customer Classes**. Add two open customer classes - *Class0* and *Class1*. *Class0* is hyperexponentially distributed with $(p, \lambda_1, \lambda_2) = (0.291, 0.182, 0.442)$. *Class1* is exponentially distributed with mean value 5.
- Double click on **Requests**. Set **routing strategy** for both *Class0* and *Class1* as **Probabilities**. Since all *Class0* customers go to the LoadBalancer, set **Probability** of the LoadBalancer as 1. Whereas, since the *Class0* customers may go either to the LoadBalancer or to the RAID0 station, set the **Probability** of both LoadBalancer and RAID0 as 0.5. Then Click on Done (see Figure 3.95).
- Double click on RAID0 and set **Fork degree** at 3 (see Figure 3.96).
- Double click on the disks, then, clicking **Edit** in the **Service Section** tab, set the mean values for all the disks - *Disk1*, *Disk2* and *Disk3* as 5 for *Class0* and 0.5 for *Class1*.
- Double click on the LoadBalancer. Set the **Routing Strategy** of *Class0* to **Shortest Queue length**, and that of *Class1* to **Shortest Response Time** (see Figure 3.97).
- By double clicking on the Web Servers, then under the **Service Section** tab, by clicking **Edit**, set the mean values for all the web servers - *WebServer1* and *WebServer2* as 1 for both the classes.
- From the menu bar **Define** → **Performance Indices** add the index **System Response Time** twice - the first one for *Class0* and the second one for *Class1*. Change the **Confidence Interval** to 0.99 and **Maximum Relative Error** to 0.05. Then add the index **Throughput**. Set its **Station/Region** as *WebServer1* (see Figure 3.98).
- From the menu bar choose **Define** → **What-if analysis**. Check the checkbox **Enable What-if analysis**. Select the **Service Times** parameter. Set **To(%)** as 150, **Steps (n. of exec.)** as 10 and **Station** as *WebServer1*. Keep the values of the **Arrival Rates** parameter as it is (To should be 150 and Steps should be 10). Steps in the **Seed** parameter should remain 10 by default. Click **Done** (see Figure 3.99).

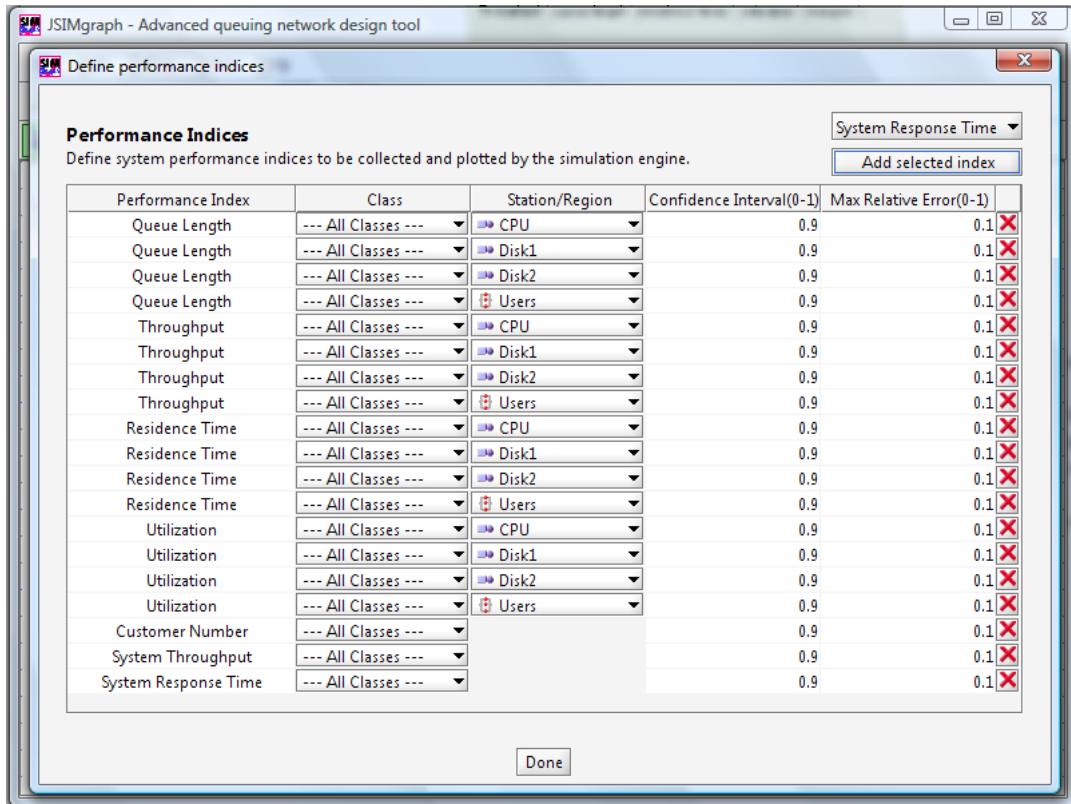


Figure 3.90: The Define Performance Indices window at the end of the selection of the indices

- To run the simulator - press **Alt+s** or select **Simulate** from the **Solve** menu or press from the toolbar. Note that if you had run the simulation for the same program before, JSIMgraph asks for your confirmation whether you want to replace the previous simulation results or not. Choose **yes** to carry on. If we look the drawing window of the Simulator, we can see the simulation going on.

The windows of Fig.s 3.100, 3.101, 3.102 show the results of the What-If Analysis. Note that the results of different simulation runs may slightly vary due to the differences in the sequence of random numbers generated with different seeds.

3.15.3 Example 3 - Using FCR for modeling Bandwidth Contention

The FCR(Finite Capacity Region) can be used to model the contention of resources that can be located in several positions in the model even if they are *not adjacent*. This feature can be particularly useful if we have to model the contention of bandwidth. The queue for entering the FCR accept priorities, so a request with high priority may enter the FCR as soon as one request exit the FCR (when the number of requests inside the FCR is equal to the max admitted).

The problem definition

Consider a configuration consisting of a workstation sending requests over an Intranet which is composed of Web server, Application Server and Database Server and can handle only up to 100 requests at any given time. The application server in the Intranet further connects itself to a remote server using Ethernet connection which clearly can handle only 1 request at any time.

How to model

- Insert Source, Routing Station, Queueing Stations and Sink.
- Double click on the added resources and rename them as shown in the Figure 3.103.
- Hold the Ctrl and select the Web Servers, Application Server and Database Server and then click the icon. It will create the first Finite Capacity Region.

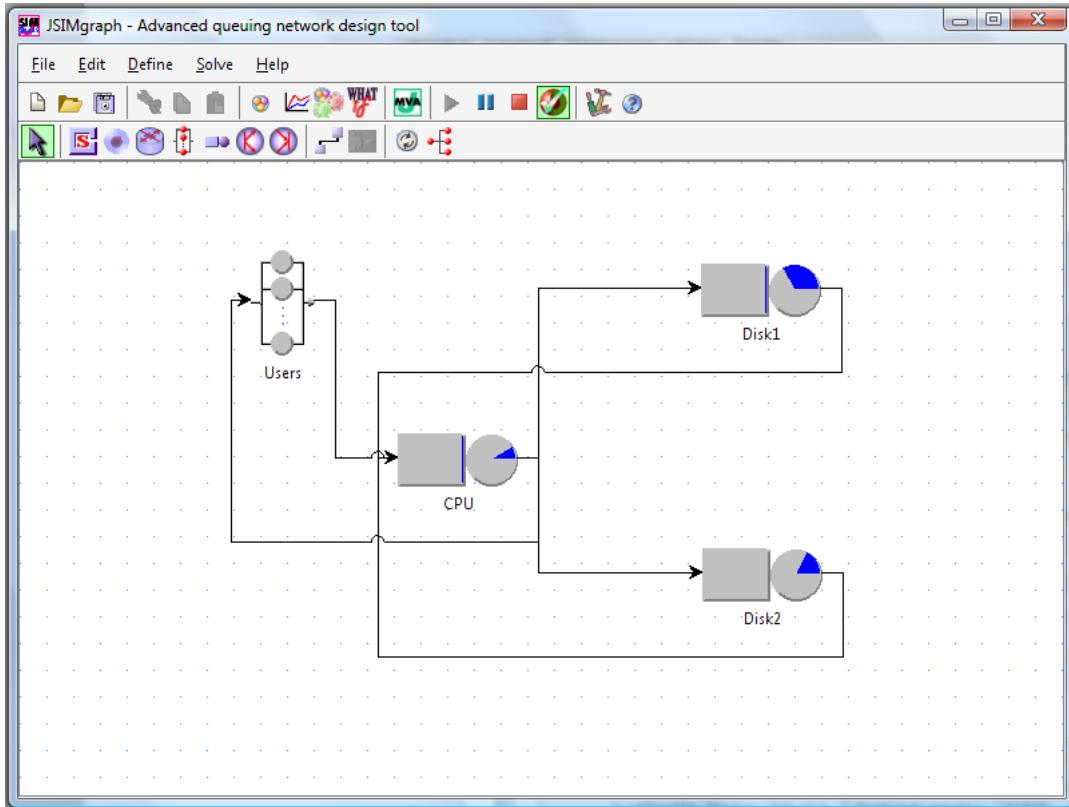


Figure 3.91: Example 1 - The layout of the model with the percentage of utilization and queue length (colored areas)

- Double click on the finite capacity region and rename it to **Intranet**, uncheck the infinite checkbox and enter a region capacity (max = 100) as shown in Figure 3.104.
- Add the classe(s) from the menu.
- Now hold the Ctrl and select the transmission system and Ethernet Cable and click icon. It will create another finite capacity region which represents data flow over a Ethernet cable.
- Double click on FCR and rename it to **Ethernet**, uncheck the infinite checkbox and set the max region capacity to 1.
- Insert the Performance indices you are interested to evaluate.
- Insert the preferred routing and queueing policies.
- Run the simulation.

It is an interesting topic of study in performance evaluation is to model the contention for a set of resources, that can be either directly connected or not connected at all. As seen above the FCR structure allows to fix the maximum number of customers in a set of resources and also allows the priority scheduling.

3.15.4 Example 4 - Closed models with class-switch.

Class-switch allows the definition of models where customers may change class (i.e., their characteristics) during the execution.

In such models the number of jobs of any class may no longer remain constant, thus the *population mix* vector is not constant (for a formal definition of the *population mix* vector please refer to section 6.2.6).

In this example we run a model with an initial population mix and analyze what is the equilibrium state of the population mix vector.

Open JSIMGraph, click on and draw the model reported in Figure 3.105. As mentioned before we want to study how the population mix vector evolves over the time, thus first of all we have to set the initial state.

Click on and, as shown in Figure 3.106, add two closed classes and set their *Population* field to 500.

In this way the initial population mix vector is [0.5, 0.5]. In order to set the **C** matrix of the class switch

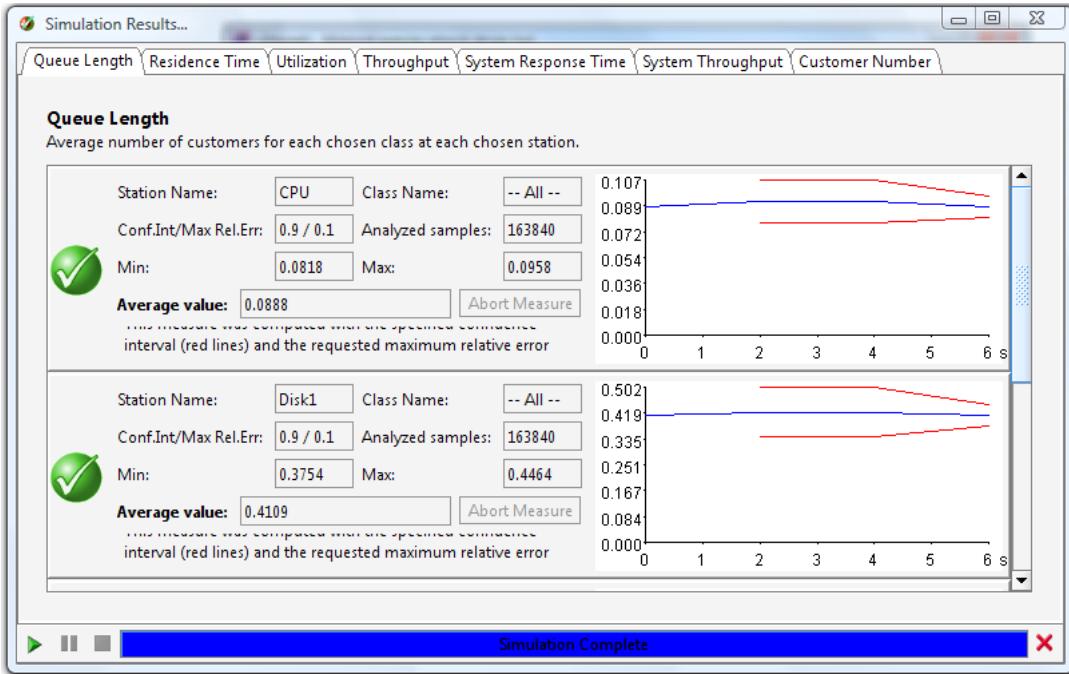


Figure 3.92: Progress of the simulation (average values and confidence intervals)

component double click on it and input the following matrix (Figure 3.107)

$$\mathbf{C} = \begin{vmatrix} 0.8 & 0.2 \\ 0.6 & 0.4 \end{vmatrix} \quad (3.10)$$

Before to start the simulation we have to define the performance indices. Our goal is to measure the equilibrium state of the population mix, thus we use the *System Number of Customers per class*.

Click on and set the performance indices as shown in Figure 3.108.

Now click on to start the simulation. As shown in Figure 3.109, the equilibrium state of the population mix is about [0.666, 0.333].

For this simple model the result obtained with simulation can be validated in an analytical way.

Indeed, considering the matrix C defined by Equation 3.10 and indicating as β_1 the percentage of jobs of *Class0* and β_2 the percentage of *Class1* at the equilibrium, the following equations hold

$$\begin{cases} \beta_1 = 0.6\beta_1 + 0.8\beta_2 \\ \beta_2 = 0.4\beta_1 + 0.2\beta_2 \\ \beta_1 + \beta_2 = 1 \end{cases} \quad (3.11)$$

The solution of the system of equations (3.11) is $\beta_1=2/3$ and $\beta_2=1/3$, thus the *population mix* vector is $\{2/3, 1/3\}$. We found these values also from simulation.

3.16 jSim Log

The jSim Log is a debug log file for the JSIMgraph to understand the anomalies in the tool. If the tool crashes during simulation or if the user finds some inconsistency in the results of the simulation then they can upload this debug log file, so that the developers can understand and fix the problem. The logging of the events are done during the simulation. The file is written to append to a maximum size of 512KB, then the older lines are discarded in order to maintain the maximum size.

3.17 Command line for JSIMgraph

It is possible to start a simulation JSIMgraph from *command line*. The only file needed is the *jsim/jsimg zml* file. The simulation engine can be started with the *JMT.jar* file invoked as following:

```
java -cp JMT.JAR jmt.commandline.Jmt sim <File.xml> [options].
```

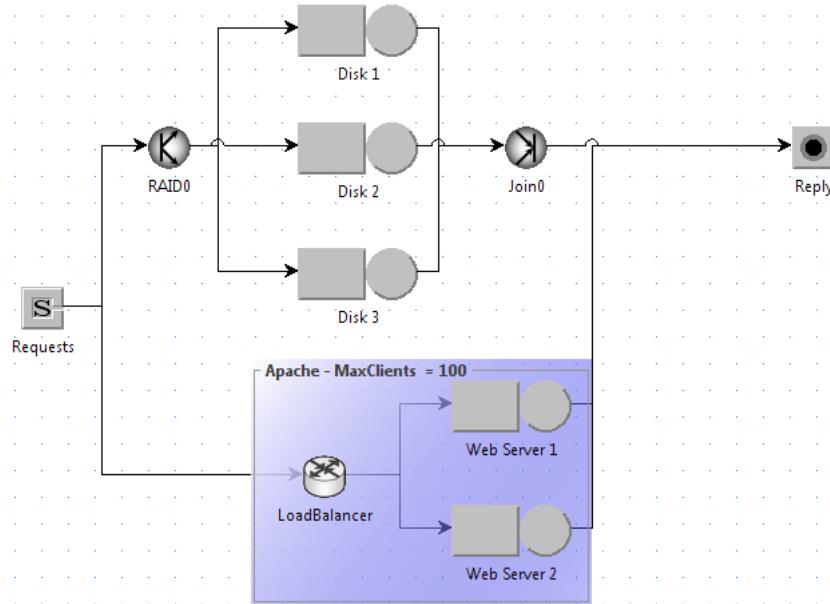


Figure 3.93: Example 2 - A system with a multiclass workload, a RAID0 storage server (modelled with Fork and Join Stations), and a web server consisting of two systems used in parallel, with a limited number of requests in execution (modelled with a Finite Capacity Region)

The options are:

-seed 1234 : sets the simulation seed to 1234

-maxtime 60 : sets the maximum simulation time to 60 seconds .

Example of a command line:

```
java -cp JMT.JAR jmt.commandline.Jmt sim c:\mymodelname.jsimg -maxtime 120 -seed 4546
```

The *JMT.jar* file is located in the same directory where the JMT tool is installed.

As for the MVA Solver, the **File.xml** parameter is a well formed XML File according to the *JMTmodel.xsd* schema described in subsection 2.8.1. At the end of the computation, performance indices will be placed into the **solutions** element of a new file which has the same filename with the input file but with "-result.jsim" appended.

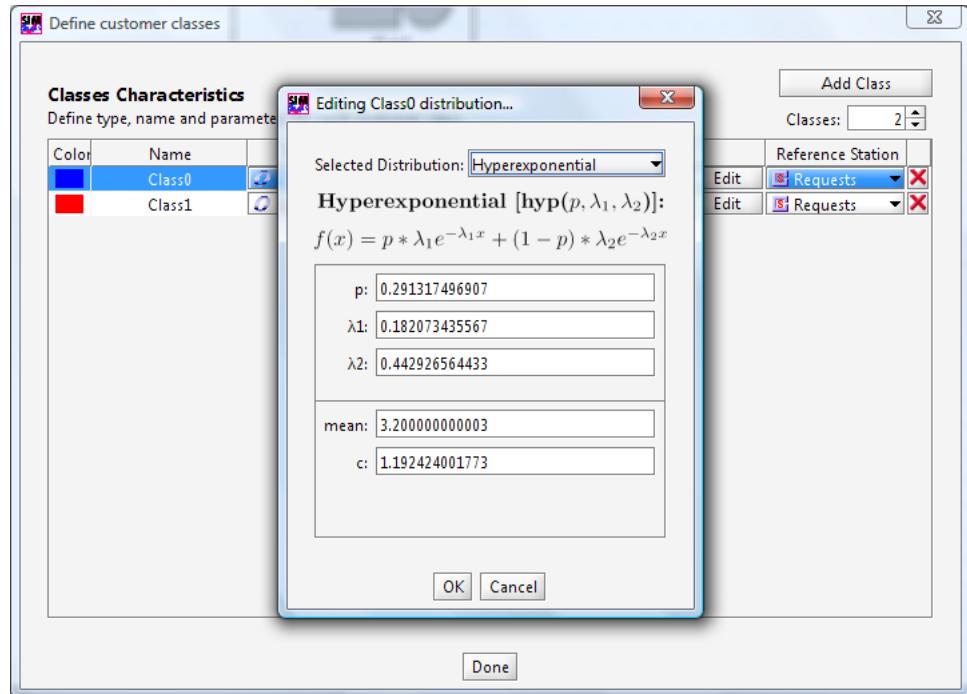


Figure 3.94: Definition of the hyperexponential distribution of *Class0* customers

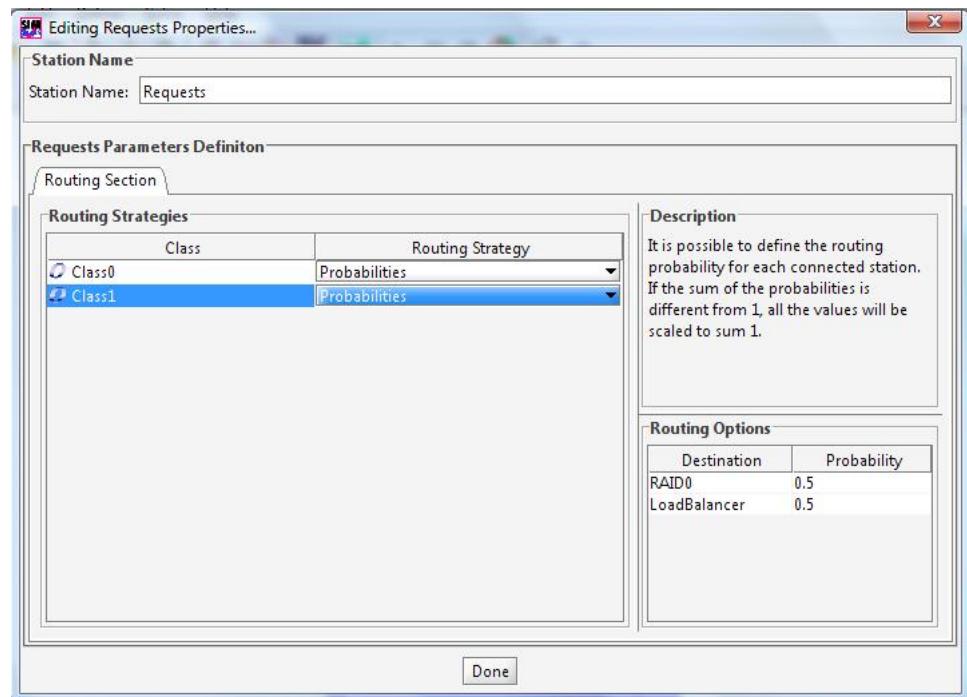


Figure 3.95: Setting the Routing strategy (*probabilities*) in output of station *Requests* for Class1 customers

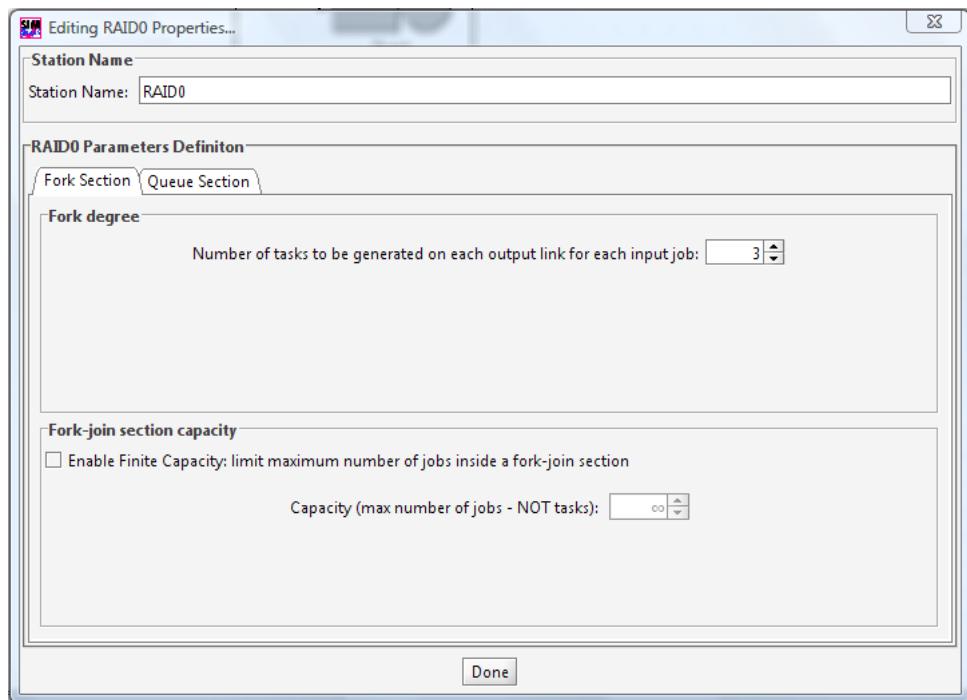
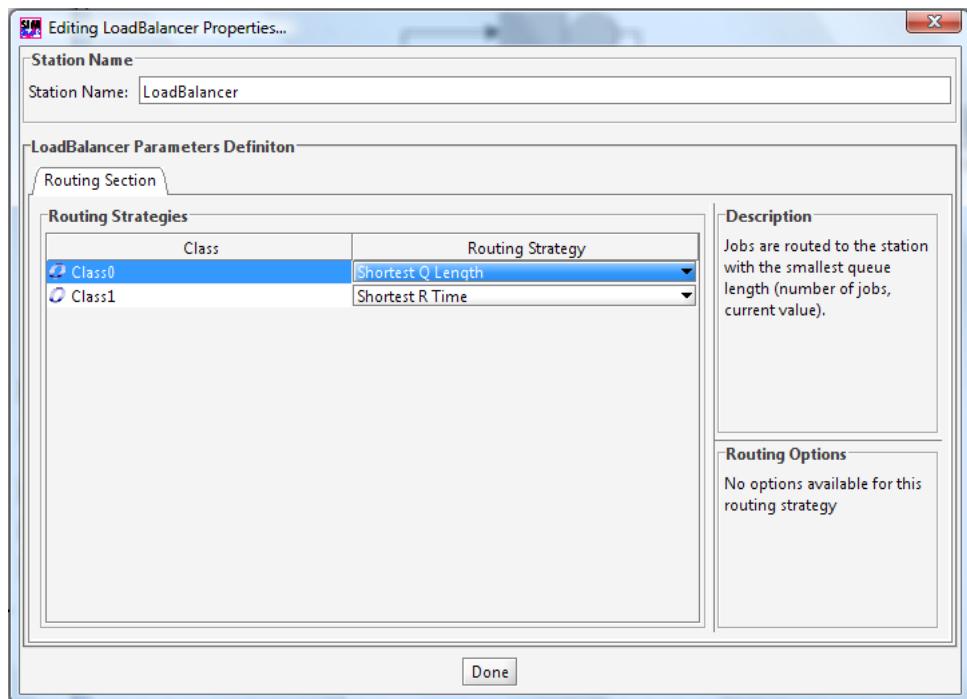
Figure 3.96: Setting the RAID0 *Fork* station properties

Figure 3.97: Edit Loadbalancer properties

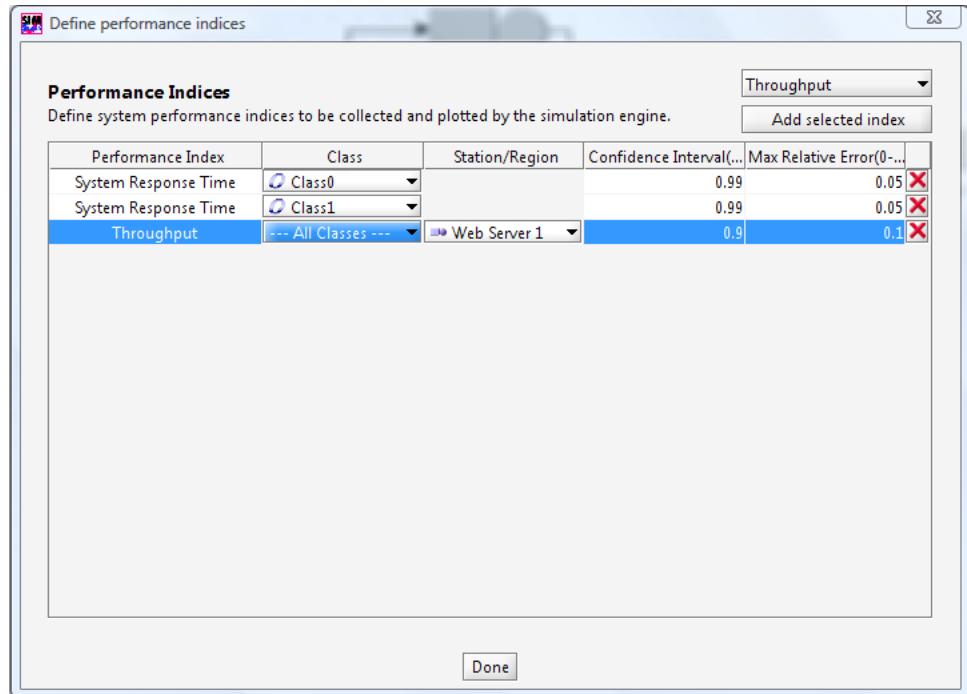


Figure 3.98: Definition of the performance indices, Confidence Interval, and Max Relative Error.

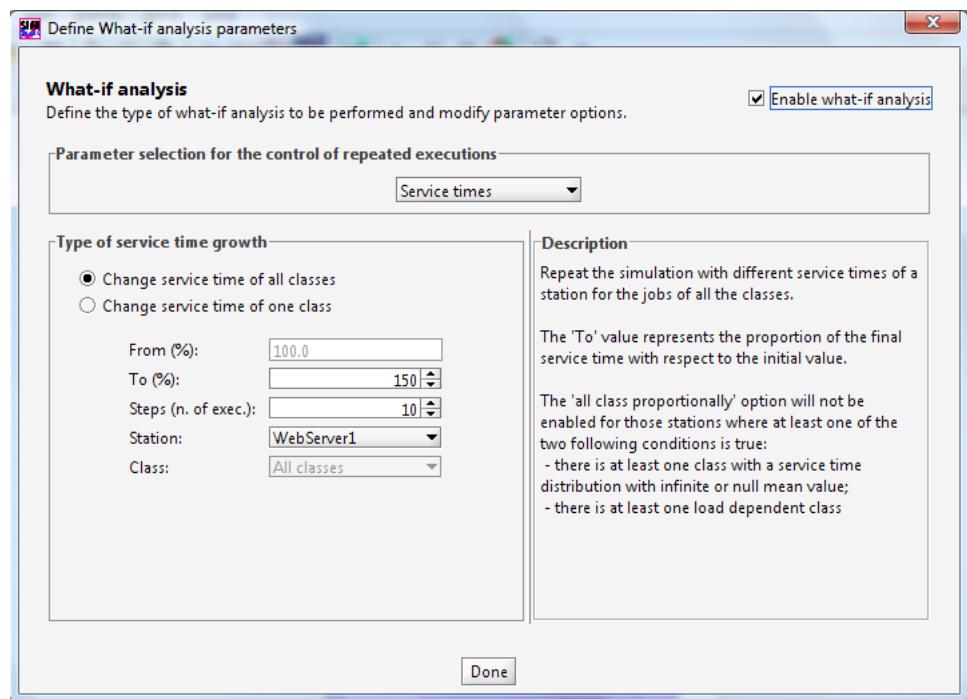
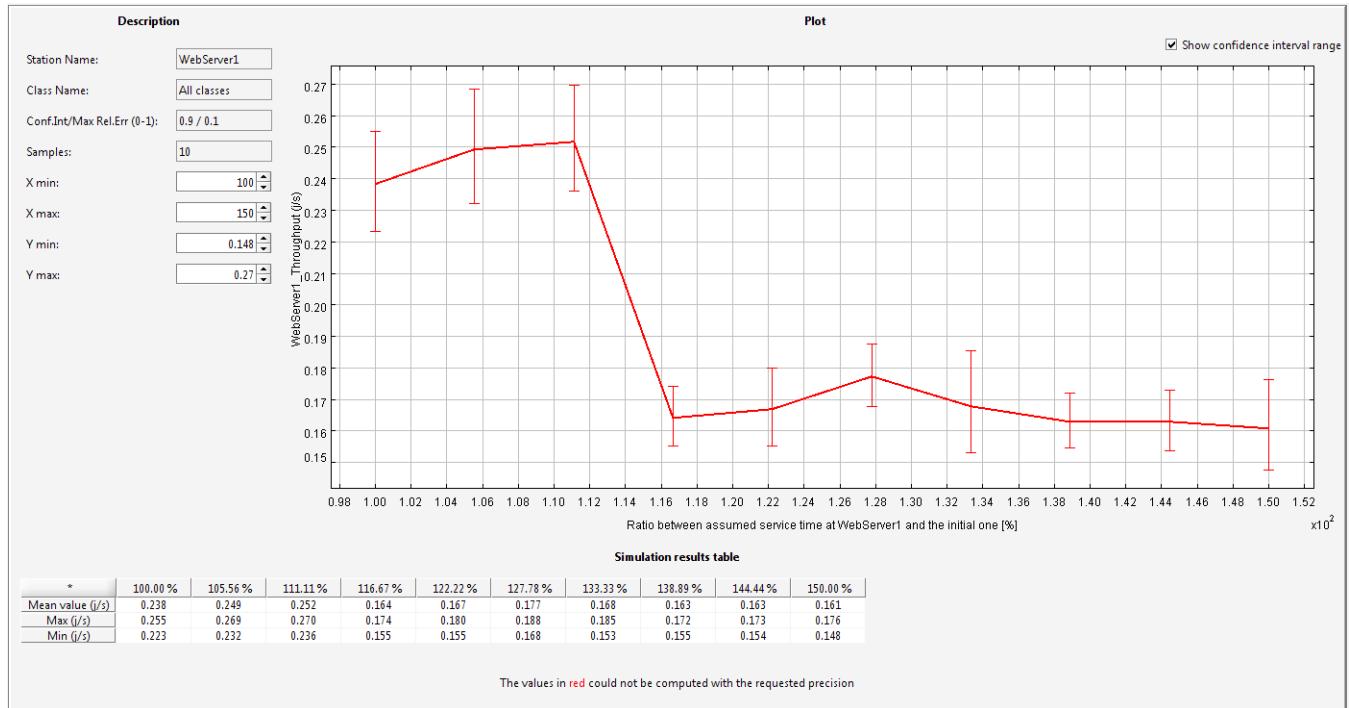
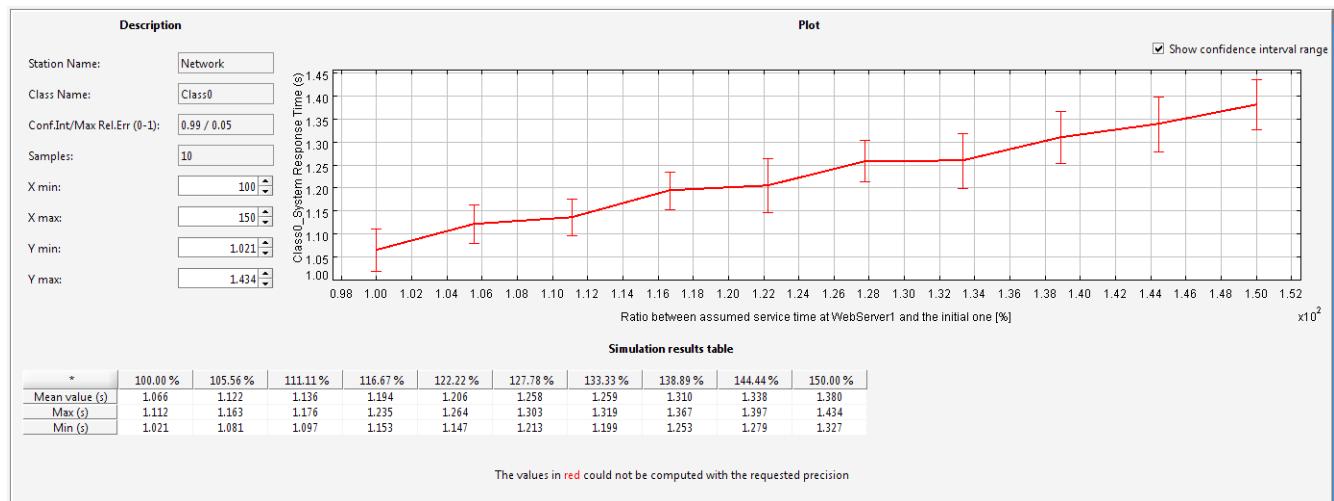
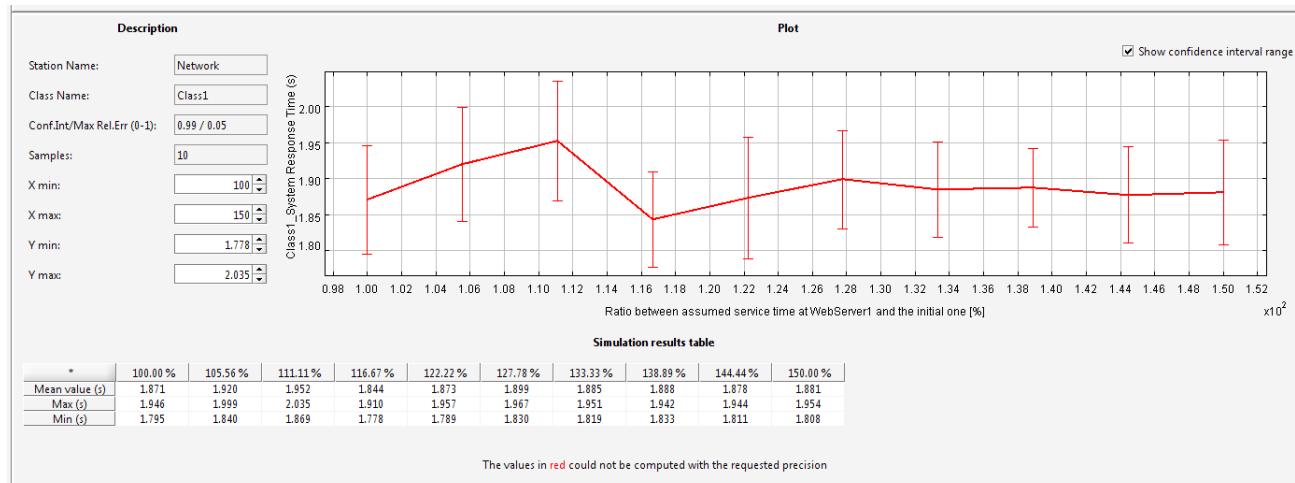


Figure 3.99: Setting the What-If-Analysis parameters.

Figure 3.100: Throughput of the station *WebServer1* for all the classes of customers.Figure 3.101: Behavior of System Response Time for *Class0* customers.Figure 3.102: Behavior of System Response Time for *Class1* customers.

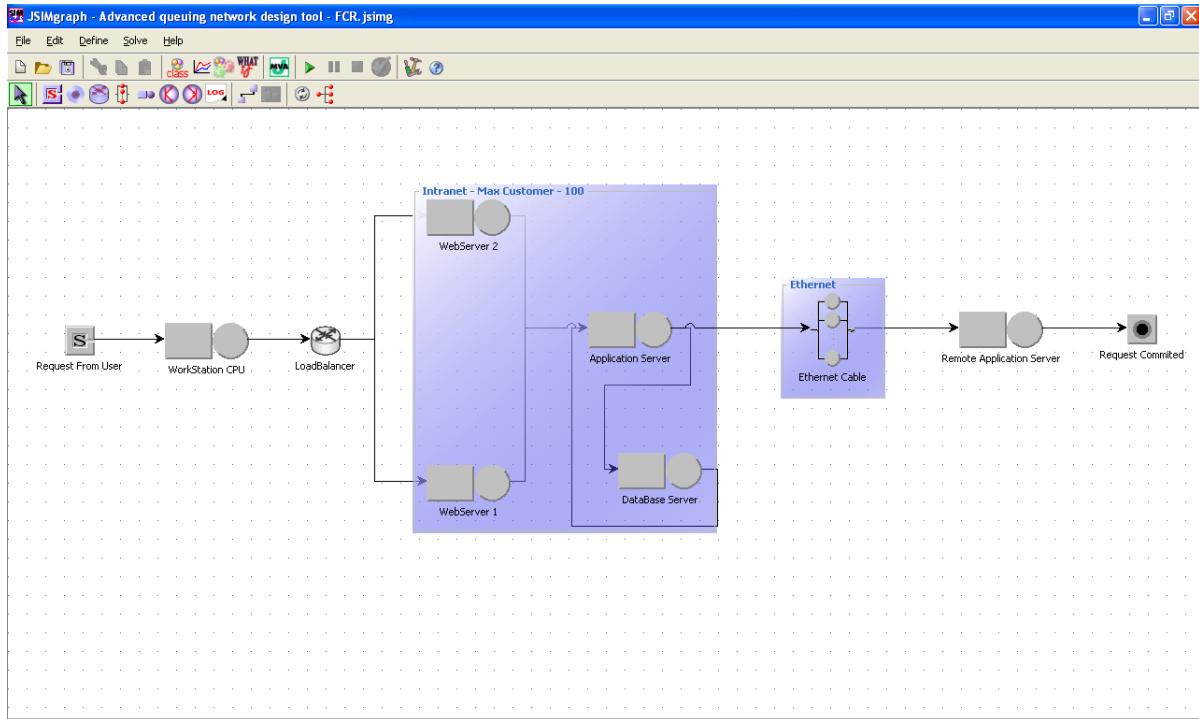


Figure 3.103: Example 3 - Model with 2 different FCRs. The first one, labelled as **Intranet**, allows maximum 100 customers to be concurrently in execution, while the second one, labelled as **Ethernet**, allows only one customer maximum in execution.

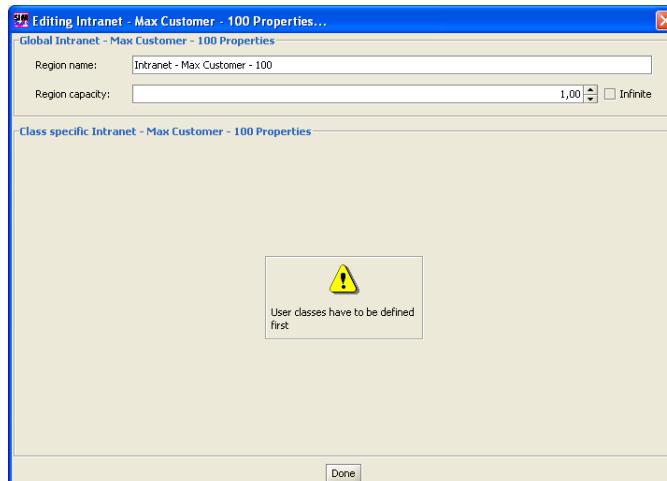


Figure 3.104: Example 3 - Setting capacity in FCR.

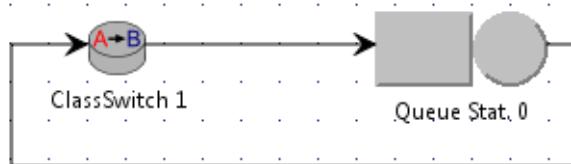


Figure 3.105: Example 4 - Two-class closed model with a class-switch station.

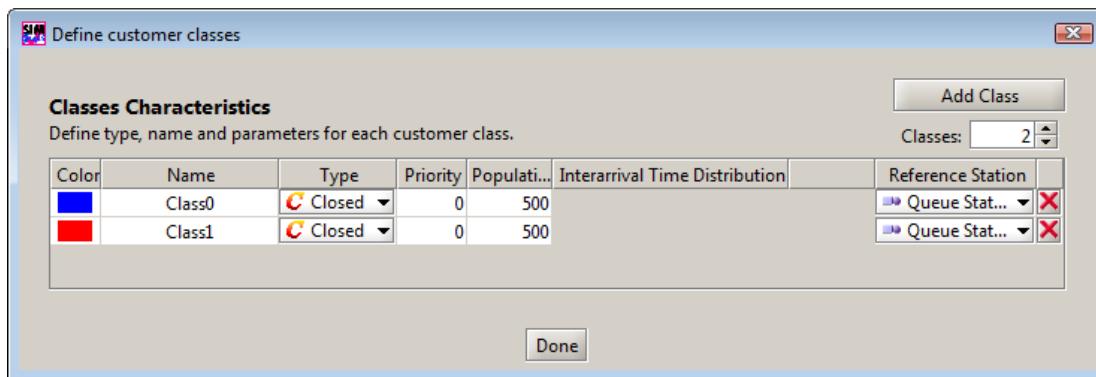


Figure 3.106: Example 4 - Initial state definition.

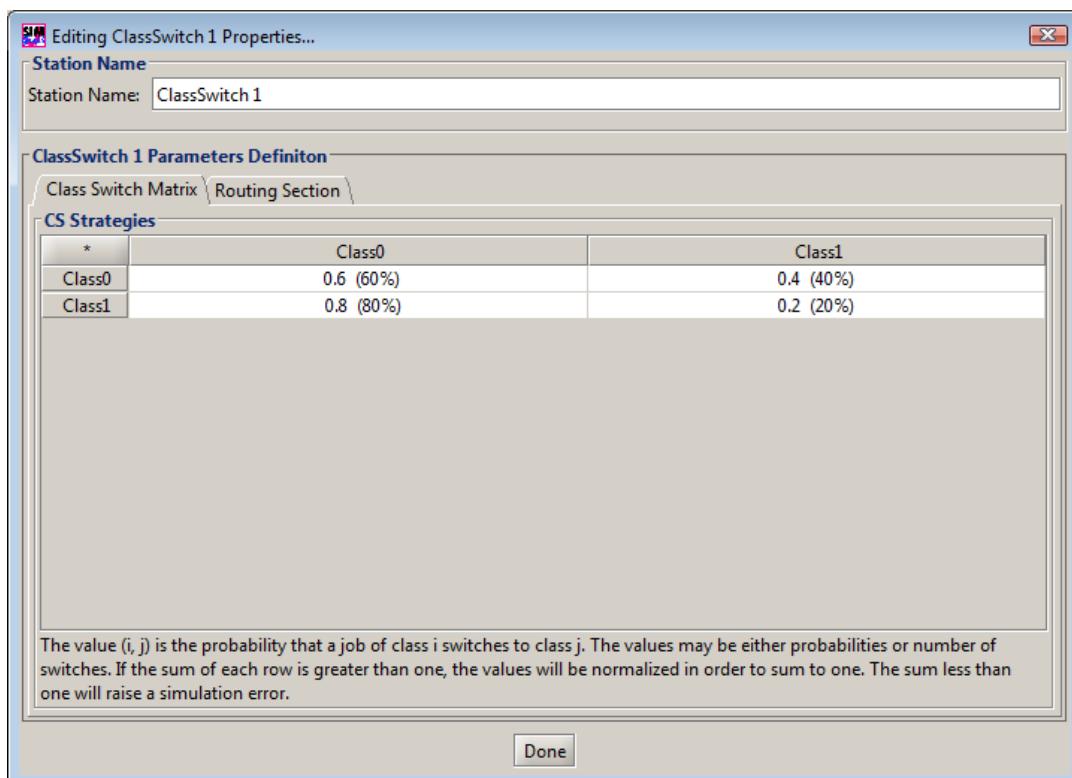


Figure 3.107: Example 4 - Class switch matrix.

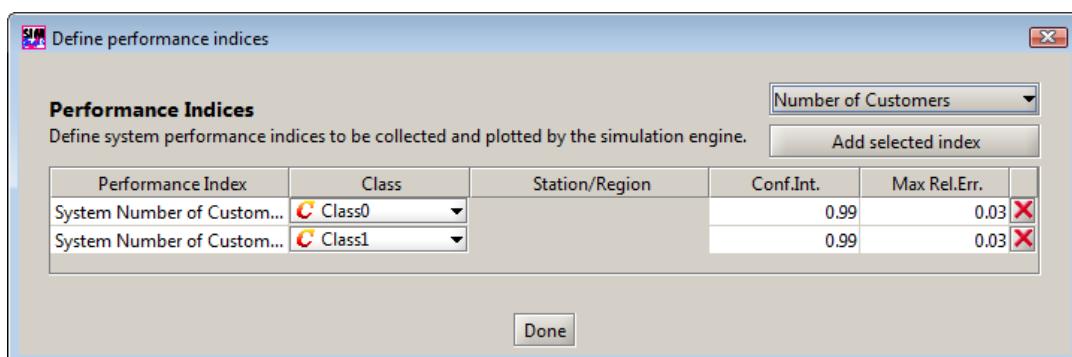


Figure 3.108: Example 4 - Performance indices definition.

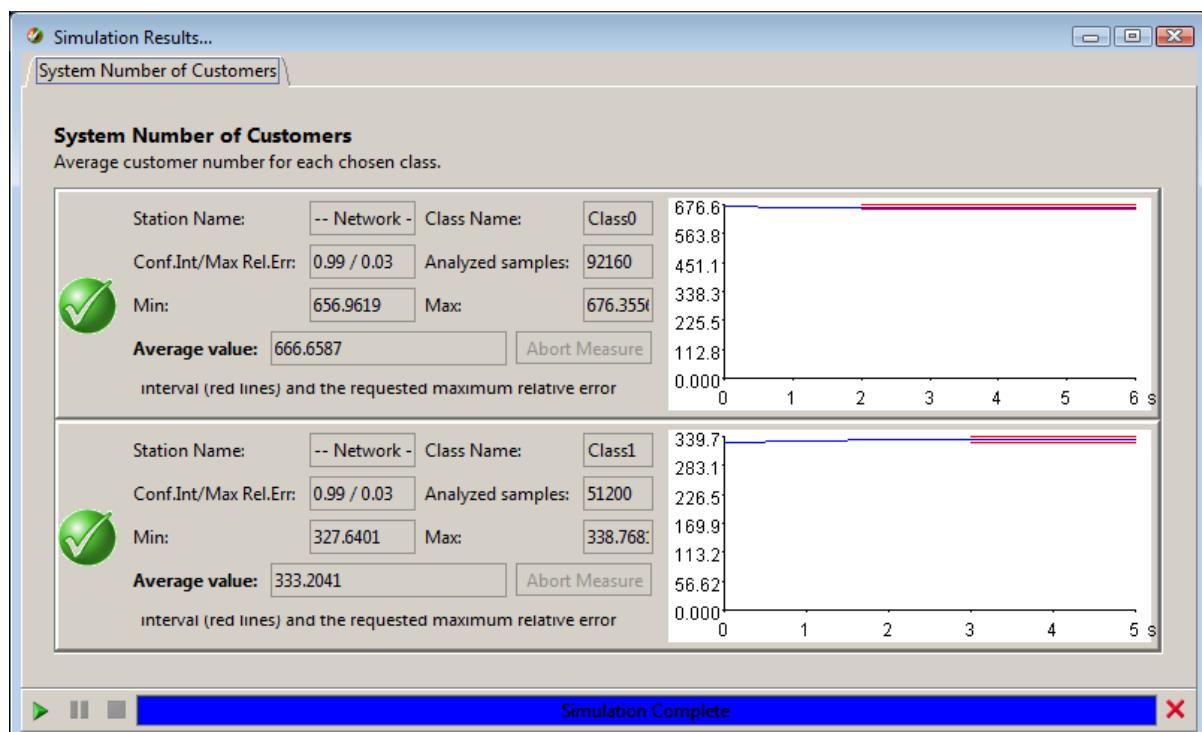


Figure 3.109: Example 4 - Results.

Chapter 4

JSIM*wiz* (Simulation - Textual)

4.1 Overview

Simulation can be applied when the characteristics of the network to be analyzed make analytical techniques no longer useful for its performance evaluation. A simulator is a dynamic model able to follow the evolution in time of both the system complexity it represents and the pattern of arrival requests to be executed.

In the JMT *suite* a discrete-event simulator JSIM for the analysis of queueing network models is provided. It can be used through two interfaces: alphanumerical (JSIM*wiz*) and graphical (JSIM*graph*). **The manual of JSIM*graph* is much more detailed than this one. If some information are omitted or unclear in this chapter you may consult the chapter of JSIM*graph*.**

An intuitive user interface allows even an unexperienced user to build with JSIM*wiz* system models with sophisticated characteristics. It helps the users to perform an evaluation study in two ways. Firstly, critical statistical decisions, such as transient detection and removal, variance estimation, and simulation length control, have been *completely automated*, thus freeing the users from taking decisions about parameters s/he may not be familiar with. The simulation is automatically stopped when all performance indexes can be estimated with the required accuracy. Secondly, a user-friendly graphical interface allows the user to describe, both the network layout and the input parameters. Furthermore, the graphical interface also provides support for the use of advanced features (several of them are for networks with very general characteristics, usually referred to as *non-product-form* networks) like fork and join of customers, blocking mechanisms, regions with capacity constraints on population, state-dependent routing strategies, user-defined general distributions, import and reuse of log data. A module for *What-If Analysis*, where a sequence of simulations is run for different values of control parameters, particularly useful in capacity planning, tuning and optimization studies, is also provided.

The simulation engine performs on-line the statistical analysis of measured performance indices, plots the collected values, discards the initial transient periods and computes the confidence intervals.

All the plots generated by a simulation can be exported in vector (e.g., eps, pdf) or raster (e.g., jpeg, png) image formats.

Main Features

Arrival rates for open classes of customers generated by Source stations and station *service times* (for any type of station in open and closed models) can be generated according to the following distributions: Burst (general), Burst (MMPP2), Constant, Erlang, Exponential, Gamma, Hyperexponential, Normal, Pareto, Poisson, Student-T, Uniform

Queueing discipline: the following strategies are available: First Come First Served (FCFS) , Last Come First Served (LCFS), Random (RAND), Shortest Job First (SJF), Longest Job First (LJF), all with or without priority.

Routing of the customers in the network, i.e., the path followed by the requests among the resources, can be described either probabilistically or according to the following strategies: Fastest service, Least utilization, Random, Round robin, Join the Shortest Queue, Shortest response time (the values of the control parameters are evaluated on the stations connected in output to the considered one), Load Dependent Routing. These strategies can be further combined among themselves through the use of a *routing station*.

Other peculiar features of the simulator are:

- Load dependent service time strategies
- Fork-and-join stations to model parallelism
- Simulation of complex traffic pattern and service times (e.g., burst)
- Blocking regions (in which the number of customer is limited)
- What-if analysis (with various control parameters)
- Customization of default values
- Import/Export of the model from/to JMVA, the exact solver (when the required analytic assumptions are satisfied)
- Logging of the job flows in any part of the model (*Logger* station)
- Graphical visualization of the evaluated performance indices together with their confidence intervals
- automatic transient detection and removal
- automatic stop of the simulation when all performance metrics can be estimated with the required accuracy.

JSIMwiz has a modular Java-based architecture that allows the introduction of new Java classes in the simulation engine without any modification to the source codes of the other classes.

4.1.1 Starting the discrete-event simulator

Selecting  button on the starting screen, Figure 4.1 window shows up. Three main areas are shown:

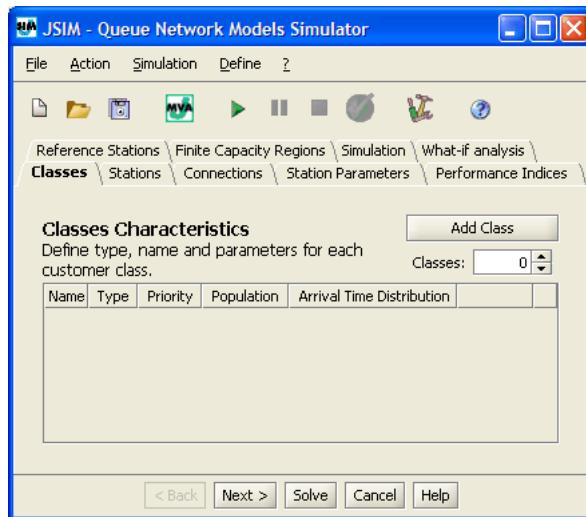


Figure 4.1: The home window of JSIMwiz simulator

Menu : it is organized into three groups of functions. To use a menu, click on the menu heading and choose the appropriate option. For the description of menu entries, see section 2.6

Toolbar : contains some buttons to speed up access to JSIM functions (e.g. New model, Open, Save...). If you move the mouse pointer over a button a tooltip will be shown up.

Page Area : this is the core of the window. All JSIM parameters are grouped in different tabs. You can modify only a subset of them by selecting the right tab, as will be shown later.

4.2 Defining a new model

To define a new model, select the New command from the File menu, or the button  or use the shortcut CTRL+N. A new model is automatically created every time JSIM is started.

The following parameters must be defined in order to complete the new model:

- Classes
- Stations
- Connections

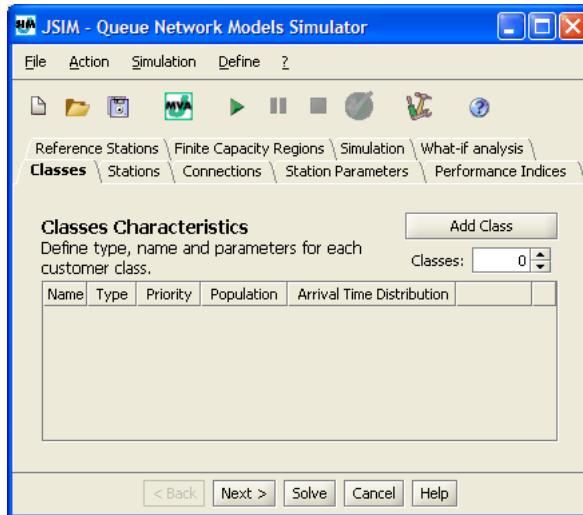
- Station parameters *
- Performance indices
- Reference stations
- Finite capacity regions *
- Simulation *

To set each parameter, follow the user manual step by step.

NOTE: if no values are provided for the parameters marked with *, default values will be used and the simulation will run anyway.

4.2.1 Define Classes

Customer classes identify different customer behavior and characteristics, such as the type (closed or open), the size of the customer population (for closed classes) or the interarrival time distribution (for open classes). They can be set using the **Classes** tab during the creation of a new model.



Adding a Class

Classes must be explicitly added to the model, either one at a time by clicking the **Add Class** button, or by selecting directly the final number of classes desired in the form **Classes: 0**. The newly added classes will be listed with default parameters.

Double click on the default name (ClassN) to change it.

Each new class has a priority in the system. A smaller number indicates a lower priority. Default value is 0 and it can be changed by double clicking on the corresponding area.

Defining the Class Type: Open Classes

After adding a class and possibly changing its name and priority, you must choose the type of customers comprising the class. Classes are created Closed by default, so if you want an Open class, select the type **Open** in the menu. The class characteristics looks like this now



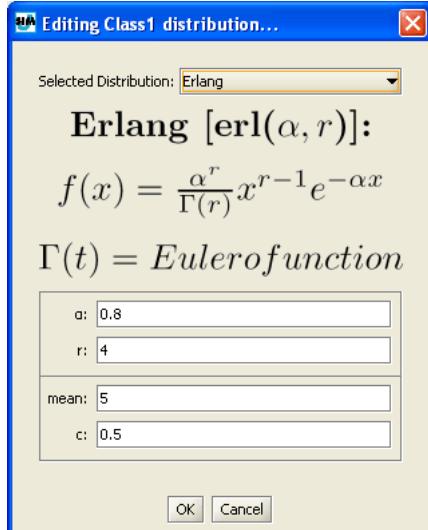
Name	Type	Priority	Population	Arrival Time Distribution	
Class5	Open	0		exp(1)	Edit X

Open classes describe customer populations that vary during time, therefore they are best characterized by the probability distribution of the interarrival time, rather than by a constant number of customers. The default Interarrival Time Distribution is $\exp(1)$ (Exponential Distribution with $\lambda = 1$).

To change the Interarrival Time Distribution click the **Edit** button



The following window will appear

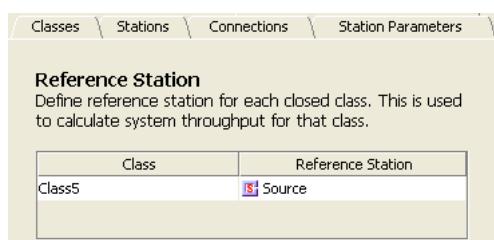


Click on the Selected Distribution drop down menu to choose from any of the following distributions (see section 3.5):

- Burst (General)
- Burst (MMPP2)
- Constant
- Erlang
- Exponential
- Gamma
- Hyperexponential
- Normal
- Pareto
- Poisson
- Replayer
- StudentT
- Uniform

In each case, it is possible to configure the distribution parameters as you wish, or use the default values. Parameters that are related each other are automatically adjusted if one is modified (for example, the figure shows how for an Erlang distribution, if you set the (α , r) pair, the (mean, c) pair is automatically adjusted to the correct value). The Replayer distribution allows you to provide data traces from files. Click OK when you are done to return to Class parameters definition.

The final step in defining a class is the definition of the Reference Station, i.e., that station in the model with respect to which the performance indices will be computed. For Open classes there is no choice since the Source station is the unchangeable default Reference Station used to compute System Throughput for all the Open classes.

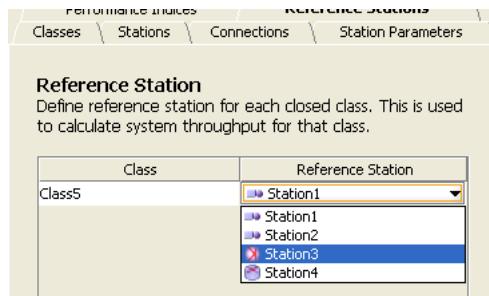


Defining the Class Type: Closed Classes

Name	Type	Priority	Population	Arrival Time Distribution	
Class5	Closed	0	1		X

Classes are created **Closed** by default, so there is not need to change the Type. Priority can be changed as in the Open class case. The population size is the parameter that characterizes a Closed class. It is fixed and does not change for the entire life of the system. By default is 1 and it can be changed by clicking on the corresponding area in the class properties matrix.

The final step is to define a **Reference Station** for the class that will be used to compute the performance indices selected for the class. Use the **Reference Station** tab menu to select the **Station**. All stations but the **sink** can be used as **reference station** for a closed class.

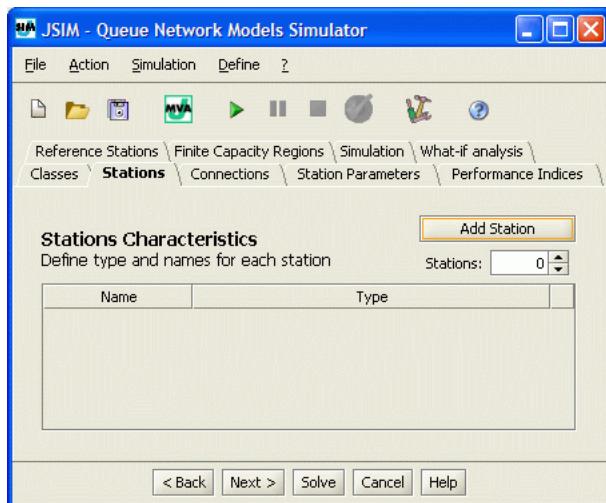


Distributions

See section 3.5

4.2.2 Define stations

When you create a new model, you must define the Stations from the **Stations** page of the tabs menu.



You can insert one station at a time, by pressing the **Add Station** button, or multiple stations all at once, by choosing the desired number in the input form **Stations:** The added stations will be listed in the page. Various types of stations are available, the default type being *server*. If you want to remove any of the stations, select the target and press the corresponding **X** delete button. Stations are name Station1, Station2, and so on by default. If you want to assign model-relevant names, left-click on a name to change and replace it. Similarly, if the default station type *Server* is not what you need, select from the drop down menu of each station the correct type.



You can choose among the following types of station:

1. Delay station:

Customers that arrive at this station are delayed for the amount of time that defines the station service time. They do not experience any queueing, since a delay station is modelled as a station with an infinite number of servers with identical service time. Because customers never have to wait for service, response time at delay stations is equal to service time, $R_i = S_i$. Furthermore, the queue length corresponds in this case to the number of customers receiving service since there is no waiting in queue: $N_i = R_i X_i = S_i X_i = U_i$. The utilization of the delay station represents the average number of customers receiving service (i.e., in think state) so it may be *greater* than 1! Delay stations are used when it is necessary to reproduce some known average delay (with the selected distribution). Application of delay stations may be to model transmission time (download, upload, ...) of large amounts of data over a network (Internet, lans, ...) or to model users think time at the browsers.

In the **Station Parameters** tab menu page, you can modify:

Service Section: in this section you can choose the service time distribution for the station. For more information, see Service section section 4.2.2.

Routing Section: in this section you can specify how serviced customers should be routed to the next station they will visit in the model. For more information, see Routing section section 4.2.2.

2. Server station:

The Server station is one of the most important components in a queuing network model. Service stations represent the service facilities of the system being modeled. A server station provides the required service to its customers. Server stations may have any (finite) number of servers. If all the servers in the service station are busy when a customer arrives at the station, the arriving customer is put in a waiting queue until its turn to receive service from the first available server is up. The queueing discipline decides which customer is served next when a server becomes free. Therefore, the response time at server stations includes service time and queuing time. Server stations may have more than one server. Their number is a parameter to be specified (default is 1).

In the **Station Parameters** tab menu page, you can modify:

Queue Section: in this section you can choose the type of queue (finite or infinite) and the policy used to select the next customer to be served. For more information, see Queue section section 4.2.2.

Service Section: in this section you can choose the service time distribution for the station. For more information, see Service section section 4.2.2.

Routing Section: in this section you can specify how serviced customers should be routed to the next station they will visit in the model. For more information, see Routing section section 4.2.2.

3. Fork station:

A JSIM Fork station is simply a station where jobs are split into tasks. No service is provided, therefore there is no service time specification. Tasks are then routed along the Fork station outgoing links. Unlike classical queueing theory fork-join queues, a JSIM Fork station is not associated with a join station automatically. Any combination of server stations, finite regions, fork-join, routing stations, etc., is possible after a Fork station. This feature allows the modeling of very general parallel behaviors, of which the traditional Fork-Join one is a special case. In JSIM the classical queueing theory Fork-Join queue behavior is obtained by connecting the Fork station to as many Server stations as the degree of parallelism requested, with one task per outgoing link. Each Server station is then connected to a Join station, where the job is recomposed. A Fork station is characterized by the forking degree, i.e., the number of tasks routed on each one of its outgoing links, and the capacity, i.e., the maximum number of jobs that can be served by the station simultaneously. Therefore, the number of sibling tasks a job is split into is given by the product of the number of outgoing links from the Fork station times the forking degree. Note that a finite station capacity makes sense only when there is a join station downstream from the fork station that can recompose the split jobs. Otherwise, inconsistencies in the model and subsequent simulation error, such as out-of-memory, may occur. No automatic checks are available at the moment that can identify such critical conditions. Both the forking degree and the capacity are section parameters to be specified in the model. As an example, a Fork station with forking degree 1, connected to three

Server stations, would split a job into 3 sibling tasks (this is a traditional Fork-Join like behavior). If no Join station is connected to any of the three Servers, a warning message is displayed since the model could quickly saturate due to the extra load (3 more jobs) created in addition to each job entering the Fork station.

In the Station Parameters page of the tabs menu, you can modify:

Fork Section: in this section you can choose the forking degree of a job on each outgoing link and the fork station capacity, i.e., the maximum number of jobs that can be served in parallel by the station. For more information, see Fork section section 4.2.2.

Queue Section: in this section you can choose the type of queue (finite or infinite) of the fork station in case its capacity is finite and jobs must wait before proceeding through the fork station. For more information, see Queue section section 4.2.2.

4. **Join station:**  Join stations are complementary to fork stations. In classical queueing network theory, a task arrives at a join station from the corresponding Fork station. In JSIM, a Join station may have incoming links from stations other than the corresponding Fork one. A Join station has no service time, as it is only used to recombine the tasks a job had been previously split into and then route the job to some other station(s). When a task arrives at a join station, it waits until all its sibling tasks have arrived. At this time, the original job is recomposed and routed to the next station. If a job arrives from a station other than the corresponding Fork, i.e., a job that was not split, it is simply routed to the next station. In this case the Join station operates as a routing station.

In the Station Parameters tab menu page, you can modify:

Routing Section: in this section you can specify how serviced customers should be routed to the next station they will visit in the model. For more information, see Routing section section 4.2.2.

5. **Routing station:**  A routing station is a dummy station, with service time equal 0, that is used to create more complex and sophisticated routing strategies by sending jobs through one or more such stations. For example, if we wanted two thirds of the incoming traffic at station Z to be randomly routed to either station A or B and the remaining third to go either to station C or D, depending on the shortest queue at the two stations, we could implement the following. Add a routing station, Y, among Z's output stations and define random routing for the three of them (A, B, Y). Then connect Y to C and D and define Join the Shortest Queue routing to C and D.

In the Station Parameters tab menu page, you can modify:

Routing Section: in this section you can specify how serviced customers should be routed to the next station they will visit in the model. For more information, see Routing section section 4.2.2.

6. **Source station:**  If the model comprises at least an open class, a sink and a source stations are created by default, as they are necessary for the simulation and cannot be removed

Name	Type
Source	 Source
Sink	 Sink

Open classes are characterized by an infinite stream of jobs that can enter the system. Source stations are used to introduce jobs in the model. Their service time is the interarrival time of each customer class and as such, it is defined as a parameter of the class the job belongs to. The routing strategy defines the first station a newly created job will visit. Only open class jobs can be routed from source stations.

In the Station Parameters tab menu page, you can modify:

Routing Section: in this section you can specify how newly created customers should be routed to the next station they will visit in the model. For more information, see Routing section section 4.2.2.

7. **Sink Station:**  Open class customers leave the system once they have received all the service the need. Sink stations are used to model customers leaving the system, as they enter the sink station but do not ever leave it. Sink stations have no parameters, only incoming connections from one or more stations, depending upon the model.

8. **Class switch station:** 

A *class switch* station allows you to define models where jobs are permitted to change class.

The *class switch* component is fully defined by the *class switch matrix*, referred as C .

Let $R = (1, \dots, r)$ the set of the classes of the system, then C is a $r \times r$ square matrix.

The element $C_{i,j}$, $i, j \leq 0$, is the probability that a job of class i entering this station switches to class j .

More details on Class Switch station properties can be found in Sect.3.10.9- *Class-switch station* of JSIMgraph.

Set or change of the properties

Double click on the Class switch icon  to open the Editing ClassSwitch Properties station's configuration dialog (see Figure 4.2). There are two sections: Class Switch Matrix and Routing Section.

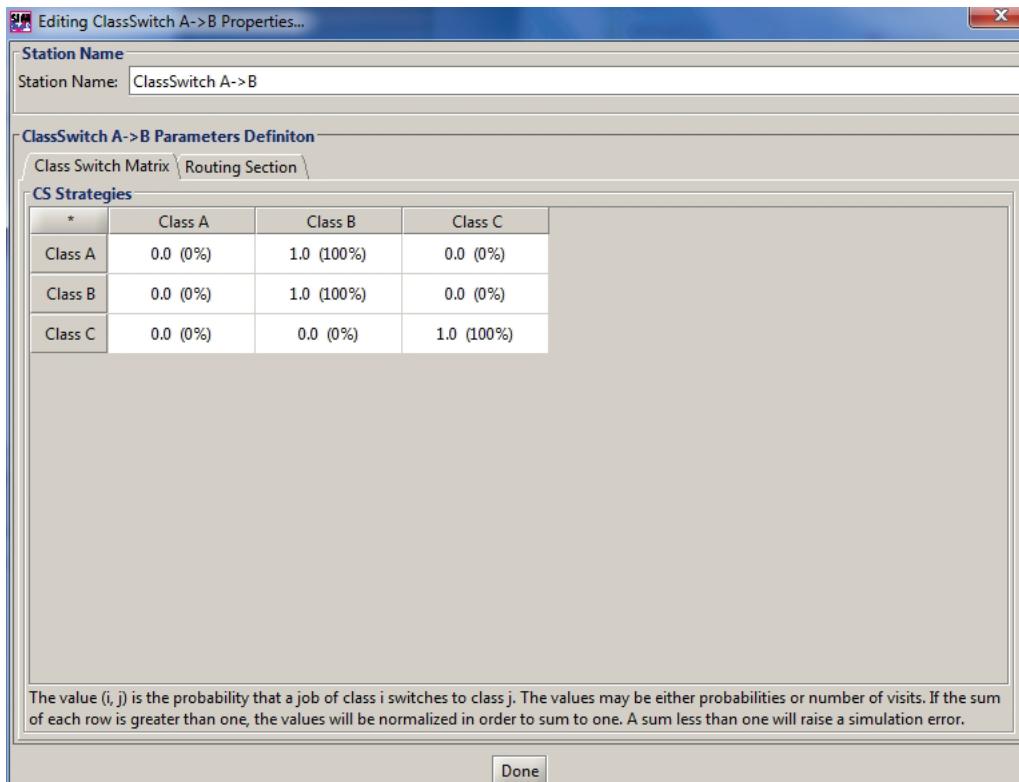


Figure 4.2: Window for the Class switch Station configuration.

Class Switch Matrix

In this section you can input the C matrix in order to control how the jobs switch among the classes of the system. Each cell of the matrix may contain either normalized or absolute values, but the sum of each row is constrained to be greater or equals than one.

Routing Section

For each class of customers, the user should select the algorithm that want to apply in order to determine the outgoing connection (i.e., the routing strategy) followed by a customer that completed its service in the current station. The following algorithms are available:

- Random
- Round Robin
- Probabilities
- Join the Shortest Queue - JSQ
- Shortest Response Time
- Least Utilization
- Fastest Service.

To know details about these algorithms, please refer to the Routing Section of subsection 3.10.1-*Source Station*.

9. **Logger station** A logging station (i.e., *logger*) reads information flowing through it and writes it to a file.

In the simplest way, it is a tool to understand and debug the traffic flow moving through the interesting part(s) of the model. Place the logger station into the model, choose the parameters, and trace the data

as it passes through the model.

Set or change of the properties

Double click on the **Logger Station** icon  to open the **Editing Logger Properties** station's configuration dialog (see Figure 4.3). There are two sections: **Logger Section** and **Routing Section**.

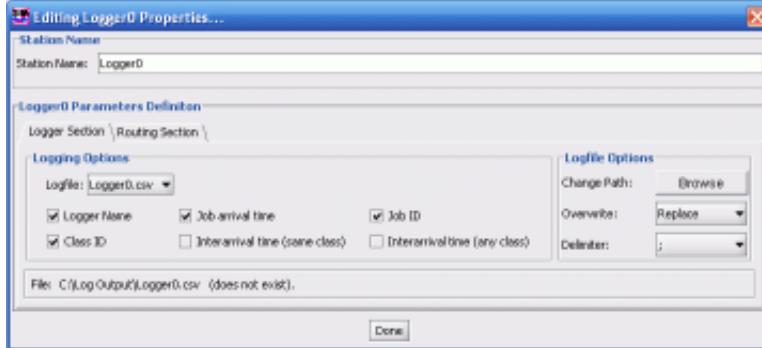


Figure 4.3: Window for the **Logger Station** configuration.

Logger Section

The configuration properties of the **Logger Section** are:

- **Logging Options:**

- The Logfile's name to use, either individual or merged (Logger0.csv or global.csv, respectively).
- The information to log (fields): Logger Name, Job Arrival Time (simulation units), unique Job ID, defined Class ID, Interarrival time of same class, Interarrival time of any class. These fields are found in the next section.

- **LogFile Options:**

- Browse button: allows changing the directory where logfiles are stored.
- Overwrite method to use when the logfile exists, and a new simulation needs to overwrite the file. Replace overwrites the file, append adds data to the end of the file.
- Delimiter chooses the character to separate between.

- **Status** displays the path and file-status of the logfile that is going to be written.

As messages flow through the **Logger** from one station to another, the following information can be logged:

- **Logger Name**, the name of the logger where the message occurred (e.g., *Logger0*)
- **Job arrival time**, this timestamp marks the current simulation time from start of simulation (not seconds)
- **Job ID**, the auto-generated unique sequence number of the message (e.g. 1,2,3...).
- **Class ID**, the name of *customer class* of message (e.g., *Class0*)
- **Interarrival time (same class)**, is a time difference between customer of the same class that passes through the logger
- **Interarrival time (any class)**, is a time difference between customers of any class that passes through the logger.

Once a **Logger** is configured, running a simulation produces a logfile with the chosen fields. An example of logfile output is:

```
LOGGERNAME;TIMESTAMP;JOBID;JOBCLASS;TIMEELAPSED_SAMECLASS; TIMEELAPSED_ANYCLASS
Logger0;0.199;1;Class0;0.000;0.199
Logger0;0.559;2;Class0;0.341;0.341
```

Fork section

How to define the Forking Behavior This section is characteristic only of fork stations. It defines the parallelism degree of a job, in terms of the number of tasks it is split into and how many jobs can be serviced concurrently.

In this section you can define the station forking degree, i.e., the number of tasks created for each job arriving at the fork station, and its capacity, i.e., the maximum number of jobs that can be in a fork-join section (when a join is present):

Fork degree
Number of tasks to be generated on each output link for each input job:
1

Fork-join section capacity
 Enable Finite Capacity: limit maximum number of jobs inside a fork-join section
Capacity (max number of jobs - NOT tasks):

Forking degree: it is the number of tasks that are routed on each outgoing link of the fork station. Therefore, each job is split into (forking degree)*(number of outgoing links) tasks. By default the forking degree is 1 and it can be modified using this form:

Number of tasks to be generated on each output link for each input job: 1

Capacity: it is the maximum number of jobs that can be served by a fork-join section simultaneously. It makes sense only if there is a join station matching the fork one. It can be finite, in which case once the limit is reached, jobs wait in the queue of the fork station. A job is removed from the queue and serviced (i.e., split into tasks) when a job is recomposed at the matching join station and leaves it. Capacity is defined using the form below, after checking the *Finite capacity...* box:

Enable Finite Capacity: limit maximum number of jobs inside a fork-join section
Capacity (max number of jobs - NOT tasks): 1

Queue section

How to Define the Queue Strategy

The Queue section is part of the **Station Parameters** definition page; it is present only for server and fork stations.

The Queue section allows the specification of the queueing capacity (whether finite or infinite) and policy. Different classes may have different policies associated with them.

Class	Queue Policy
Class1	FCFS
Class2	FCFS

Capacity: a station can accept any customer and let them wait in queue, in which case its capacity is considered infinite, or it can only accept a finite number of customers. In this case its capacity is finite, with a length to be specified in the form length: 0

Queue policy: it is the algorithm used to decide which customer to serve next. A variety of factors can contribute to the order in which customers are served, such as arrival order, priorities associated with a class, the amount of service already provided to customers, etc.

In JSIM queueing disciplines based on arrival order and priority are the only available, namely:

FCFS: Customers are served in the order in which they arrive at the station. If the model is exported to MVA, the following constraint is enforced in the exported model because the MVA analytical algorithm (see the BCMP theorem in [BCMP75]) requires in a multiple class environment the customers of all the classes must have the same average service time $S_{c,k}$ at a FCFS queue station. In order to take care of the differences among the service requirements of the different classes, the total number of visits to the station per each class $V_{c,k}$ is adjusted in order to obtain the correct values of service demands $D_{c,k}$.

FCFS (Priority): Customers are ordered according to their arrival time but customers with higher priority jump ahead of customers with lower priority (a *small* priority number means low priority). Customers with the same priority are served FCFS.

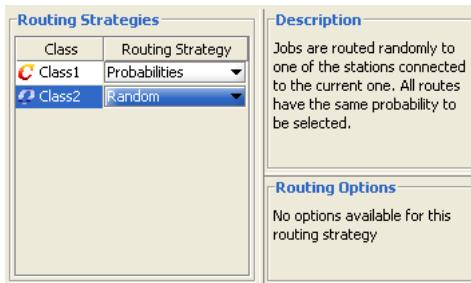
LCFS: An arriving job jumps ahead of the queue and will be served first. The LCFS discipline implemented in JSIM is not of the preemptive-resume type.

LCFS (Priority): The next customer to be served is one with the highest priority (conventionally a *small* priority number means low priority), so an arriving customer can only jump ahead of the queue of the other customers with equal or smaller priority. Customers with the same priority are served LCFS.

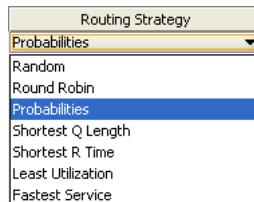
Processor Sharing (PS): A Processor Sharing server works as all the customers are processed simultaneously in the station, but devotes to each of them a fraction of its total capacity inversely proportional to the number of customers. It can be seen as a RR scheduling with a quantum size zero so that the control of the server circulates infinitely rapidly among all the customers. If the station has *multiple servers* (greater than 1), when there are more customers in execution than servers, each server splits its capacity equally across the customers. In the other case, the capacity of a server is completely allocated to the customer it has to execute, so its service time is the same as with FCFS, for example. Thus, it will never happen that a customer is executed with a service time less than the time it requires as if it is alone in the station.

Routing section

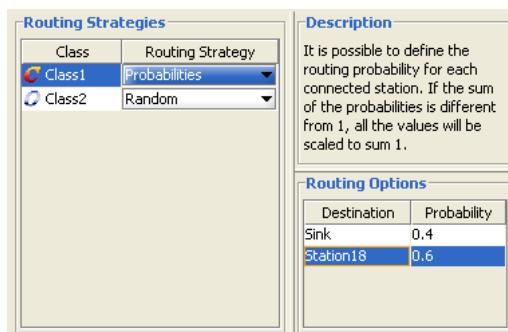
How to Define the Routing Strategy The Routing section is part of the **Station Parameters** definition page defined for all stations, except for fork and sink stations. In the routing section, for every class defined, you may decide how the completed jobs are routed to the other devices connected to station for which the routing strategy is defined.



For each class, the routing algorithm to be used on the outgoing links of the station is selected from this menu:

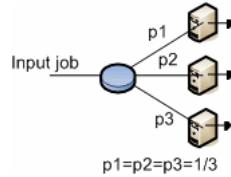


By clicking an algorithm, a brief explanation of the selected algorithm is shown and routing options can be specified, where necessary:

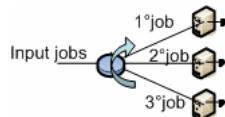


You can choose among the following algorithms (NOTE: in each of the pictures illustrating the algorithms, the blue station implements the routing strategy to the other devices):

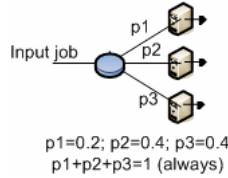
Random: with this strategy, jobs are routed randomly to one of the stations connected to the routing device. The outgoing links are selected with the same probability. The figure illustrates the routing strategy with 3 output links. For each link the probability to be selected is $1/3$.



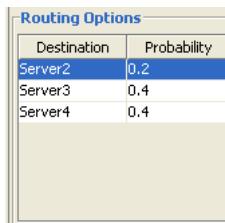
Round Robin: with this algorithm, jobs are cyclically routed to the outgoing links according to a circular routing. As the figure shows, the first job is sent to the top station, the second job is sent to the central station, and the third job is sent to the bottom station. The next job would be sent to the top station again, and so on.



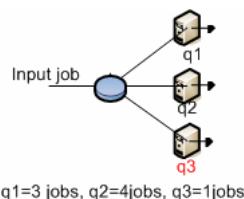
Probabilities: with this algorithm, you can define the routing probability for each outgoing link. The sum of all probabilities must equal 1. If the values provided do not satisfy the constraint, JSIM automatically normalizes the values before the simulation starts.



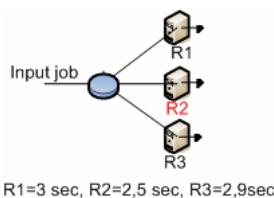
This strategy requires that you define the probability for each output link via the panel on the bottom right of the window.



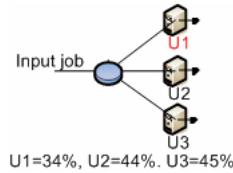
Join the Shortest Queue: with this strategy, each job is routed to the device that has the smallest queue length, i.e., number of jobs waiting, at the time the job leaves the routing station. The figure shows a case where the queue lengths at the devices are 3, 2, and 1 jobs, respectively, from top to bottom. The exiting job will be routed to the bottom station, since its queue is the shortest(1 job).



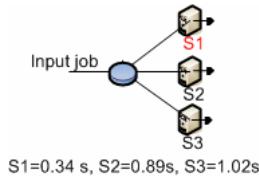
Shortest Response Time: with this algorithm, jobs are sent to the station where the average response time for the job's class is the smallest at the moment a job leaves the routing station. The figure shows that at the time of routing, the middle station has the smallest average response time, R , so the job will be sent to it.



Least Utilization: with this strategy, the destination device is chosen as the one with the smallest average utilization at the time routing is performed. In the example depicted in the picture, the top station is the least utilized, so it will receive the next job to leave the blue station.



Fastest Service: with this strategy, a job is routed to the device with the smallest average service time, S , for the job's class. In the figure, the exiting job will be routed to the top station since its service time is the minimum among the three.



Service section

How to Define the Service Strategy This section is present in server and delay stations. This section allows the specification of the number of servers, for server stations, and the service time distribution, for both server and delay stations.

Delay stations are infinite servers with identical service time, therefore they only need the service time distribution. The infinite number of servers provides for equal average response time for all jobs, as no job waits in queue for service.

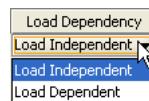
In this section, the load dependent or independent nature of the service time is also specified for each class in server stations:

Number of Servers			
Number: <input type="text" value="1"/>			
Service Time Distributions			
Class	Load Dependency	Service Time Distribution	
Class1	Load Independent ▾	exp(1)	Edit
Class2	Load Independent ▾	exp(1)	Edit

The number of servers in a server station can be modified using the corresponding input area:

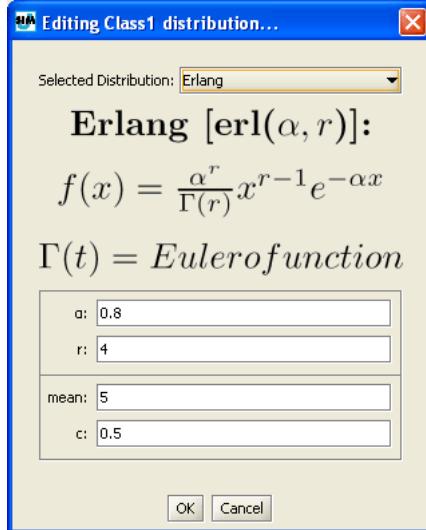
Number:

For each class, you must specify whether the service time is Load Dependent or Load Independent using this menu:



A load independent service indicates that, regardless of the number of jobs that are in the station, the system will serve all jobs following a fixed policy modelled by the chosen statistical distribution.

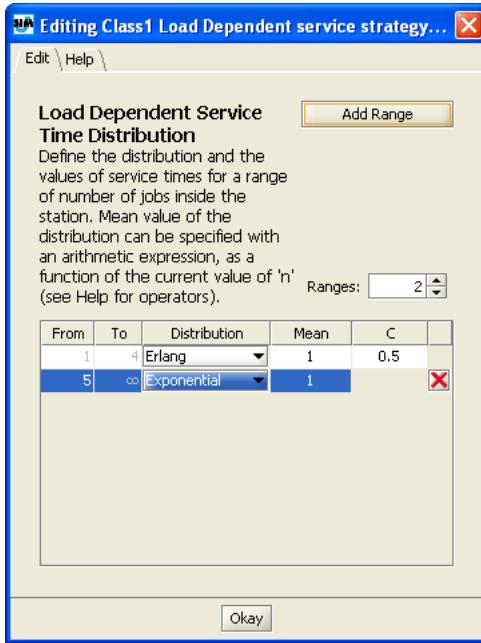
For each class, the Service Time Distribution is set to Exponential with average equal to 1. It can be modified by clicking the button and inserting all the required parameters from this window:



Click the drop down menu and choose the service time distribution among the following:

- Burst (General)
- Burst (MMPP2)
- Constant
- Erlang
- Exponential
- Gamma
- Hyperexponential
- Normal
- Pareto
- Poisson
- Replayer
- StudentT
- Uniform

A load dependent service time indicates that the amount of time the server spends with each customer depends upon the current number of customers in the station. A set of intervals for the number of jobs in the station is specified, either by adding one range at a time via the **Add Range** button or by specifying the total number at once. Each range must then be specified by its lower (**From**) and upper (**To**) extremes. Each such range can be associated with different service times, as for the distribution, the mean and the coefficient of variation, or a subset thereof. To set the parameters of a Load Dependent service time, click the **Edit** button and then specify the parameters for each added range.



For each customer number range you must specify the following parameters:

Distribution: you can choose among Burst (general), Burst (MMPP2), Pareto, Erlang, Exponential, Hyper-exponential, Poisson, Uniform, Constant, Gamma and Normal distribution.

Mean: the mean value of each distribution is specified in the *Mean* form by double clicking on it. Insert a number or an arithmetic expression that will be evaluated with JFEP - Java Fast Expression Parser. For a complete list of the command supported by JFEP you can read the *Help* tab or see the JFEP web site at <http://jfep.sourceforge.net/>

- c: The coefficient of variation of each distribution (when C exist) can be specified by double clicking on the *c* form. For example, in the previous picture two policies are defined: From 1 to 4 jobs in the station, the server will behave according to an Erlang distribution with mean = 1 and c=0.5. For any number of jobs greater or equal to 5 in the station, the system will behave according to an Exponential distribution with mean = 1. If you want to delete a range click X

4.2.3 Define Connections

The **Connections** tab allows you to define how stations are connected with each other. In order to create a connection from station *i* to a station *j*, check the table entry (i,j) in the connection matrix (rows identify source stations, columns identify destination stations)

Station Connections		
Click on table entry (i,j) to connect station i to station j.		
	Station1	Station2
Station1	<input type="checkbox"/>	<input type="checkbox"/>
Station2	<input type="checkbox"/>	<input type="checkbox"/>

NOTE: if there are open classes in the model, the Source and Sink station automatically created by the system appear in the connection matrix. A *Source* station may have only outgoing links, a *Sink* station may have only incoming links.

	Source	Sink	Station1	Station2
Source	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Sink	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Station1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Station2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

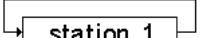
To define a consistent model a Source station must have at least one outgoing connection and a Sink station must have an incoming connection.

Example 1: if you want to connect station1 to station2 in this way you must check this box

	Station1	Station2
Station1	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Station2	<input type="checkbox"/>	<input type="checkbox"/>

Example2: if you want to connect station1 to station2 in this way  you must check this box

	Station1	Station2
Station1	<input type="checkbox"/>	<input type="checkbox"/>
Station2	<input checked="" type="checkbox"/>	<input type="checkbox"/>

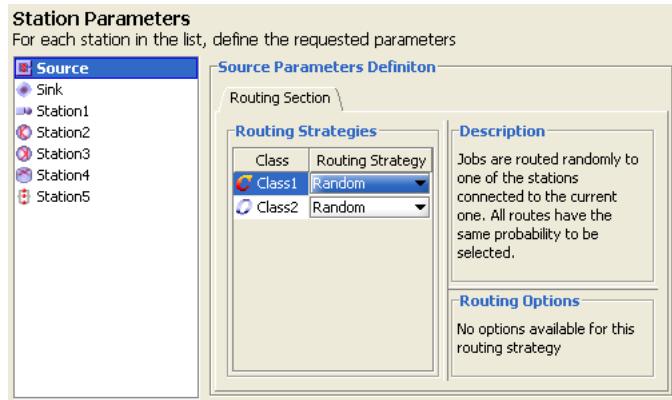
Example3: if you want to connect station1 to itself (with a feedback loop)  you must check this box

	Station1	Station2
Station1	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Station2	<input type="checkbox"/>	<input type="checkbox"/>

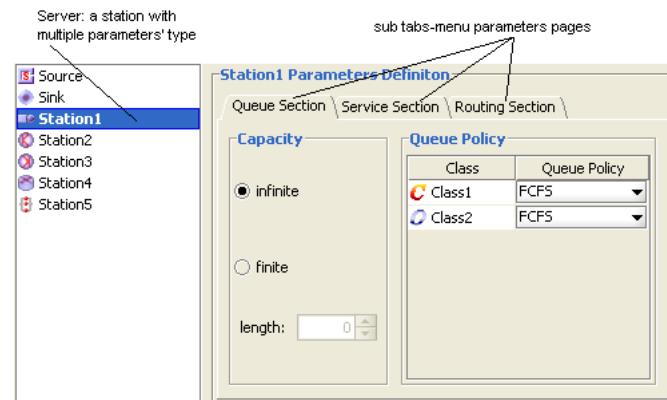
NOTE: if connections among the stations are inconsistent, the system displays error-warning messages. For more information about connection errors, read ref.

4.2.4 Station Parameters

The **Station Parameters** tab allows you to define the characteristic parameters of each station. For each station, a different menu is presented depending upon the station type. Queuing, service, routing and forking, or subsets thereof, are the characteristics to be defined through a series of tabs. Default settings are provided that can be modified at the user's need. The Sink station does not have any parameter.



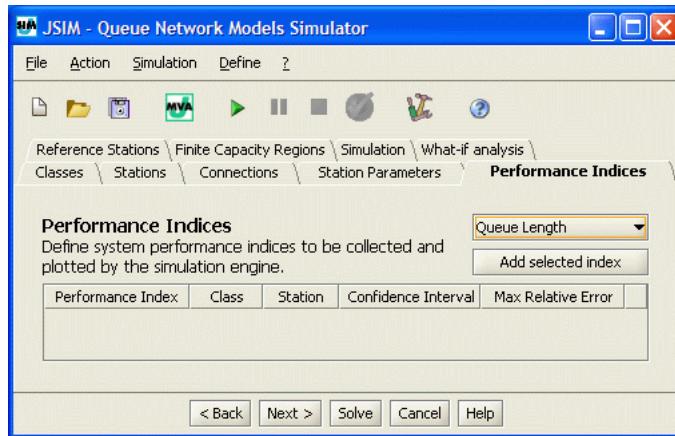
Example (with a server station):



NOTE: You can find detailed information about station parameters subsection 4.2.2.

4.2.5 Define Performance Indices

Performance Indices are selected using the **Performance Indices** tab.



You can choose any subset of indices from the list below to be plotted as the model output:

Number of Customers Number of customers at a station, both waiting and receiving service.

Queue Time Average time spent by the customers waiting in a station queue. It does not include the Service Time.

Residence Time Total time spent at a station by a customer, both queueing and receiving service, considering all the visits at the station.

Response Time Average time spent in a station by a customer for a single request (it is the sum of Queueing time and Service time).

Response Time per Sink average time spent in system by a customer before dropping at the selected sink.

Utilization Percentage of time a resource is used w.r.t. the system lifetime; it varies from 0 (0%), when the station is always idle, to a maximum of 1 (100%), when the station is constantly busy serving customers for the entire system lifetime. Utilization may be greater than 1 if a station has more than one server.

Throughput Rate at which customers departs from a station, i.e., the number of services completed in a time unit.

Throughput per Sink rate at which customers departs from the system with respect to the selected sink, i.e., the number of requests completed in a time unit that reach a given sink.

System Response Time Average time a customer spends in the system in order to receive service from the various stations it visits. It corresponds to the intuitive notion of response time, as the interval between the submission of a request and the reception of the response.

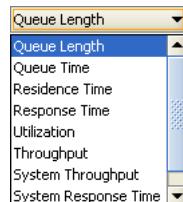
System Throughput Rate at which customers departs from the system.

System Number of Customers Average number of customers in the system. If the index is associated with a closed class, then it is equal to the number of customers in the class.

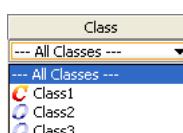
System Power The optimal operational point of a system is the point corresponding to the maximum System Throughput X with the minimum System Response time R, i.e., the value of the ratio X/R is maximized in this point. This ratio is known as *System Power*.

Each index is associated with a class and a station and will be computed within a given Confidence Interval and Max Relative Error, both defined on the (0-1) range, by performing the following steps:

1. Select the index you want to add to the model from this menu:



2. Click **Add selected index** and the index will be added to the panel. Next the index parameters must be set.
3. Select from the Class menu a single class, or All Classes, for which the index must be computed.



4. Select the Station for which the index must be computed from Station menu. In case of system wide indices, namely, System Throughput and System Response Time, this option is not available.



5. Double click on the values to modify the default values for the Confidence Interval size of the solution and for the Max Relative Error of the greatest sample error, if you want more/less accurate results.

Confidence Interval	Max Relative Error
0.9	0.1

6. Repeat these steps for all the indices you want to include in the model output.

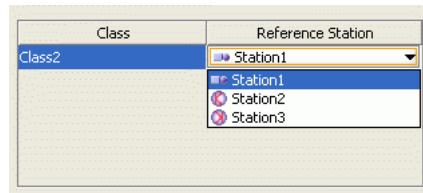
NOTE: erroneous parameter settings will be detected only when the simulation is started, raising a warning or an error message.

4.2.6 Reference Stations

The **Reference Stations** tab allows you to specify the Reference Station for each customer class. For each customer class, a reference station must be specified in order to compute system throughput for that class. For open classes, there is only one possible reference station, that is, the Source station. Such an association is done by the system automatically each time an open class is created and cannot be modified.

Class	Reference Station
Class1	Source

For each closed class, any of the existing stations can be selected using the scroll menu below



NOTE: if a reference station is missing for any of the classes, an error message is returned when the simulation will start.

4.2.7 Finite Capacity Regions

The **Finite Capacity Regions** tab allows you to define Finite Capacity Regions in the model. Finite Capacity Regions can either be added one at a time by clicking the *Add Region* button or all at once by selecting the desired number in the *Regions* selector.

Add Region
Regions: <input type="button" value="1"/>

When a new region is created, two new sub areas devoted to the parameters of the region, namely the stations involved and class properties when in the region, appear on the screen on the right.

<table border="1"> <tr> <td>Name</td> <td>Capacity</td> <td>∞</td> <td><input checked="" type="checkbox"/></td> <td><input type="button" value="X"/></td> </tr> <tr> <td>FCRegion4</td> <td>∞</td> <td>∞</td> <td><input checked="" type="checkbox"/></td> <td><input type="button" value="X"/></td> </tr> <tr> <td>FCRegion5</td> <td>∞</td> <td>∞</td> <td><input checked="" type="checkbox"/></td> <td><input type="button" value="X"/></td> </tr> </table>	Name	Capacity	∞	<input checked="" type="checkbox"/>	<input type="button" value="X"/>	FCRegion4	∞	∞	<input checked="" type="checkbox"/>	<input type="button" value="X"/>	FCRegion5	∞	∞	<input checked="" type="checkbox"/>	<input type="button" value="X"/>	<p>Stations in FCRegion4</p> <table border="1"> <tr> <td>Station name</td> <td><input type="button" value="Add Station"/></td> </tr> <tr> <td>Station1</td> <td><input type="button" value="X"/></td> </tr> </table> <p>Class specific FCRegion4 Properties</p> <table border="1"> <tr> <td>Class</td> <td>Capacity</td> <td>∞</td> <td><input checked="" type="checkbox"/></td> <td>Drop</td> </tr> <tr> <td>Class1</td> <td>∞</td> <td>∞</td> <td><input checked="" type="checkbox"/></td> <td><input type="button" value="False"/></td> </tr> <tr> <td>Class2</td> <td>∞</td> <td>∞</td> <td><input checked="" type="checkbox"/></td> <td><input type="button" value="False"/></td> </tr> </table>	Station name	<input type="button" value="Add Station"/>	Station1	<input type="button" value="X"/>	Class	Capacity	∞	<input checked="" type="checkbox"/>	Drop	Class1	∞	∞	<input checked="" type="checkbox"/>	<input type="button" value="False"/>	Class2	∞	∞	<input checked="" type="checkbox"/>	<input type="button" value="False"/>
Name	Capacity	∞	<input checked="" type="checkbox"/>	<input type="button" value="X"/>																															
FCRegion4	∞	∞	<input checked="" type="checkbox"/>	<input type="button" value="X"/>																															
FCRegion5	∞	∞	<input checked="" type="checkbox"/>	<input type="button" value="X"/>																															
Station name	<input type="button" value="Add Station"/>																																		
Station1	<input type="button" value="X"/>																																		
Class	Capacity	∞	<input checked="" type="checkbox"/>	Drop																															
Class1	∞	∞	<input checked="" type="checkbox"/>	<input type="button" value="False"/>																															
Class2	∞	∞	<input checked="" type="checkbox"/>	<input type="button" value="False"/>																															

For each region, define first the capacity (infinite by default). If the check in the Infinity box is removed, the desired number can be input in the Capacity field.

Name	Capacity	∞	<input checked="" type="checkbox"/>	X
FCRegion4	∞	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	X
FCRegion5	∞	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	X

Then for each region define which stations are part of that region. Stations are added in alphabetical order on their names. If the model has more than one station, a drop down menu from the station name allows you to change the station to add.

Stations in FCRegion4

Station name	Add Station
Station1	X
Stations: 1	

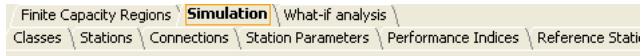
Finally, in the bottom right panel, you can define class specific properties for the finite capacity region selected. Region capacity for that class (finite or infinite -the default value) and the dropping characteristic (true or false) in case the capacity is exceeded are defined here.

Class specific FCRegion4 Properties

Class	Capacity	∞	Drop
Class1	∞	<input checked="" type="checkbox"/>	False
Class2	∞	<input checked="" type="checkbox"/>	False

4.2.8 Define Simulation Parameters

The Simulation Parameters and Initial State of the model are defined using the **Simulation** tab.



Simulation parameters: In the top section of this windows you can edit general simulation parameters.

Simulation Seed: The simulation seed is a number used by the simulation engine to generate pseudo-random numbers. As these numbers are pseudo-random, if you change the seed, you will obtain a different sequence of pseudo-random numbers. If a simulation is repeated using the same seed, the same sequence of pseudo-random numbers will be generated, thus leading to identical results. The default value is random, which indicates that the simulation engine will pick a seed of its choice in a pseudo-random fashion each time it is started; uncheck *random* and insert a number if you want a custom simulation.

Maximum duration (sec): It represents the maximum amount of time in seconds that the simulation will run. If the simulation ends before the maximum duration, the parameter is ignored and does not affect the results. The default value is *infinite* deselect it and specify the preferred maximum time if you do not want the simulation to run for a possibly very long time. In this case, the simulation stops when the time limit is reached, although a solution may not be available yet.

Maximum number of samples: It is the greatest number of samples for each index that JSIM collects before ending the simulation. During a simulation, measurements can be stopped in case of:

- Success, if the results have reached the required Confidence Interval and the Max Relative Error
- Failure, if the simulation has analyzed the maximum number of samples but has not reached the required Confidence Interval or Max Relative Error
- Failure, if timeout occurs before successfully calculating the final results.

The default value for the maximum number of samples is 500,000; you may increase it (for a more accurate simulation) or decrease it (for a faster simulation).

Representation Interval (sec): This is the granularity at which results are plotted on the screen, i.e., the time interval before a new point is added to the graphs, as the simulation proceeds. A large value will make the simulation to proceed slower, as the graphs are updated less often. Small values will provide an impression of better *responsiveness* from the simulation, as graphs are updated more frequently.

Initial state: Initial state is the model situation at time 0, typically expressed by the number of customers in each station before starting the simulation. For closed customer classes, all jobs are initially allocated to their reference station. You can modify this allocation, as long as the total number of jobs remains the one defined in the Classes (subsection 4.2.1) tab. For open customer classes, it is possible to initialize each station with any desired number of jobs. The following table represents an example of an initial state of a model with three stations and two classes.

	Station1	Station2	Station3
Class1 ($N_i = 6$)	6	0	0
Class2	0	0	0

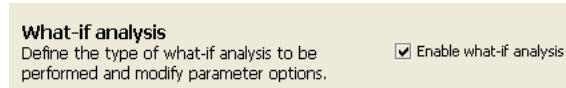
4.2.9 Define what if analysis

The parameters of a what-if analysis are defined using the **What-if-analysis** tab.



A What-If Analysis consists of a series of simulations in which one or more parameters are varied over a specified range. This allows the observation of system behavior under a spectrum of conditions, unlike the single JSIM simulation run where the system is observed under a specific set of configuration parameters. By default the what-if-analysis is not enabled. It must be activated explicitly and its parameters defined. **Activating the What-If Analysis**

After completing the definition of the model and selecting the **What-if analysis** tab, check the Enable what-if analysis checkbox to activate it.



Selecting the What-If Analysis Parameter

After enabling the what-if analysis, it is possible to select the parameter to control the series of simulation runs using the menu below:



When you select a what-if analysis parameter, the bottom section of the window will change depending upon the parameter. In the right portion a description is provided of the selected parameter and of the impact of its variation. In the left portion the details of the parameter range (From and To fields) and the number of executions (Steps) on the range are provided. The set of modifiable parameters depends upon the number and type of classes in the model:

- In a single class model, you simply select the parameters you want to change during simulation.
- In a multiclass model, you select the parameter and specify whether you want to apply the variation to all classes or just to one class.

Number of Customers (only for models with closed classes) JSIM repeats the simulation changing the number of jobs in each run, starting from the number inserted in the *From N* field, to the value inserted in the *To N* field. The simulation is repeated *Steps (n. of exec.)* number of times.

Type of population growth

Increase number of job of all closed classes
 Increase number of job of one closed class

From N:	10
To N:	11
Steps (n. of exec.):	2
Class:	Chiusa

Population mix

	Chiusa
N _i	10
B _i	1.00

In the figure above a what-if analysis is planned on a single class model. The initial value of the number of customers is not modifiable from this window, as it is part of the **Classes** tab. The final value is specified in the field *To N*. In this case, with a final value of 20 and 6 Steps, simulations are run for 10, 12, 14, 16, 18 and 20 customers, respectively. Only the customer number in the class selected in the *Class* (Chiusa, in the picture) will be changed. The remaining classes will keep their initial number of customers. The simulator makes sure that the sum of the percentages of customers in various classes add up to 1, as shown in the *Population mix* table on the bottom of the window. If the *all-classes* option is selected, the overall population is increased while keeping the relative proportion of jobs in the various classes constant. Because the number of customers in each class can only be an integer number, only the population vectors with integer components can be considered. Therefore, the actual number of executions may be smaller than the one specified.

Population Mix: (only for models with two closed classes) The population mix describes the way the population is divided between the two class, i.e., the percentage of customers in each class over the total population. Because of the complexity of the underlying modelling, this type of analysis is possible only for models with two closed classes. Mixed class models can be analyzed too, as long as there are two closed classes. Only the closed classes will be considered.

Initial B:	0.082
Final B:	0
Steps (n. of exec.):	9
Class:	Class1

In order to allow for a complete analysis of the population mix, in this case the initial value of the percentage of customers in one of the two classes, the one selected through the **Class** field, can be modified. Its default value is the ratio of the class population to the total population of closed customers, defined in the **Class** tab. Both the final and the initial *beta* are numbers on the range [0-1].

Arrival Rate: (only if there are open classes) Arrival rate is the frequency at which jobs arrive at a station during a period of time. Similarly to the number of customers, the arrival rate can be changed for one specific open class or for all the open classes in the model. If a single class is selected, the final arrival rate and the number of steps must be specified. The initial arrival rate is specified in the Arrival Rate section of the **Classes** tab and it is not modifiable here. If the arrival rate is to be changed for all classes, the final value is expressed as a percentage, which is applied to all classes.

Change arrival rates of all open classes
 Change the arrival rate of one open class

From (%):	100.0
To (%):	150
Steps (n. of exec.):	10
Class:	All open classes

The figure above shows the settings for a what-if analysis on the arrival rate of all the open classes. The *To* field is seto to 150%, which means that for each class the final arrival rate will be one and a half times the initial value. 10 runs will be exectued with equally spaced (in percentage) intermediate values.

Service time (for all types of classes) Service Time is the time required by a customer class at each visit at a station. In this case, besides the final value and the number of runs to be executed, the station and the customer class (or all the classes) whose service time will be varied must be specified.

From (s):	0.2
To (s):	0.4
Steps (n. of exec.):	10
Station:	Server1
Class:	Class1

The figure above shows the settings for a what-if analysis of the service time of class Class1 at station Server1. The service time distribution will not change. Only its average will be modified to span the range defined by the initial value (specified in the **Station Parameters** tab) and the final value specified here in the *To* field. If the *All classes* option is selected, the range of service time to explore is expressed in percentage, starting from the initial value specified at model definition (100%). The station where the service time change is applied must be specified.

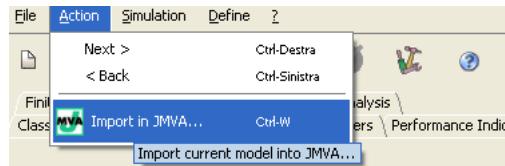
Seed (for all types of classes)

Steps (n. of exec.):	10
----------------------	----

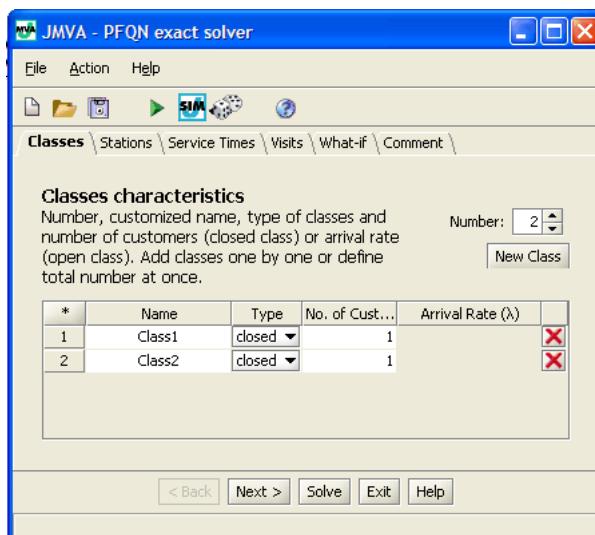
Unlike the previous cases, where the analysis is performed for a range of values of one of the model parameters in order to investigate the system behavior under a variety of conditions, a what-if analysis on the seed aims at evaluating the sensitivity of the simulation engine to numerical conditions, in particular to the initial value fed to the pseudo-random number generator, i.e., the seed. The Simulation engine uses a pseudo-random number generator to generate the sequence of values used in each execution. By changing the seed, a different sequence of values is produced, thus leading to different numerical results. The first value is the one defined in the **Simulation Parameters** tab. In this panel, the number of executions is specified and the simulation engine generates as many pseudo-random seeds to be used in the executions.

4.3 Import in JMVA

After creating a simulation model, you can export it to the analytic solver component of the JMT suite, namely JMVA. In the Action menu, click *Export to MVA*.



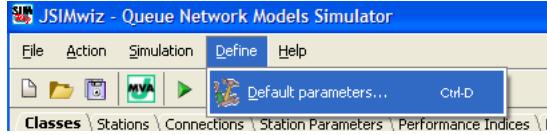
If there are errors in the model, i.e., conditions not allowed in models with analytical solution, a dialog window with information about such errors appears (See section 4.6). If you want to continue with the analytical solution, you must correct the errors. When the model satisfies all the constraints for analytical solution, a JMVA window appears on the screen and the model can be solved with JMVA.



Refer to JMVA user's guide (chapter 2) for specific help on JMVA functionalities.

4.4 Modify default parameters

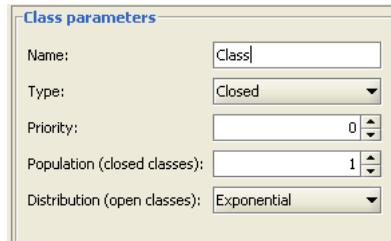
The simulator default settings as for Class, Station, Simulation, and Finite Capacity Region parameters, may be changed using the **Define** menu in the menu bar. Click the **Default parameters**



or the *Define default values of model parameters* button. In JSIM all parameters have predefined, or default, values. Such values can be change to suit the user's most common modelling activities. Defaults can be modified for the following sections:

- **Class Parameters**
- **Station Parameters**
- **Simulation Parameters**
- **Finite Capacity Region (FCR) Parameters**

Class Parameters These settings define the default class parameters used when a new class is created. For detailed information about classes, see subsection 4.2.1.



Name: the default name for each newly created class of customers is *Class*, followed by a progressive integer, starting from 1, indicating how many classes you have created so far. It can be reset to any alphanumerical string, which will be followed by the same numbering scheme.

Type: the default class type is Closed. If open classes are used more often, you may want to change to Open as default, so as to minimize the type changes in the class definition section.

Priority: the default class priority is 0. Higher numbers correspond to higher priority.

Population: this parameter applies only to *closed classes*; the default value is 1, i.e., all closed classes are created with 1 customer in each of them. Change the value if you want larger populations by default in each closed class.

Distribution: this parameter applies only to *open classes*; the default value is *Exponential* since it is the most popular distribution that characterizes customer interarrival times at a system. Change it to any of the distributions available if most of your customer interarrival times follow a non-exponential pattern.

Station Parameters These settings are general parameters for every type of station. For a detailed description of station types, see subsection 4.2.2

Station parameters	
Name:	Station
Type:	Server
Queue Capacity:	1 <input type="button" value="▲"/> <input type="button" value="▼"/> <input checked="" type="checkbox"/> Infinite
Number of Servers:	1 <input type="button" value="▲"/> <input type="button" value="▼"/>
Queue Strategy:	FCFS
Service Distribution:	Exponential
Delay Service Distribution:	Exponential
Routing Strategy:	Random
Fork Capacity:	1 <input type="button" value="▲"/> <input type="button" value="▼"/> <input checked="" type="checkbox"/> Infinite
Drop Rule:	Drop
Fork degree:	1 <input type="button" value="▲"/> <input type="button" value="▼"/>

Name: the default name of each newly created station is **Station** followed by an increasing integer, starting from 1, indicating how many stations have been created so far. It can be reset to any alphanumerical string, which will be followed by the same numbering scheme.

Type: the default station type is **Queue**, since this is the most popular type of station in performance models. Possible type of stations are **Delay**, **Queue**, **Fork**, **Join**, **Router**, **Logger**, **ClassSwitch**.

Queue Capacity: this parameter applies only to **Queue**, **Fork** stations; the default value is infinite, i.e., an infinite number of customers can queue in such stations. It can be reset to finite, with a finite value specified, by checking out the **Infinite** check box.

Number of Servers: this parameter applies only to **Queue** stations; the default value is 1, i.e., single server. It can be changed to any finite value .

Queue Strategy: this parameter applies only to **Queue** and **Fork** station types; the default value is FCFS and can be changed to LCFS, RAND, SJF, LJF. A priority among the job classes can be specified with all these disciplines.

Service Distribution: this parameter applies only to **Queue** stations; the default value is Exponential, as it is the most popular when modeling device service time. It can be changed to any of the available distributions if most of the devices modeled are non-exponential.

Delay Service Distribution: this parameter applies only to **Delay** stations; the default value is Exponential but it can be changed to any of the distributions available .

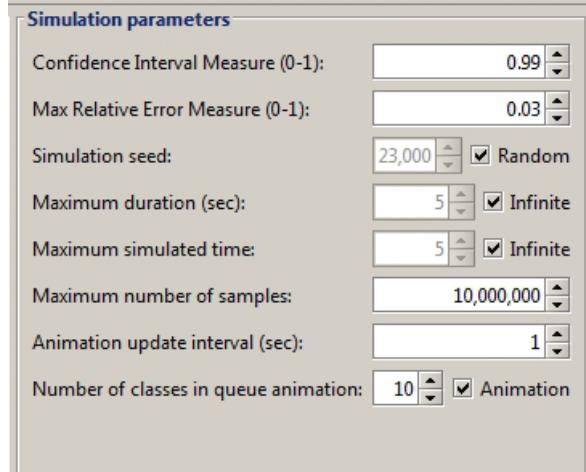
Routing Strategy: this parameter applies only to **Delay**, **Queue**, **Join**, **Logger**, **Router**, **ClassSwitch**; the default value is Random and it can be changed to any of the available routing strategies, namely Random, Round robin, Probabilities, Join the Shortest Queue, Shortest Response time, Least utilization, Fastest service, Load Dependent.

Drop Rule: this parameter applies only to **Fork** stations. When a finite capacity is defined, the default value of the Drop Rule is Drop, i.e., all customers exceeding the station capacity are discarded. Two other policies are possible: Waiting in Queue, BAS blocking (BAS, Blocking After Service: block the customers in the station before the one considered if its maximum capacity is reached). When the capacity is infinite, the Drop Rule is disabled by default.

Fork Capacity: this parameter applies only to **Fork** stations; the default value is infinite, i.e., there is no limit on the number of customers inside a *Fork-Join* section of the network. It can be changed to finite, by checking the **Enable Finite Capacity** checkbox and specifying a finite number.

Forking Degree: this parameter applies only to **Fork** stations; the default value is 1, i.e., one task is generated for each outgoing link of the **Fork** station for each input customer. It can be changed to any finite value, thus increasing the number of tasks each customer is split into on each parallel link.

Simulation Parameters These parameters define the simulation behavior from a statistical point of view. For more information, see subsection 4.2.8 for simulation parameters or subsection 4.2.8 for Confidence Interval and Max Relative Error.



Confidence Interval Measure: this parameter is set by default at 99%, a commonly used value as it provides a good trade-off between results accuracy and simulation time; larger values will lead to more accurate results at the expenses of an increase in the time the simulation takes to complete, smaller values will achieve the opposite effect.

Max Relative Error Measure: this parameter is set by default at 3%; smaller values will increase results accuracy while bigger values allow for larger errors in the samples. This metric is intended as the maximum ratio between the half-width of the confidence interval and the estimated mean.

Simulation Seed: this parameter is used to initialize the pseudo-random number generator; the generated sequence of pseudo-random numbers is correlated with the seed used. A **Random** value is selected by default, or a user may define its own value.

Maximum Duration: this parameter is set to infinite by default, so that even lengthy simulations can complete and satisfy even narrow confidence intervals; finite values (in seconds) may force termination before the end of the simulation.

Maximum Simulated time: this parameter is set to **Infinite** by default, this is the time simulated during the simulation run. As a function of the objective of the study, a user may want to stop the simulation at a given time. In this case, the user may uncheck the **Infinite** check box and type the desired value of the simulated time.

Maximum Number of Samples: this parameter is set by default to 10,000,000; with a smaller number of samples it may not be possible to achieve the requested confidence interval, a larger number may not necessarily increase the results accuracy and simply extend the simulation time.

Animation Update Interval: this parameter indicates the time interval between consecutive graph updates on the screen; the default value is 1 sec, as it provides for a smooth progression of the graphs on the screen. Larger values will make the evolution of the simulation appear jerky.

Number of classes in queue animation: this parameter controls the number of classes for which graphs will be plotted for the selected performance indexes; by setting the default value to 10, all classes are represented in most models. Graph animation is enabled by default but can be disabled.

Finite Capacity Region (FCR) Parameters These parameters define the default values for newly created Finite Capacity regions. For information about Finite Capacity Regions, see subsection 4.2.1

Name: the default name of each newly created Finite Capacity Region is **FCRegion**, followed by a progres-

sive integer, starting from 1, indicating how many classes you have created so far. It can be reset to any alphanumerical string, which will be followed by the same numbering scheme.

Global Region Capacity: the default value of this parameter is infinite, i.e., there is no upper limit to the total number of customers allowed in the region; the value can be changed to finite, and a number must be specified.

Region Capacity per Class: the default value of this parameter is infinite, i.e., there is no upper limit to the per class total number of customers allowed in the region; the value can be changed to finite and a number must be specified.

Drop: the default value of this parameter is **False**, i.e., no customer is ever discarded when arriving at the region; it can be changed to **True**, in which case customers in excess of the region capacity are discarded.

4.5 Modify the Current Model

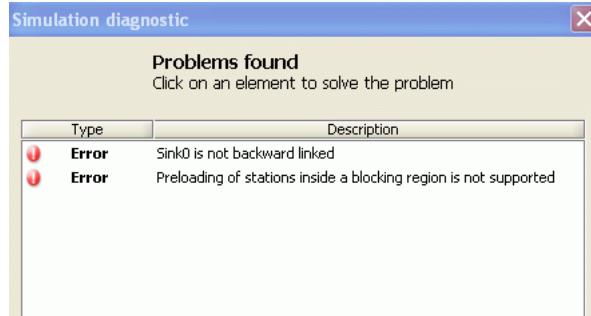
After creating a model and possibly running a simulation, you can go back to the model and modify it. To modify the current model parameters after a simulation, close the simulation windows with the  button and select the tab of the feature you wish to modify. No constraints on the order apply in this case, since all the model parameters are already defined. If no simulation was run, simply select the tab of interest.



Parameters are changed the same way they were set when creating the model the first time section 4.2.

4.6 Error and warning messages

When you start the simulation, JSIM analyzes the model and if there are errors or inconsistencies, a diagnostic window will pop up, describing the problems found.



In what follows, a list of common problems and the respective solutions are presented:

-  **Error** Source0 is not forward linked

This error occurs when the station (source or join) has not outgoing, or forward, links to any other station in the model. Only Sink stations do not have forward links. To see how to connect two stations, see subsection 4.2.3.

-  **Error** Sink0 is not backward linked

Each sink station must have at least an incoming, or backward, link from other stations, for open class jobs to be able to leave the system. Only the Source station does not have a backward link. To see how to connect stations, see subsection 4.2.3.

-  **Error** No reference station defined for Class4

For each class you must define a Reference Station that is used to compute the performance indices for the class. To see how to define a reference station, see subsection 4.2.6.

-  **Error** No performance indices defined

This error occurs when you try to start the simulation but no performance index is defined. Performance indices are defined through subsection 4.2.5.

- **Warning** Fork found but no join
- **Error** Join without fork

Fork and Join stations should be inserted together in the model. If you have inserted only one of the two stations, when the simulation is run JSIM will show a diagnostic message. Having a Fork without a Join is possible, although it may lead the system to saturate quickly, hence the Warning message. Having a Join without a Fork is a mistake, hence the Error message. The missing station must be added with the corresponding links, see subsection subsection 4.2.2 and subsection subsection 4.2.3 respectively.

- **Error** No classes defined

Customer classes are a mandatory parameter of a model. If you forget to define any, the simulator will raise an error. Add classes as described in ??.

- **Error** A performance index is defined more than once

In the definition of the model output, the same index has been added more than once for the same station and class. Multiple occurrences must be removed, see subsection subsection 4.2.5.

- **Error** Close class Class1 routed to station Server0 linked only to sink

Customers of closed classes keep circulating in the system. They may not visit a Sink station or a station that is connected on the outgoing link only to the Sink, since this would cause them to leave the system. The station connections must be changed, see subsection 4.2.3.

- "Round Robin" routing strategy in Class0 for Source is not allowed. This was considered as RandomRouting

When exporting a JSIM model to JMVA, a few constraints apply as for the admissible routing strategies. Round Robin routing is not implemented in JMVA, so it will be automatically transformed into Random, if you click the *Continue* button. Otherwise, you can change it as described in subsection subsection 4.2.4.

- **Warning** Different service times inside FCFS station Server0

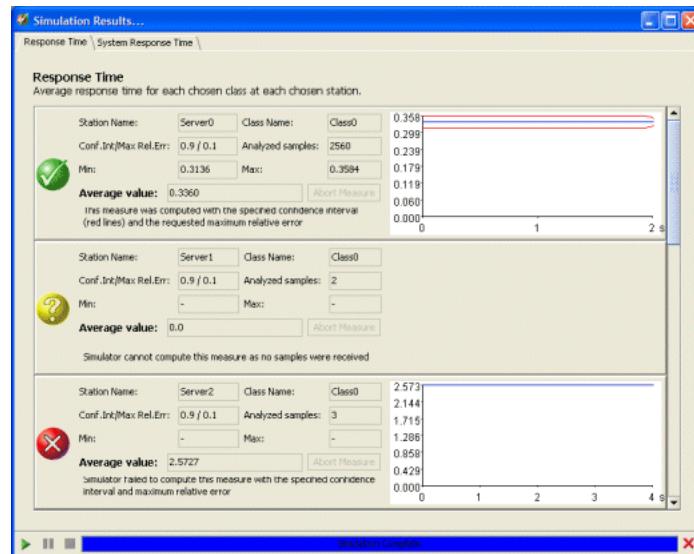
When exporting a JSIM model to JMVA, a few constraints apply as for the admissible service time distributions. A FCFS station must have exponentially distributed service time with the same mean for all the classes of customers that visit the station. If you click the *Continue* button, the station service time is reset to the default value, the same for all classes. Otherwise, you can change it as described in subsection 4.2.4.

- **Error** Undefined station in performance index

When you add a new performance index, the station for which it is defined must be specified, otherwise the error message above appears. Specify the missing station as described in subsection subsection 4.2.5.

4.7 Simulation Results

When a simulation terminates successfully, performance indices are plotted on tabbed windows, as illustrated below.



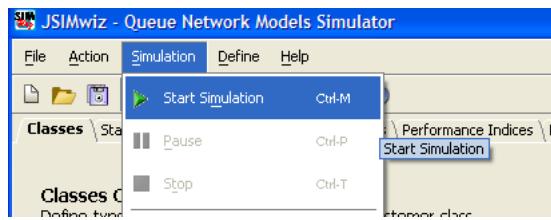
In each window, results for all the stations for which the performance index is specified are listed. Numerical values and graphs are given. Successful results are indicated by a checkmark sign on a green bullet. In case of errors or of early termination, a cross on a red bullet indicates that the results obtained are not within the requested confidence interval. In case of syntactically correct components that make no sense from a modelling

point of view, e.g., a station that is never visited by any customer, a question mark on a yellow bullet indicates that the simulator could not compute the index for lack of measurements. Values are available for:

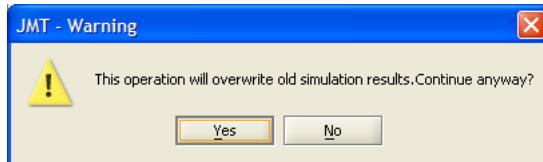
- Station Name: This is the name of the station for which the index is computed.
- Class Name: This is the name of the class for which the index is computed at the station (it could be *All*, to mean All Classes).
- Conf.In / Max Rel.Err.: This is the Confidence Interval and Maximum Relative Error of the computed index.
- Analyzed Samples: This is the number of samples used to compute the performance index.
- Min.: This is the minimum value observed for the index.
- Max.: This is the maximum value observed for the index.
- Average Value: This is the computed average value of the index, usually the value of greater interest.

4.8 Start Simulation

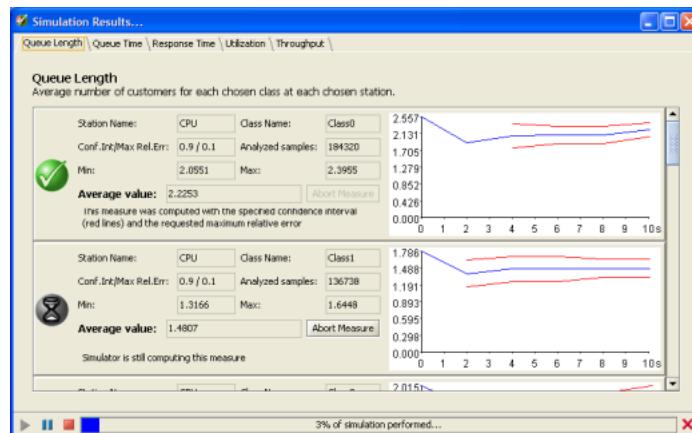
When a model is complete and the Simulation Parameters have been defined, you can start the simulation clicking the button or selecting *Start Simulation* from the Simulation menu



If there are errors and/or potentially critical conditions, error and/or warning messages will appear, see **??**. In case of errors, the simulation may not start and errors must be corrected. In case of warnings, you can still start the simulation but the results may not be consistent. If another simulation was executed before the current one, JSIM will warn you that previous simulation results will be overwritten if you continue. Click Yes if you do not care about previous results, click No if you wish to save previous results first and then restart the simulation.



After the simulation has started, the results window appears, with partial values. In particular, for each performance index and for each station the index has been selected, the current number of analyzed samples, the current average value and the graph of the latter are constantly updated. The graph plots in blue the current average value estimated by the simulator and in red the confidence intervals. Confidence intervals appear in the graph when the simulator has gathered sufficient samples to compute a reasonably accurate confidence interval: note that the number of samples required for the confidence intervals to appear is not constant and depends also on other factors such as the degree of fluctuation of the average value estimate.



An hourglass indicates that the computation of that index is not finished yet. A check mark in a green bullet indicates that the computation of that index has successfully terminated. In this case, the minimum and maximum average are reported as well. At the bottom of the result window are the simulation control buttons, namely the pause button (double bar), the start button (right pointing triangle), and the stop button (square). The status bar indicates the percentage of simulation executed so far, both graphically and numerically.

Chapter 5

JMCH (Markov Chain)

5.1 Introduction

JMCH provides a graphical representation of the states of the Markov Chain corresponding to a single station models, with limited ($M/M/1/k$) or infinite queue size ($M/M/1$), and multiple server stations with c servers ($M/M/c$) and limited queue size k ($M/M/c/k$). It is possible to change the arrival rate λ and service time S of the station at simulation run time and, if the model is of limited capacity, the size k of the queue can also be changed dynamically.

Effort have been done in order to implement a graphical interface with animation. Users may have the visual perception of the bursts of traffic and of their effects on the queue length and on the utilization of the server(s). The exact analytical results are computed and are also shown for comparison purposes.

5.2 Starting the JMCH solver

Selecting the  button on the starting screen, the dialog window for the selection of the type of station to be considered is shown (see Figure 5.1).

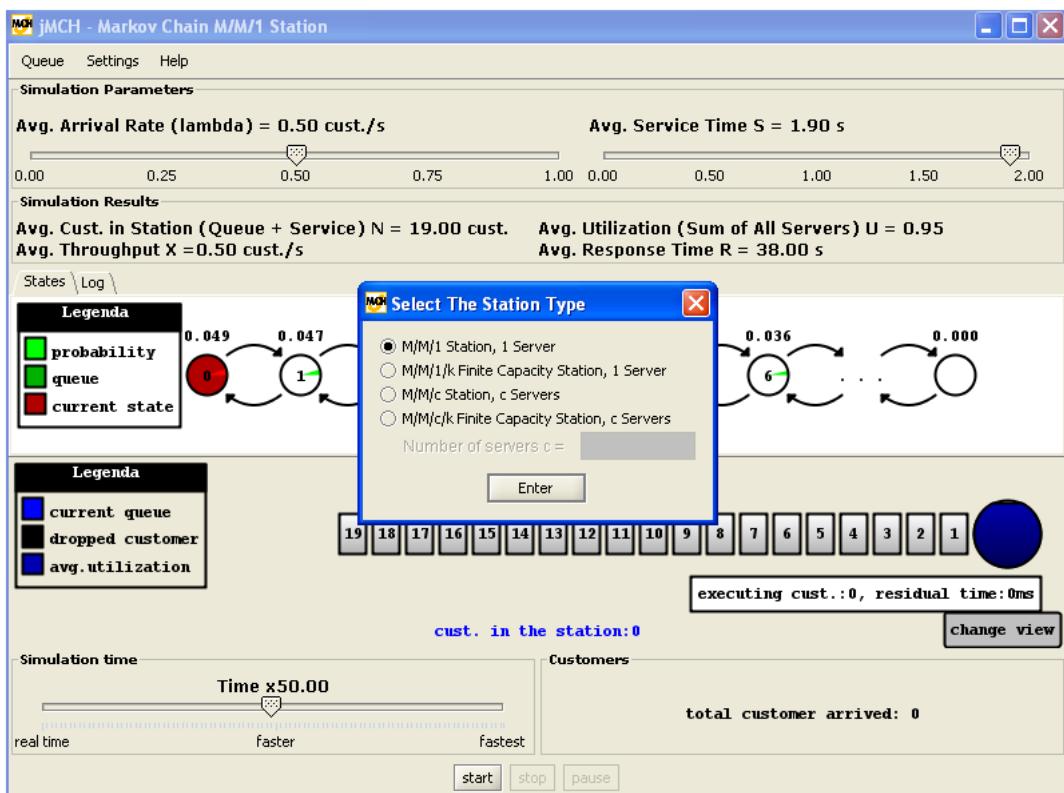


Figure 5.1: JMCH start screen

The type of station can be modified later by using the menu item Queue - Change station type . Four station types are simulated (see Figure 5.2):

- M/M/1: 1 server and infinite queue size.
- M/M/1/k: 1 server and finite queue size k . The queue size k can be set dynamically while the simulation is running. The minimum value of k is 2.
- M/M/c: c servers (homogeneous) and infinite queue size. The number c of the servers should be set with this dialog box and it cannot be changed dynamically while the simulation is running.
- M/M/c/k: c servers (homogeneous) and finite queue size k . The number c of the servers should be set with this dialog box and it cannot be changed dynamically while the simulation is running. The queue size k can be set dynamically while the simulation is running. The minimum value of k is $c+1$.

When a multiple server station is selected, the text field for the number c of servers is activated.

When the station type is set, the windows of Figure 5.1 is shown.



Figure 5.2: JMCH station dialog

In the main view user can check the type of station selected as seen from the title bar. The menu bar consists of: Queue, Setting and Help. In the Queue menu user can change the type of the station. In the Setting menu user can set the colors of the user interface and also size of the icons. To start the Simulation user needs to Press Start button, on pressing Start the dialog Figure 5.3 is displayed. The options displayed are

- Unlimited
- Limited(Type in)

If users select **unlimited** the simulation must be stopped manually else it runs forever. In this case the animation of the queue length and of the Markov chain states can be observed more clearly. If users select **limited**, the simulation runs for the given number of customers. Then, the simulation starts running, as can be seen in Figure 5.4

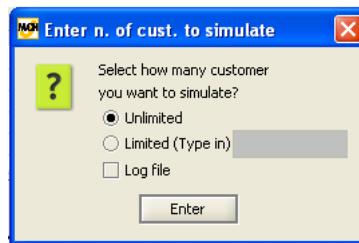


Figure 5.3: JMCH Number of Customers

5.3 Input parameters

The top most pane known as *Simulation Parameters* Figure 5.4, is for setting simulation parameters:

- λ : Average arrival rate [customers per second], the distribution of interarrival times is exponential with mean $1/\lambda$.
- S : Average service time for each customer [seconds], the values are exponentially distributed
- k : Maximum station size: is the maximum number of customers allowed in the station. This is the total number of customers including those in queue and those in the server(s). The minimum value of k is 2.

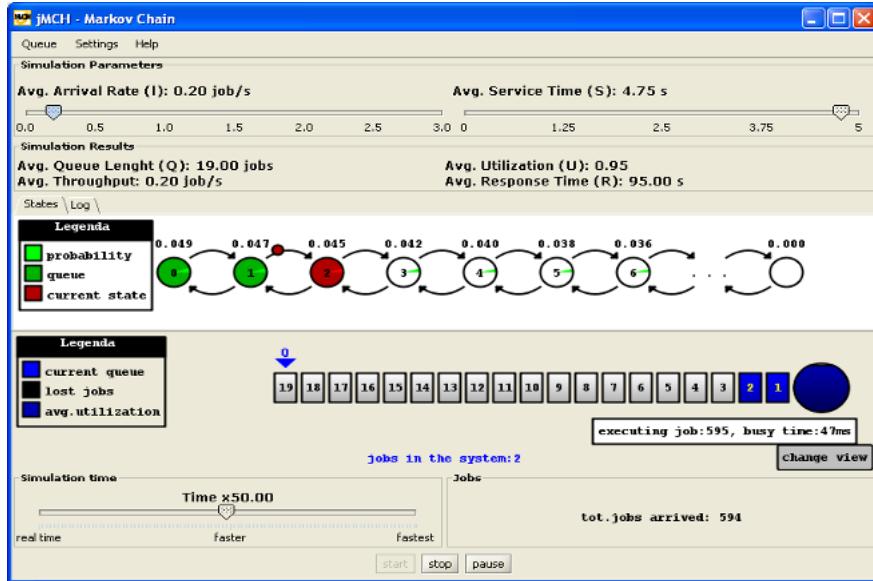


Figure 5.4: JMCH Simulation running

According to the parameters selected (type of station, number of servers, max capacity, arrival rate, service times) the following performance indices are analytically computed and displayed:

- *mean number of customers* in the station (either in queue and in the servers)
- *throughput* (that coincides with the arrival rate)
- *utilization*
- *mean response time*
- *probability of the states* of the Markov Chain.

5.4 Output results

The pane *Simulation Results* consists of two possible views **States** and **Log**. The first view, called **States** displays the probabilities of the states (analytically computed) and the migration among them with animation obtained through simulation.

The second view is the **Log** screen which shows the data, explained as below, for each customer:

- *Cust.ID*: the unique **id** assigned to each customer by a counter.
- *Arrival Time*: shows the instant of time of the creation of the customer.
- *Start Execution*: the instant of time in which the customer start to be executed from one of the servers.
- *Server ID*: it shows the id of the server if there are more than one.
- *Exit system*: the instant of time in which the customer exits from the system.

NOTE: If the station has a limited queue and there is no empty place, the new customer will be dropped and this event will be logged as *job dropped*.

The pane below the *Simulation Results* shows the status of the servers and the queue.

It has two types of views. The first view shows the utilization of the station. The second view shows the percentage of the current job.

The last pane displays the Simulation time and number of customers. The former displays the speed of the simulation, and the latter displays the total number of the customers. If the simulation is set with limited number of customers, then this area shows the customers remaining. In the bottom there are three buttons for the simulation Start, Stop and Pause. The user should set the parameters before starting the simulation. However, the parameters can also be changed during the simulation. If the simulation is stopped, the log can be saved as a tab separated text file.

5.4.1 Logger

Logging of events can also be obtained from JMCH Simulation. If users wants to see the *arrival time*, *the execution time (start and stop times)*, *the server id* where the customer is being served for each customer entering the system then they have to select the checkbox in Figure 5.5 where also the location of the log file should be provided. The Figure 5.6 shows a sample of log output. The log file can be found in the specified

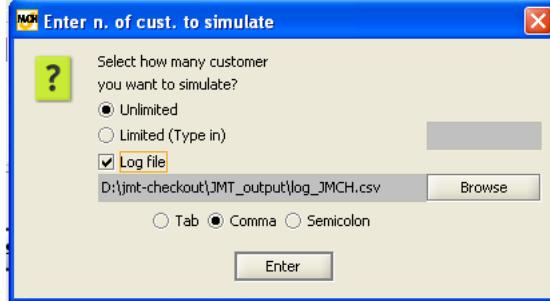


Figure 5.5: JMCH Logger location

location.

	A	B	C	D	E	F
1	Cust. ID	Arrival Time	Start Exec	Server ID	Exit System	
2	1	1.39	1.39	0	1.42	
3	2	2.57	2.57	0	2.63	
4	3	2.71	2.71	0	2.79	
5	4	3.31	3.31	0	3.38	
6	5	3.68	3.68	0	3.68	
7	6	4.08	4.08	0	4.15	
8	7	4.83	4.83	0	5.2	
9	8	4.83	5.2	0	5.57	
10	9	6.46	6.46	0	6.58	
11	10	7.99	7.99	0	8.39	

Figure 5.6: JMCH Log output

Chapter 6

JABA (Asymptotic Bound Analysis)

6.1 Overview

Product-form queueing network models are used for modelling the performance of many type of systems, from large computing infrastructures to distributed applications. The complexity of modern systems makes the application of exact solution techniques, such as the convolution algorithm or the MVA, prohibitively expensive in terms of computational resource requirements. Also approximate solution techniques become less accurate or more expensive with the growing complexity of the models. The alternative is represented by *asymptotic* techniques that can efficiently determine asymptotic values for several performance indices such as throughput, response time and queue lengths. The asymptotic techniques are particularly useful in tuning studies where one needs to evaluate the performance gains of different tuning alternatives. The key to determine the asymptotic performances is the knowledge of the queueing center(s) with the highest utilization, i.e. the *bottleneck station(s)*. Multiclass models can exhibit multiple simultaneous bottlenecks depending of the population mix [BS96][BS97]. While identifying the bottleneck stations under a single-class workload is a well-established practice, no simple methodology for multiclass models has yet been found. JABA provides such a technique, called *Polyhedral Analysis*, using convex polytopes based approach presented in [CS04]. An example of application of this technique to identify the bottlenecks in a two-class workload and of the enhancement of the performance of the system is provided in [CS11].

Among the non-bottleneck stations, we distinguish two different types: *dominated* and *masked-off* stations. This distinction is important since the *masked-off* stations, despite having lower utilization than the bottleneck center(s), may still exhibit the largest queue-length and hence the highest response times. *Dominated* stations, instead, typically play a marginal role in determining system performance, and have always the smallest utilization and queue-lengths.

6.1.1 Starting the alphanumeric JABA solver

Selecting  button on the starting screen, Figure 6.1 the JABA window shows up.

Three main areas are shown:

Menu : it is organized into three groups of functions. To use a menu, click on the menu heading and choose the appropriate option. For the description of menu entries, see section 6.3

Toolbar : contains some buttons to speed up access to JABA functions (e.g. New model, Open, Save... See section 6.3 for details). If you move the mouse pointer over a button a tooltip will be shown up.

Page Area : this is the core of the window. All JABA parameters are grouped in different tabs. You can modify only a subset of them by selecting the proper tab, as will be shown later.

6.2 Model definition

Models with two or three customer classes provide estimates of which stations are potential bottleneck. For a brief description of basic terminology please refer to Appendix A.

The workload is characterized for each station by the service demands of every customer class. At least JABA works with 2 classes of customers therefore a matrix of service demands is required [LZGS84].

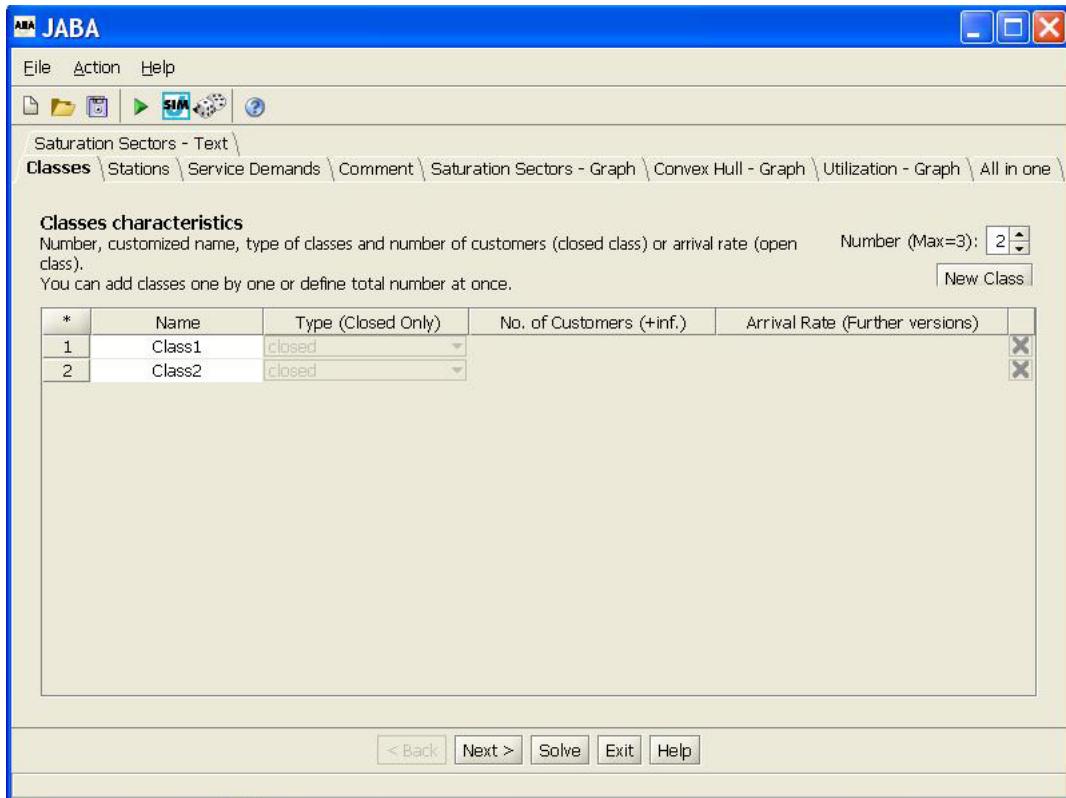


Figure 6.1: Classes tab

6.2.1 Defining a new model

To define a new model select toolbar button or the *New* command from *File* menu. The following parameters must be defined:

1. **Classes**
2. **Stations** (service centers)
3. **Service demands** (or Service Times and Visits)
4. Optional short **Comment**

The execution of JABA produces the following graphs:

- Saturation Sector - graphics
- Convex Hull - graphics
- Utilization - graphics

and a textual report concerning the coordinates of the saturation sectors:

- Saturation Sectors - text

Input tabs

As shown in Figure 6.1, the parameters that must be entered in order to define a new model are divided in four tabs: **Classes**, **Stations**, **Service Demands** and **Comment**.

The number of tabs become five, if you click *Service Times and Visits* button in *Service Demands Tab*. As will be discussed in subsection 6.2.4, the **Service Demands Tab** will be hidden and it will appear **Service Times Tab** and **Visit Tab**. You can navigate across tabs:

- using sequential wizard buttons, if enabled, at the bottom of the window (Figure 6.2)
- using sequential buttons located in menu
- using the tab selector, clicking on the corresponding tab (Figure 6.3)



Figure 6.2: Wizard buttons

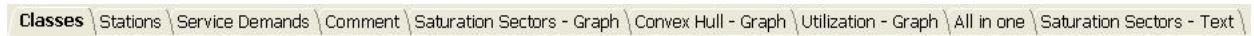


Figure 6.3: Tab selector

6.2.2 Classes Tab

A screenshot of this tab can be seen in Figure 6.1. This tab allows to set the number of customer classes. It is possible to define only two or three classes.

The number of classes in the model can be specified in the corresponding input area, shown in Figure 6.4 and can be modified using the keyboard or the spin controls.

Number (Max=3):	<input type="text" value="2"/>
<input type="button" value="New Class"/>	

Figure 6.4: Number of classes

Using the delete button associated to a specific class, a class can be removed provided that there will be at least one class after the deletion. Similar result may be obtained using spin controls, decreasing classes number; in this case last inserted class will be removed.

Default class names are *Class1*, *Class2*, ... *ClassN*. The model can be personalized by changing these names.

6.2.3 Stations Tab

The number of stations of the model can be specified in the corresponding input area (Figure 6.5) and can be modified using the keyboard or the spin controls.

Using the delete button associated to a specific station, a station can be removed provided that there will be at least one station after the deletion. Similar result may be obtained decreasing the number of stations using spin controls; in this case the last inserted station will be removed.

Default station names are *Station1*, *Station2*, ... *StationN*. In order to personalize your model, you can change and give names other than default ones.

In Figure 6.6 there is only one station with default name *Station4* and there are three stations with personalized names: *CPU*, *Disk1* and *Disk2*.

6.2.4 Service Demands, Service Times and Visits Tabs

Service Demands can be defined in two ways:

- directly, by entering Service Demands (D_{kc})
- indirectly, by entering Service Times (S_{kc}) and Visits (V_{kc})

Service demand D_{kc} is the total service requirement, that is the average amount of time that a customer of class c spends in service at station k during a complete interaction with the system, i.e. a complete execution. Service time S_{kc} is the average time spent by a customer of class c at station k for a single visit at that station while V_{kc} is the average number of visits at that resource for each interaction with the system.

Remember that $D_{kc} = V_{kc} * S_{kc}$ so it is simple to compute the service demands matrix starting from service times and visits matrices. Inverse calculation is performed with the following algorithm:

$$V_{kj} = \begin{cases} 1 & \text{if } D_{kc} > 0 \\ 0 & \text{if } D_{kc} = 0 \end{cases}$$

$$S_{kc} = \begin{cases} D_{kc} & \text{if } D_{kc} > 0 \\ 0 & \text{if } D_{kc} = 0 \end{cases}$$

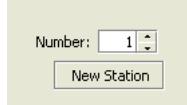


Figure 6.5: Number of stations

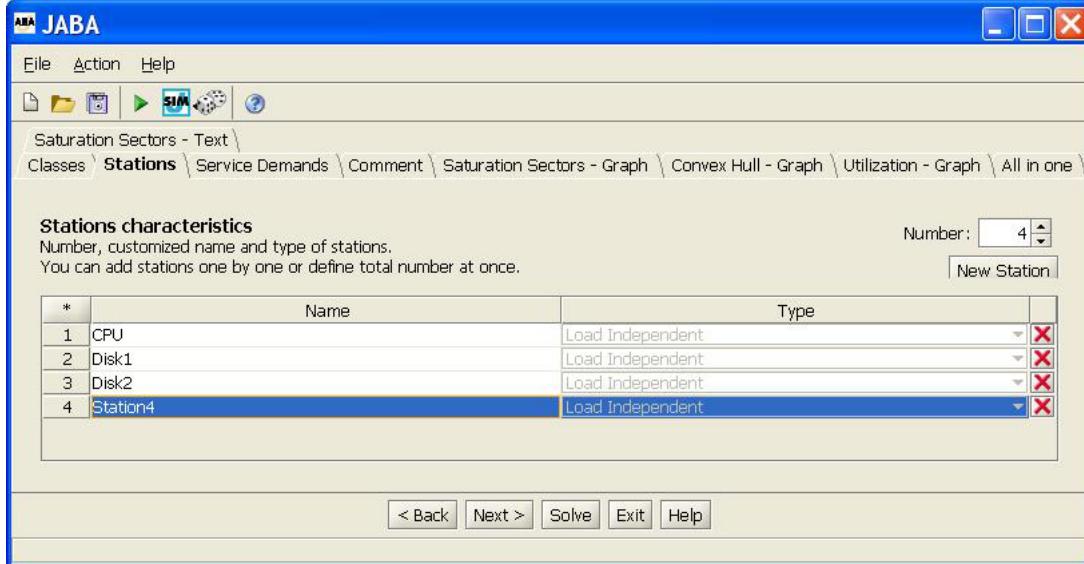


Figure 6.6: Defining the stations name

Service Demands Tab

In this tab you can insert directly Service Demands D_{kc} for each pair {station k -class c } in the model. Figure 6.7 shown a reference screenshot can be seen: notice that a value for every D_{kc} element of the D -matrix has already been specified because the default value assigned to newly created stations is zero.

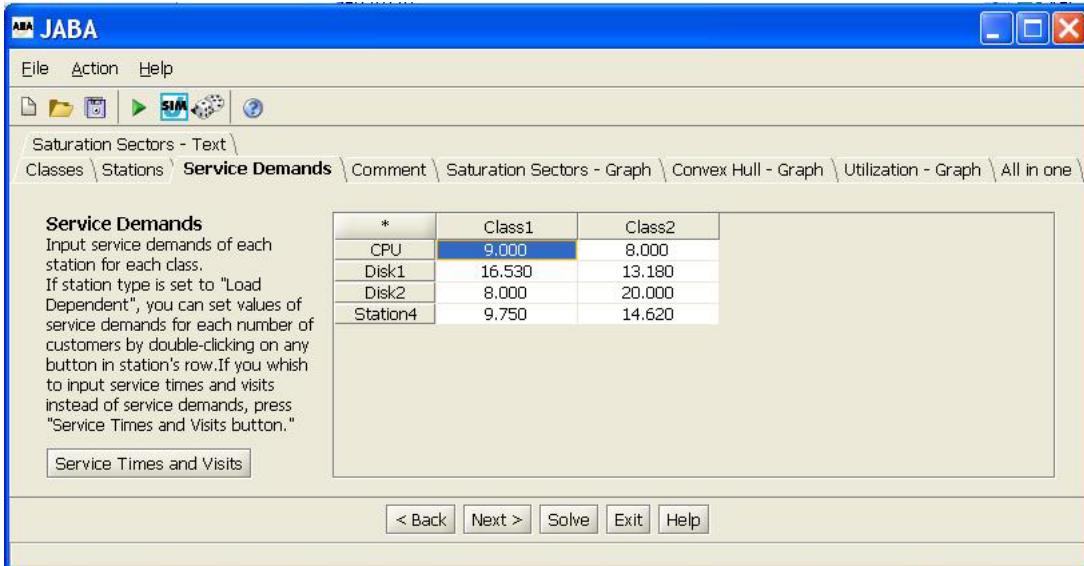


Figure 6.7: The Service Demands Tab

In Figure 6.7, each job of *Class1* requires an average service demand time of 6 sec to *CPU*, 16.53 sec to *Disk1*, 8 sec to *Disk2* and 9.75 sec to *Station4*.

Service Times and Visits Tabs

In the former tab you can insert the Service Times S_{kc} for each pair {station k -class c } in the model, in the latter you can enter the visits number V_{kc} (See Figure 6.8).

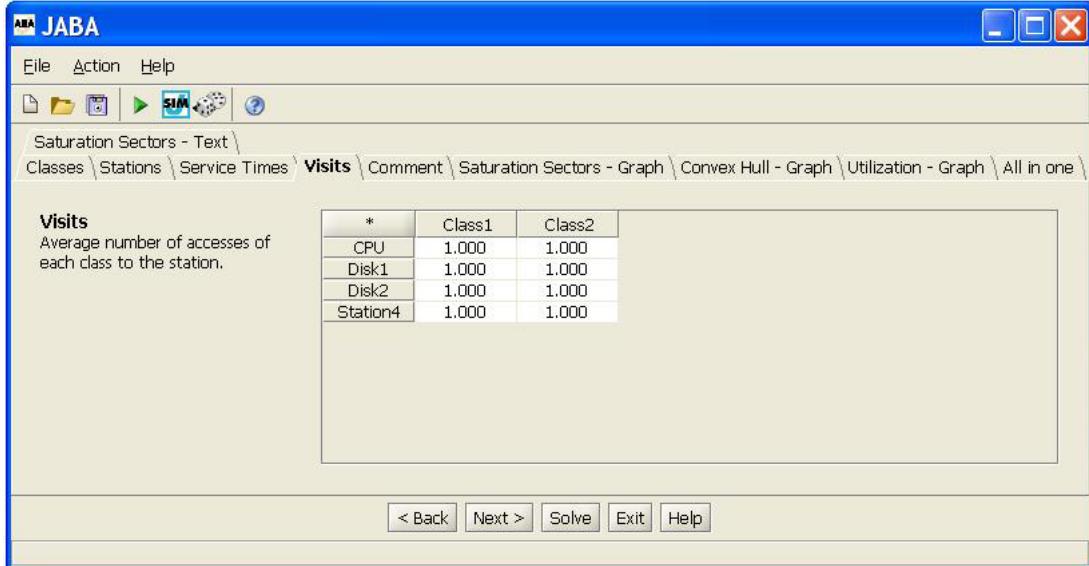


Figure 6.8: Visits Tab

The layout of these tabs is similar to the one of the **Service Demand Tab** described in the previous paragraph. The default value for each element of the Service Times (S) matrix is zero, while it's one for Visits' matrix elements.

6.2.5 Comment Tab

In this Tab, a short - optional - comment about the model can be inserted; it will be saved with the other model parameters.

6.2.6 Saturation Sector - Graph

Using the **Solve** command the Saturation Sector graph appears.

Two-class workload

The population of the system (i.e., the number of customers of the different classes in execution) is defined with the vector $\mathbf{N} = (N_1, N_2)$ where N_1 is the number of customers belonging to class1 and N_2 is the number of customers of class2. We define the *population mix* corresponding to the population \mathbf{N} as the vector $\boldsymbol{\beta} = \{\beta_1, \beta_2\}$ whose components are all non-negative and are given by

$$\beta_r = \frac{N_r}{N} \quad \sum_r \beta_r = 1 \quad (6.1)$$

We study the asymptotic behavior of a system under a particular type of population growth that consists of letting the total number of customers N in the system to grow to infinity keeping constant the population mix $\boldsymbol{\beta}$ and that we call proportional population growth. In multiclass queueing networks the ratio between the (global) utilizations of two arbitrary service stations is not constant, but depends on the population mix. Thus, in general, different population mixes can yield different bottlenecks. Under this assumption of population growth, we define as *system bottlenecks* the stations for which the following expression holds:

$$\lim_{N \rightarrow \infty} U_i(\mathbf{N}) = \lim_{N \rightarrow \infty} \sum_r U_{ir}(\mathbf{N}) = 1. \quad (6.2)$$

These stations will be referred also as *saturating stations*. In general, different values of $\boldsymbol{\beta}$ may yield different sets of system bottlenecks. Special types of system bottlenecks are the *natural bottlenecks*. The class-r natural bottleneck is the station that saturates when the workload consists only of class-r customers ($\beta_r = 1$) and the number of customers grows to infinity.

In the more general case in which different classes have distinct natural bottlenecks, proportional population growths corresponding to different population mixes may identify different sets of bottleneck stations. This means that, keeping the total population N of the system constant (and large) and varying the population

mix, we may observe the *bottleneck migration* phenomenon. In this situation, it is possible to find a set of mixes, represented as an interval $[\beta'_1, \beta''_1]$, where multiple stations are bottlenecks, i.e., saturate concurrently. We define this interval as *saturation sector* and its edges correspond to *switching points* where stations may change their bottleneck/non-bottleneck status. Depending on the values of the service demands a system may have one or more saturation sectors.

JABA represents the saturation sectors and the switching points through a two-dimensional graph, see e.g. Figure 6.9.

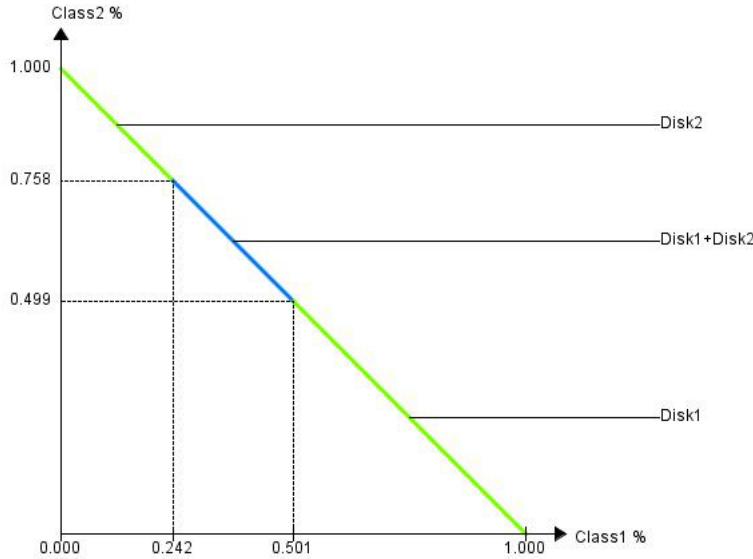


Figure 6.9: Saturation Sector graph. The labels refer to the stations that saturate in the corresponding interval.

In the example of Fig.6.9 we may observe that *Disk1* is a bottleneck for the mixes population from $\beta'_1 = 0.242$ to $\beta''_1 = 1$. The station *Disk2* is a bottleneck for the mixes population from $\beta'_1 = 0$ to $\beta''_1 = 0.501$. The switching points are $(0.242, 0.758)$ and $(0.501, 0.499)$. The blue sector represents the mixes where two stations are bottlenecks concurrently. Green sectors represent the mixes where only one station saturates. In the case where more than two stations saturate concurrently, red color will be used.

Three-class workload

Sometimes a two-class model does not describe properly the workload you want to study, because more than two clusters of customers can be identified. In this case JABA allows you to define a three-class model to fit better the behavior of the customers of the system. Exactly for the two-class, also for the three-class model the stations for which holds Equation 6.2 are called *system bottlenecks* and will be referred also as *saturating stations*. In this context β is a three-dimensional vector and different values of β may lead to different sets of *system bottlenecks*. JABA uses a triangle to show for each value of β which stations will be bottlenecks. The vertices of this triangle represent the values $[1,0,0]$, $[0,1,0]$ and $[0,0,1]$ of β . The inside of this triangle will be divided into sub-areas and each area represents a population mix range where one, two or more stations are bottleneck at the same time. It is clearly understandable that in this situation there are no more *switching points* (such as in the two-class model) but instead *switching segments*. In the example of Figure 6.10 we can observe a big area, on the top of the triangle, that represents the range of mix population where only *Station4* is a bottleneck. In the center of the triangle there is a little red area that represent the range of mix population where *Disk1*, *Disk2* and *Station4* are all bottleneck. The color of a sub-area has the following meaning:

- just one station is bottleneck for the values of β identified by a *yellow* area.
- two stations are bottleneck for the values of β identified by a *brown* area.
- more than two stations are bottleneck for the values of β identified by a *red* area.

This graph is useful for understanding when stations became bottlenecks; sometimes is not simple to get the exact values of the *switching segment*, in order to obtain them select the “Saturation Sector - Text” tab subsection 6.2.10.

6.2.7 Convex Hull - Graph

Using the **Solve** command and selecting the “Convex Hull - Graph” tab the Convex Hull graph will be shown.

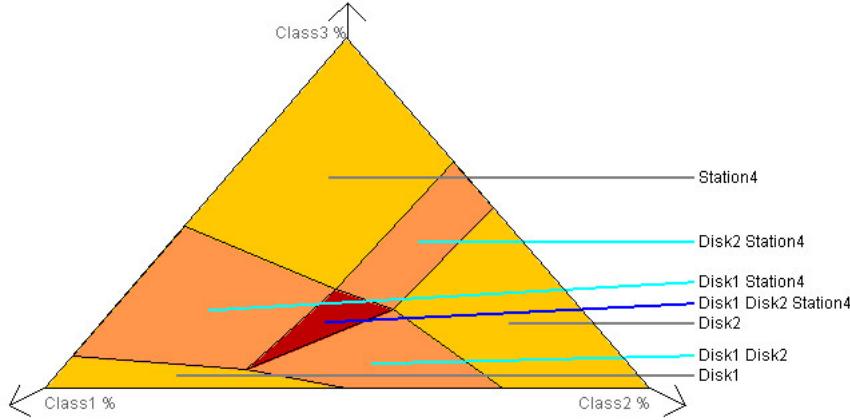


Figure 6.10: Saturation Sector graph

The Convex Hull graph implements the *polyhedral analysis* technique, a technique, based on the theory of convex polyhedra, for identifying the bottlenecks of multi-class queueing networks with constant-rate servers.

Polyhedral technique

Let $\mathbf{R} = \{1, 2, \dots, r\}$ be the set of customer classes indices and $\mathbf{M} = \{1, 2, \dots, m\}$ the set of station indices. The average service demand required by class- r customers on station i will be indicated with $D_{i,r}$. The following matrix describes compactly the system

$$\mathbf{D} = \begin{bmatrix} D_{1,1} & D_{1,2} & \cdots & D_{1,r} \\ D_{2,1} & D_{2,2} & \cdots & D_{2,r} \\ \vdots & \vdots & \ddots & \vdots \\ D_{m,1} & D_{m,2} & \cdots & D_{m,r} \end{bmatrix}$$

This technique introduces a taxonomy of stations. *Potential bottleneck set* Φ is the set of stations that can become bottlenecks for some feasible population of the system. The stations that cannot become bottlenecks for any feasible population are grouped in the set of non-bottleneck stations $\Psi = \mathbf{M} \setminus \Phi$. Among these it is possible to distinguish two kinds of stations: a station $j \in \Psi$ is said to be *dominated* by $i \in \mathbf{M}$ iff $D_{jr} < D_{ir}, \forall r \in \mathbf{R}$ and all non-dominated stations $k \in \Psi$ are called *masked-off* stations. It is known [CS04] that all potential bottlenecks lie on the boundary of the *characteristic polytope* of the system. Viewing the matrix \mathbf{D} as a set of m points in a r -dimensional space, the *characteristic polytope* of a system is the convex-hull of the set of points $\mathbf{D} \cup \text{proj}(\mathbf{D})$, where $\text{proj}(\mathbf{D})$ is the set of all vectors derived by a by setting to zero k of its components, for all possible $k = 1, \dots, r$ and for all possible positions.

JABA shows which stations of a system may saturate building the *characteristic polytope*.

Two-class workload

In two-class models each station corresponds to a point on a graph whose co-ordinates are represented by the service demand of the two customer classes. For example, a station with service demands 10 sec for class 1 and 15 sec for class 2 is represented as a point with coordinates (10,15).

In the example of Figure 6.11, we can see that *Disk1* and *Disk2* (depicted in red) lie on the boundary of the convex hull, thus are potential bottlenecks. *CPU* (green) is instead a *dominated* non-bottleneck station, since it is dominated by *Station4* and *Disk1*. *Station4* (blue) is also in the interior of the convex hull, but it is not *dominated*, so it is a *masked-off* station.

In order to gain exact information about the coordinates of a point it is sufficient to move the mouse on it and additional information will appear after the station name. Clicking (left button) on the line that it connects two bottleneck stations you can obtain information about the saturation sector such as the interval of mix population that make possible the bottleneck and also the throughput of the two classes.

Now suppose that we have to analyze the upgrade of the station *Station4*, the new *Station4* will have half demand for both the customer's classes compared to the old one. In order to do this we can change the value in the demand's table of JABA or click on the point (left button) and drag it in the new position. While dragging the point temporary co-ordinates are shown and when the point is released all data are update and a new graph is painted. As showed in the Figure 6.13, it is possible that a area of the graph could be crowded of points and

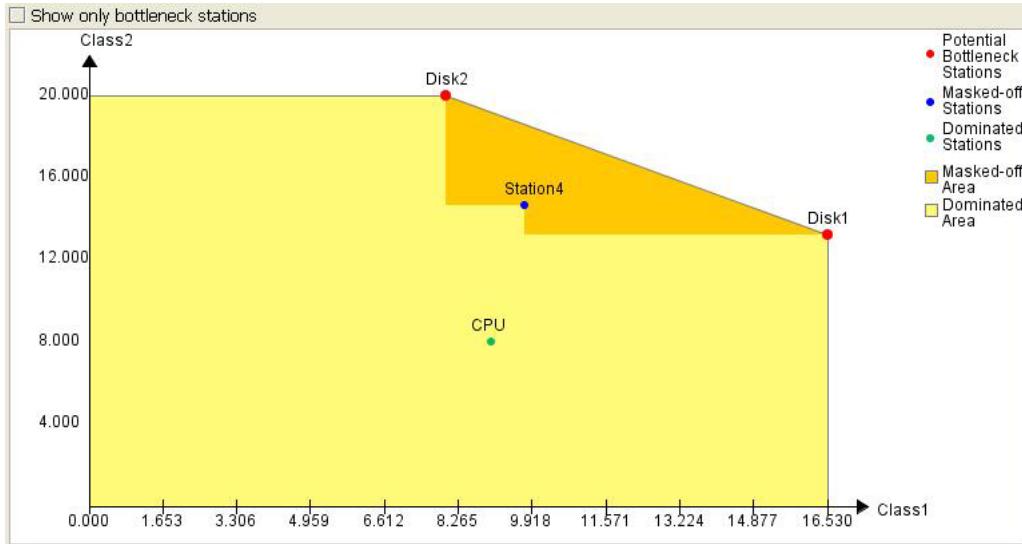


Figure 6.11: Convex Hull graph

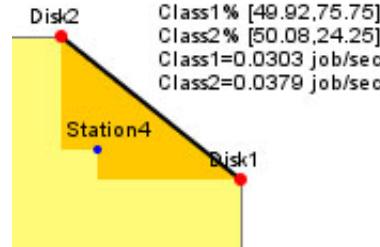


Figure 6.12: Convex Hull graph while saturation sector is selected

it is difficult to read the name of the station; at first we can try to change the zoom, we can therefore zooming in or out with a right-click on the graph.

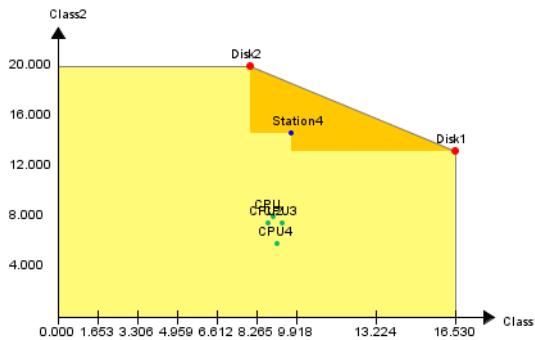


Figure 6.13: Convex Hull graph whith a crowded area

If the zooming is no enough we can try filtering the zone and freeing only some points. In order to filter the area is enough to select it keeping the mouse's left button pressed. The background of the selected area will become light-blue and the labels of points will disappear. Now we try to reduce the filtered area adding some free area; to do that we select the area that we wish to free keeping the mouse's right button pressed. In the following example we have set the tallest point free. Only the name of the station that is in the free area is showed.

Three-class workload

If you define a three-class model the convex-hull is a 3d object (Figure 6.15), dragging this three-dimensional object JABA allows you to rotate it showing its different faces. Beside the graph JABA will show a set of options that allow you to

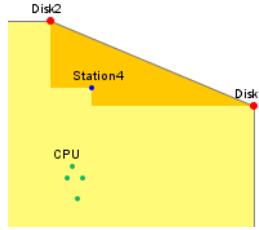


Figure 6.14: Convex Hull graph with a filtered area

- set the render mode (solid, wireframe, points)
- hide or show the names of the stations
- hide or show the non-bottleneck stations
- select a station

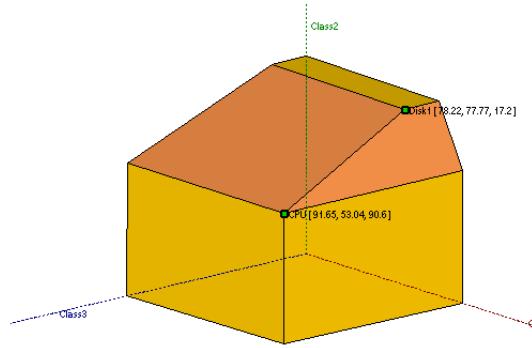


Figure 6.15: Convex Hull graph with a 3 class workload

6.2.8 Utilization - Graph

If you are working on a two-class model using the **Solve** command and selecting the “Utilization - Graph” tab the Utilization graph will be shown. Using a graphical method JABA shows you the behavior of the utilization of the stations varying the population mix of the system.

Graphical method

This method takes as input the description of the system and produces a graph showing the behavior of the utilization for every stations.

Considering a system with two class of customers and m stations the following matrix describes compactly the system

$$\mathbf{D} = \begin{bmatrix} D_{1,1} & D_{1,2} \\ \dots & \dots \\ D_{m,1} & D_{m,2} \end{bmatrix}$$

Where $D_{i,j}$ is the average service demand required by class-j customers on station i .

In order to explain this method we will use a running example with the matrix

$$\mathbf{D} = \begin{bmatrix} 9 & 8 \\ 16.530 & 13.180 \\ 8 & 20 \\ 9.750 & 14.620 \end{bmatrix}$$

The output of the method will be a graph of m functions. Every function is related with a station, it shows the value of the utilization of the related station for every possible population mix of customers. In order to plot the functions will be used a Cartesian-plane, on the abscissas the percentage of class-1 customers and on the ordinates the utilization Figure 6.16.

The following proposition describes the behavior of the utilization function and it is very useful for our goal.

Proposition 1: the utilization of every stations is a *polygonal chain* and slope changes may occur only when the abscissa is equal to the first component of a *switching-points* (the output of *Saturation Sector Graph*).



Figure 6.16: The Cartesian plane used to plot the Utilization-Graph.

In order to highlight this behavior we divide the abscissa-axis into segments using the *switching-points*, from now on we will indicate with $\mathbf{S} = \{1, \dots, s\}$ the set of these segments. In Figure 6.17 it is shown this division for our running example.

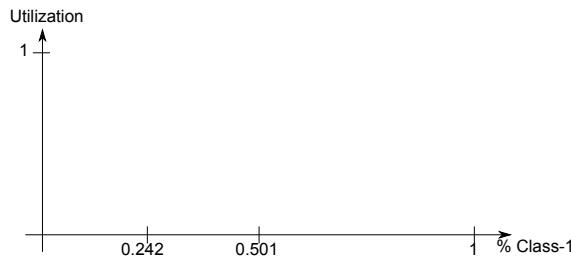


Figure 6.17: Division of the abscissa-axis of the Utilization-Graph.

Thanks to *Proposition 1* all we need is

- for every segment s in \mathbf{S} the slope of the utilization of every station i , indicated as $slope_{s,i}$
- for every station i the value of the utilization when the abscissa is equal to zero, indicated as $U_i(0)$

Indicating with b_s the station that saturates in the segment $s \in S$ ¹, the following formulas give us these information

$$slope_{s,i} = \begin{cases} 0 & \text{if } s \text{ is a saturation sector} \\ \frac{D_{i,1}}{D_{b_s,1}} - \frac{D_{i,2}}{D_{b_s,2}} & \text{otherwise} \end{cases} \quad (6.3)$$

$$U_i(0) = \frac{D_{i,2}}{D_{b_1,2}} \quad (6.4)$$

Using Equation 6.3 and Equation 6.4 JABA plots for every station the behavior of the utilization, Figure 6.18.

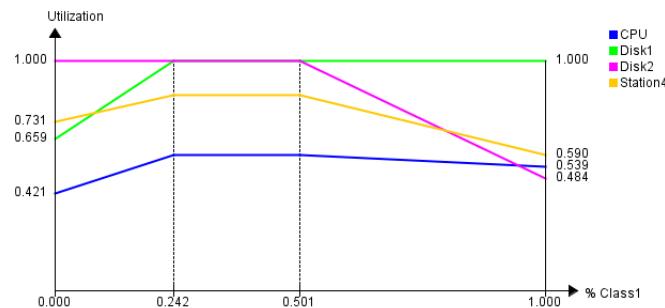


Figure 6.18: Utilization graph

6.2.9 All In One - graph

If you are working on a two-class model using the `Solve` command and selecting the `All In One` tab the Saturation-Sector graph, the Convex-Hull graph and the Utilization graph will be shown together. If you use this type of composite graph, it is interesting to point out that you may change with the mouse a point in the Convex Hull (i.e., a value of the service demand of a station) and immediately you will see the effects on the other two graphs (i.e., Saturation Sector and Utilization graphs) since they are updated online.

¹This is meaningful only for non saturation sectors.

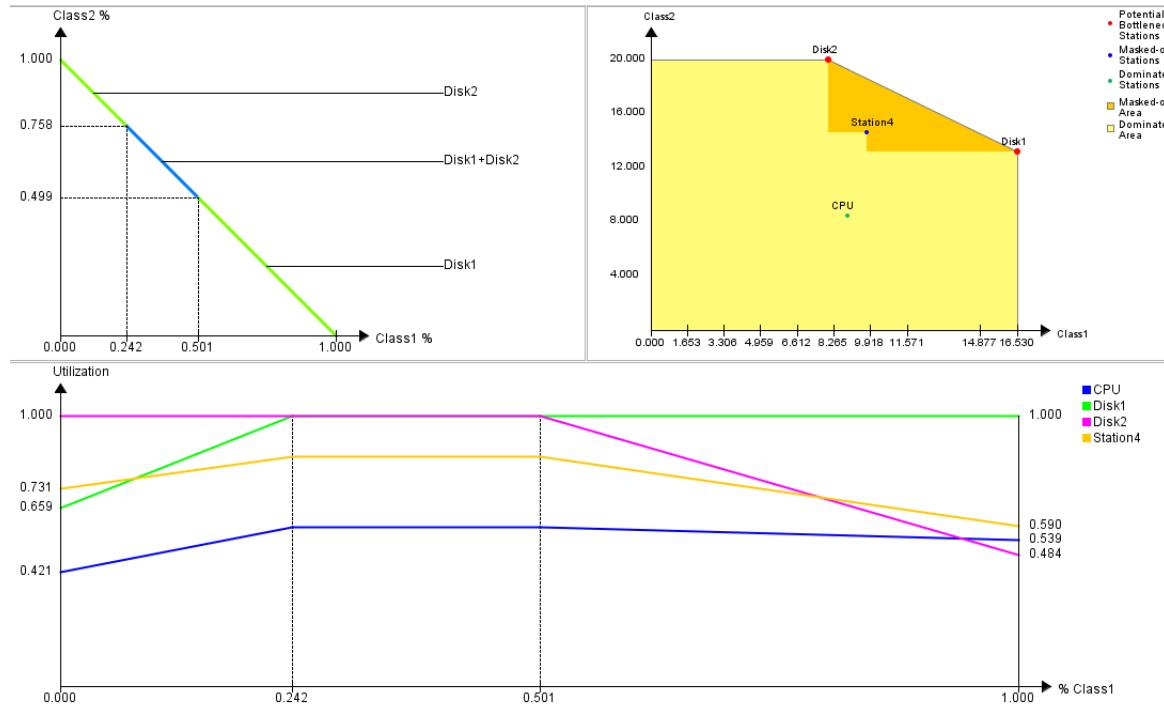


Figure 6.19: All In One graph

6.2.10 Saturation Sector - Text

It's a simple report about the saturation sector, for each saturation sector you can find:

- The station that are bottleneck
- The switching point or the switching segment bound points.

This tab could be helpful in the Saturation Sector graph of three classes of costumers subsection 6.2.6

6.2.11 Modification of a model

To modify system parameters return to the main window and enter new data or moving a station in Convex Hull - graph tab (see subsection 6.2.7). After the modifications, if you use **Solve** command, the new graphs will show. You can **save** this new model with the previous name - overwriting the previous one - or **save it** with a different name or in a different directory.

6.3 Menu entries

6.3.1 File

New

Use this command in order to create a new JABA model.

Shortcut on Toolbar:

Accelerator Key: **CTRL+N**

Open

Use this command to open an existing model. You can only open one model at time, to edit two or more models start more than one instance of JABA. If current model was modified since its creation or last save action, a popup window will be shown for confirmation.

It's possible to open not only models saved with JABA (*.jaba), but also with other programs of the suite (for example JMVA *.jmva, JSIM *.jsim and JMODEL *.jmodel). Whenever a foreign data file is opened, a conversion is performed and error/warnings occurred during conversion will be reported in a window.

Models are stored in XML format, see *JMT system manual* for a detailed description.

Shortcut on Toolbar:



Accelerator Key:

CTRL+O

Save

Use this command in order to save the active document with its current name in the selected directory.

When you save a document for the first time, JABA displays the Save As dialog box so you can rename your document. If you save a model after its resolution, results are stored with model definition data.

Shortcut on Toolbar:



Accelerator Key:

CTRL+S

Exit

Use this command in order to end a JABA session. You can also use the Close command on the application Control menu. If current model was modified since its creation or last save action, a popup window will be shown for confirmation.

Accelerator Key: CTRL+Q

6.3.2 Action

Solve

Use this command when model description is terminated and you want to start the solution of the model. At the end of the process the Saturation Sector - graph subsection 6.2.6 will show.

Shortcut on Toolbar:



Accelerator Key:

CTRL+L

Randomize

Use this command in order to insert random values into Service Demands - or Service Times - table.

Shortcut on Toolbar:



Accelerator Key:

CTRL+R

6.3.3 Help

JABA Help

Not still available.

6.4 Examples

In this section we will describe some examples of model parametrization and solution using JABA exact solver. Step-by-step instructions are provided in two examples:

1. A two class model (subsection 6.4.1)
2. A three class model (subsection 6.4.2)

6.4.1 Example 1 - A two class model

Solve the two class model specified in Figure 6.20.

There are three stations (named *CPU*, *Disk1* and *Disk2*). Service demands for each station are reported in Table 6.1.

	CPU	Disk1	Disk2
FirstClass	2.60	7.02	4.81
SecondClass	7.02	4.51	5.70

Table 6.1: Example 1 - service demand

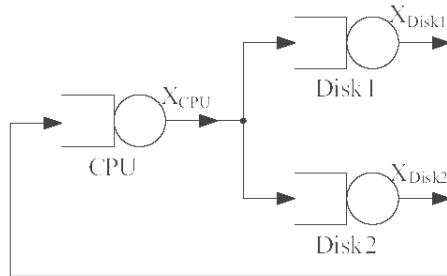


Figure 6.20: Example 1 - network topology

Step 1 - Classes Tab

- use New command to create a new JABA document
- by default, you have already two classes
- if you like, substitute default *Class1* and *Class2* name with a customized one (*FirstClass* and *SecondClass* in our example)

At the end of this step, the **Classes** Tab should look like Figure 6.21.

Classes characteristics				
Number, customized name, type of classes and number of customers (closed class) or arrival rate (open class).				Number (Max=3): <input type="text" value="2"/>
You can add classes one by one or define total number at once.				
*	Name	Type (Closed ...)	No. of Customers (...)	Arrival Rate (Further ve...)
1	FirstClass	closed		<input checked="" type="checkbox"/>
2	SecondClass	closed		<input checked="" type="checkbox"/>

Figure 6.21: Example 1 - input data (Classes Tab)

Step 2 - Stations Tab

- use **Next >** command to switch to **Stations** Tab
- digit number 3 into stations number textbox or select number 3 using spin controls or push *New Station* button twice. Now your model has three stations with a default name
- if you want you can change station names. Substitute *CPU* for default name *Station1*, substitute *Disk1* for default name *Station2*, substitute *Disk2* for default name *Station3*

At the end of this step, the **Stations** Tab should look like Figure 6.22.

Step 3 - Service Demand Tabs

- use **Next >** command to switch to **Service Demands** Tab
- you can input all Demands in the table.
- press *Service Time and Visit* button if you don't know the Service Demands of the three stations. After button pressure, the **Service Demands** Tab will be hidden and **Service times** Tab and **Visit** Tab will appear. Now Service Times and number of Visits should be typed.

At this point, the **Service Demands** Tab should look like Figure 6.23.

Step 4 - Saturation Sectors - Graphics

Use **Solve** command to start the solution of input model. In the **Saturation Sector - Graphic Tab** will be displayed a graph like the one of Figure 6.24.

Stations characteristics
 Number, customized name and type of stations.
 You can add stations one by one or define total number at once.

Number:

*	Name	Type
1	CPU	Load Independent <input checked="" type="checkbox"/>
2	Disk1	Load Independent <input checked="" type="checkbox"/>
3	Disk2	Load Independent <input checked="" type="checkbox"/>

Figure 6.22: Example 1 - input data (Stations Tab)

Convex Hull - Graphics \ Saturation Sectors - Text \

Classes \ Stations \ **Service Demands** \ Comment \ Saturation Sectors - Graphics

Service Demands
 Input service demands of each station for each class.
 If station type is set to "Load Dependent", you can set values of service demands for each number of customers by double-clicking on any button in station's row. If you whish to input service times and visits instead of service demands, press "Service Times and Visits" button.

*	FirstClass	SecondClass
CPU	2.60	2.13
Disk1	7.02	4.51
Disk2	4.81	5.70

Figure 6.23: Example 1 - input data (Service Demand Tab)

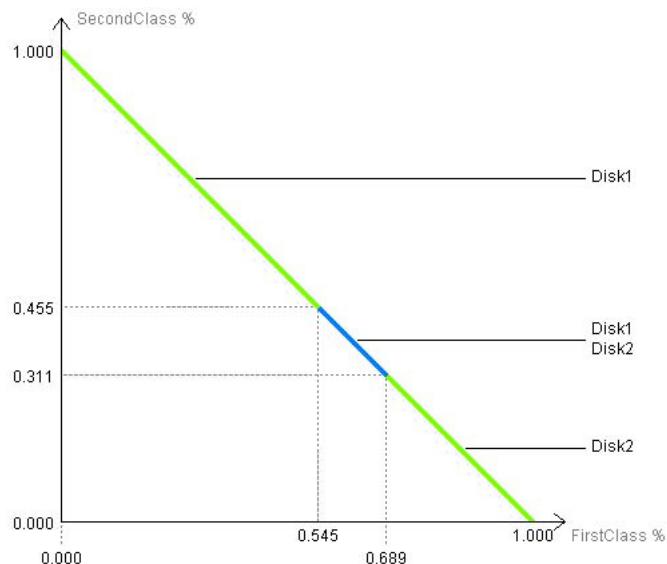


Figure 6.24: Example 1 - Saturation Sectors Graphics

This graph show the range of mix population where two or more stations are both bottleneck. In this example *Disk1* and *Disk2* are both bottleneck when *FirstClass* is among 0.545 - 0.689 and *SecondClass* is among 0.311 - 0.455

Step 5 - Convex Hull - Graphics

Using **Next >** command to switch to **Convex Hull - Graphics** and a graph like Figure 6.25 will be shown.

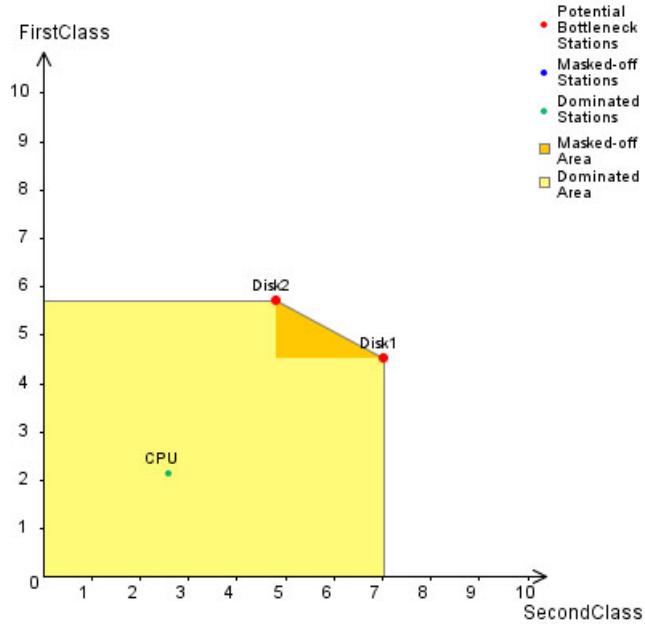


Figure 6.25: Example 1 - Convex Hull - Graphics

This graph implements the polyhedra analysis technique. The points on this graph represent the stations. Dominated stations are green, masked-off ones are blue and bottleneck ones are red. If you click on a station, additional information will be shown, otherwise you can drag a station and see what will change in your model.

Step 6 - Saturation Sectors - Text

If you use **Next >** command again you will see the *Saturation Sectors - Text*, a simple textual report about the Saturation Sectors.

6.4.2 Example 2 - A three class model

Solve the multiclass open model specified in Figure 6.26. The model is characterized by three *A* , *B* and *C*.

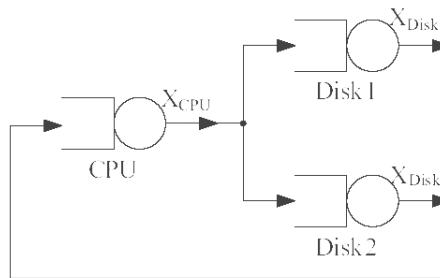


Figure 6.26: Example 2 - network topology

There are three stations, identified with names *CPU*, *Disk1* and *Disk2*. Service times and visits for stations are shown in Table 6.2 and Table 6.3.

Step 1 - Classes Tab

It is the same procedure of the Example 1 (subsection 6.4.1). You have only to add one more class.

	CPU	Disk1	Disk2
Class A [s]	0.01	0.38	0.30
Class B [s]	0.02	0.62	0.80
Class C [s]	0.09	0.42	0.50

Table 6.2: Example 2 - service times

	CPU	Disk1	Disk2
Class A	101.0	60.0	40.0
Class B	44.0	16.0	27.0
Class C	63.0	21.0	35.0

Table 6.3: Example 2 - number of visits

Step 2 - Stations Tab

It is the same procedure of the Example 1 (subsection 6.4.1).

Step 3 - Service Times and Visits Tabs

- use **Next >** command to switch to **Service Demands Tab**
- press *Service Time and Visit* button if you don't know the Service Demands of the three stations, Now Service Times and number of Visits should be typed. After button pressure, the **Service Demands Tab** will be hidden and **Service times Tab** and **Visit Tab** will appear
- you can input all Service Times in the table.

At this point, the **Service Times Tab** should look like Figure 6.27.

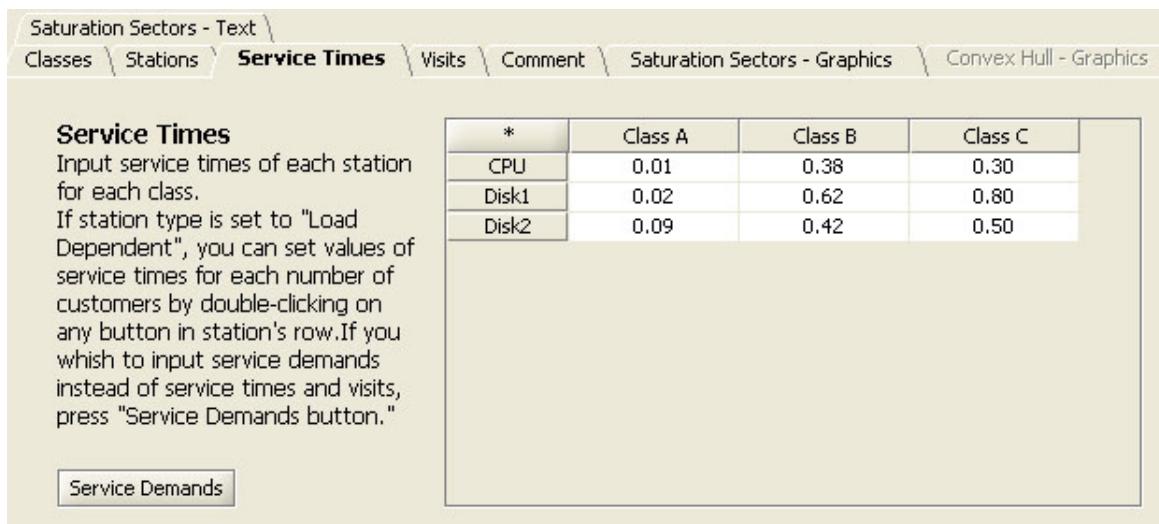


Figure 6.27: Example 2 - input data (Service Times Tab)

- use **Next >** command to switch to **Visits Tab**
- input number of visits for each center in the table.

At the end of this step, the **Visits Tab** looks like Figure 6.28.

Step 4 - Saturation Sectors - Graphics

Use **Solve** command to start the solution of the input model. In the *Saturation Sector - graph Tab* will be displayed a graph like the one of Figure 6.29.

This graph show the range of mix population where two or more stations are both bottleneck. For example the orange area is a range of mix population in which *Disk1* and *Disk2* are both bottleneck.

Step 5 - Saturation Sectors - Text

If you use **Next >** command again you will see the *Saturation Sectors - Text*, a simple textual report about the Saturation Sectors.

*	A	B	C
CPU	101.00	60.00	40.00
Disk1	44.00	16.00	27.00
Disk2	63.00	21.00	35.00

Figure 6.28: Example 2 - input data (Visits Tab)

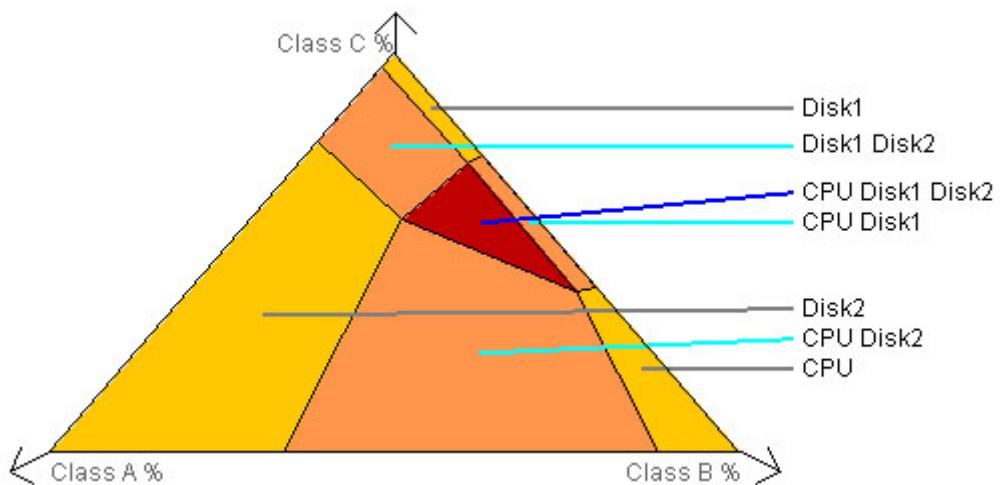


Figure 6.29: Example 2 - Saturation Sectors Graphics

Chapter 7

JWAT - Workload Analyzer Tool

A computer system can be viewed as a set of hardware and software resources that are used in a time-variant fashion by the processing requests generated by the user. During any given time interval, the users submit their processing requests to the systems by inputting sets of programs, data, commands, requests for web sites or file downloads, etc. All these input requests are usually designated by the collective term of *workload*. Every time the value of a system or network performance index is given, the workload under which that values obtained must be reported or, at any rate, known, since performance cannot be expressed by quantities independent of the system's workload. Thus, no evaluation problem can be adequately solved if the workloads to be processed by the systems or transmitted over a network are not specified.

The quantitative description of a workload's characteristics is commonly called *workload characterization*. A characterization is usually done in terms of workload parameters that can affect system behavior and are defined in a form suitable for a desired use. Thus, a workload is characterized correctly if, and only if, its result is a set of quantitative parameters selected according to the goals of the characterization operation. Workload characterization is fundamentally important in all performance evaluation studies and is indispensable for designing useful workload models.

A workload may be regarded as a set of vectors in a space with a number of dimensions equal to the number of the workload parameters used to describe each element considered. Since the amount of resulting data is generally considerable, their analysis for the purpose of identifying groups of components with similar characteristics will have to be performed by statistical techniques that can handle multidimensional samples, that is, techniques that deal with multiple factors.

The JWAT tool is based on the application of a set of statistical techniques oriented towards the characterization of log data representing resource utilizations, traffic of requests, user web paths, etc. Its application provides the input data for the models to be used in all types of performance evaluation studies. Functions for fitting experimental data in order to obtain the values that can be used to parameterize the arrival rates and service times of the model are provided.



The main window of JWAT (Figure 7.1) is opened pressing the **WAT** button in the JMT suite main window. Through this window, it is possible to select one of the three main components of JWAT:



Workload Analysis: Characterization of the workload of a system through the analysis of the log files applying a clustering algorithm (k-Means or Fuzzy k-Means) and other statistical techniques. The input data can be loaded directly from standard log files (e.g., Apache log files, IIS) or from files with any format described by the users. Several graphical representations of the results are also provided for their statistical comparison (histograms, pie-charts, dispersion matrix, QQ-Plot, QQ-Plot matrix, scatter plots, ...).



Fitting: Application of statistical hypothesis testing on the data of a log file for both Pareto and Exponential distribution and subsequent estimation of the parameters. Several graphic representations are provided in order to make a visual assessment of the fitting of the data to the available distributions: QQ-Plot, cumulative distribution function (CDF) and probability density function (pdf).



Traffic Analysis: Characterization of the arrival traffic of requests analyzing the timestamp in a log file and deriving the parameters that refer to the burstiness of requests

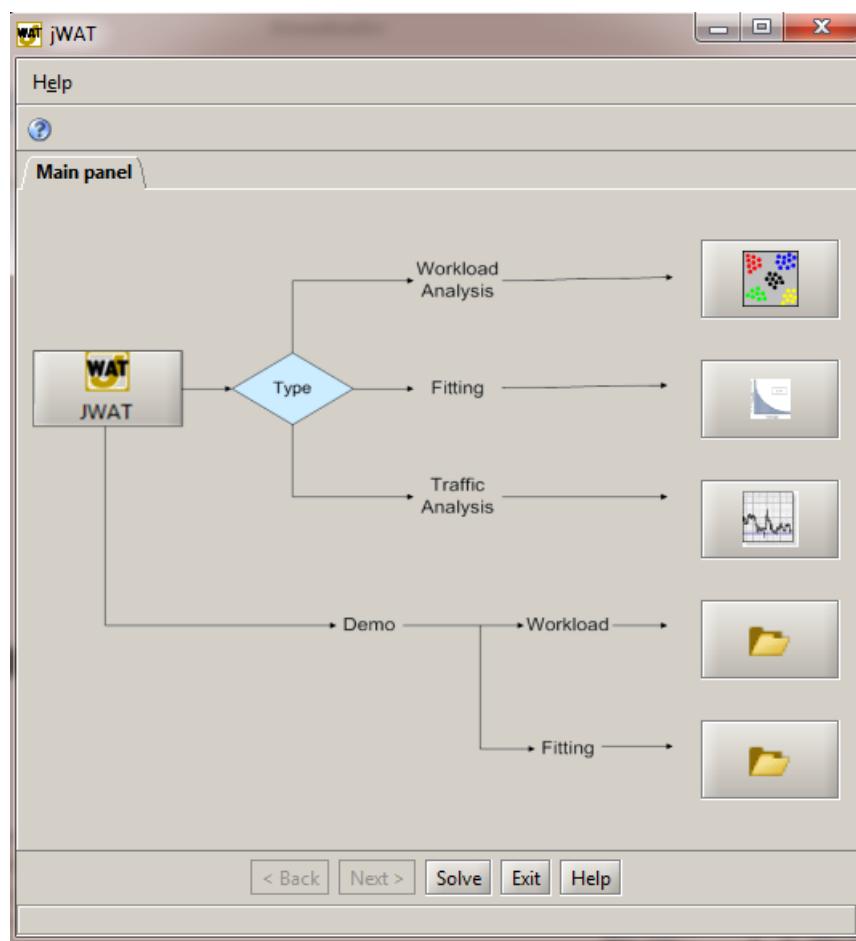


Figure 7.1: Main window of JWAT - Workload Analyzer Tool

7.1 Workload analysis

To perform a workload analysis press the button  of the JWAT window and the window of Figure 7.2 will be opened. This application help the user to perform in the proper sequence the various steps of the

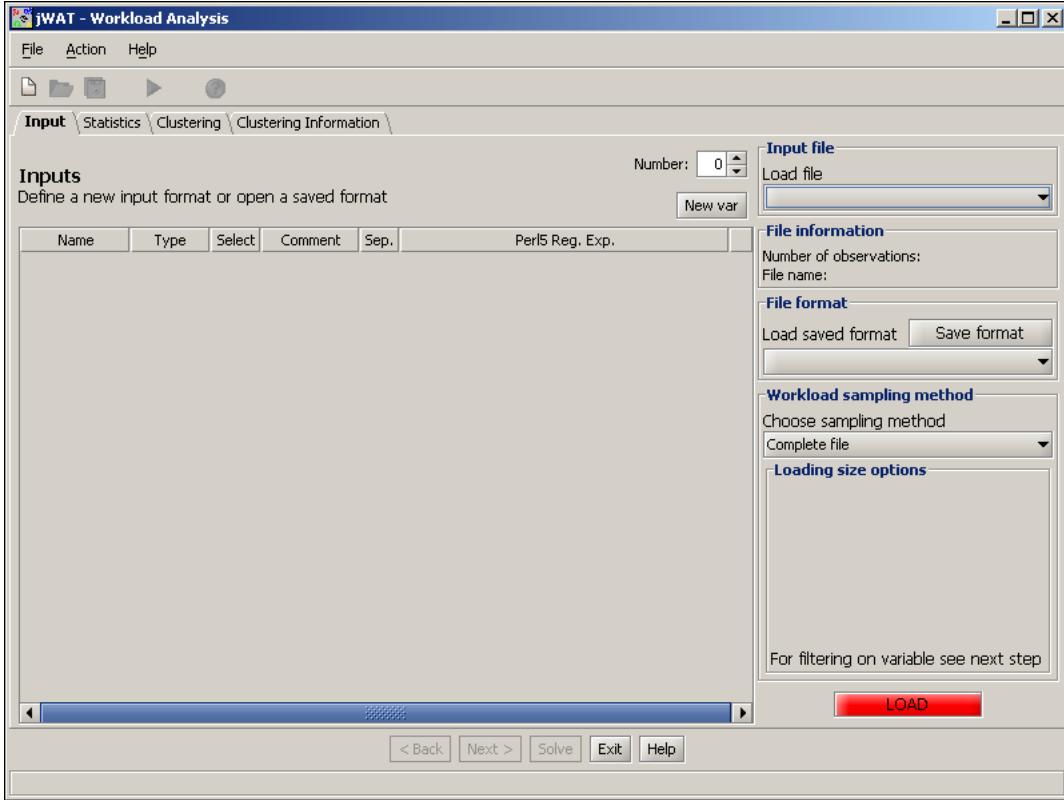


Figure 7.2: Main window for the Workload analysis

workload characterization from the data loading to the statistical analysis, to the results visualization and to their evaluation. The main components of the workload analysis window are:

- **Menu:** three groups of functions are available: File, Action, Help. To utilize the menu select the desired option. For the description of menu options see Section subsection 7.1.8.
- **Toolbar:** several buttons are available to facilitate and to speed up the access to the functions (e.g, New input file, Help ... see Section subsection 7.1.8). When the cursor is over a button tooltips appear.

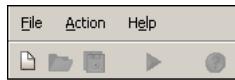


Figure 7.3: Application toolbar

- **Tabbed pane:** It concerns the main functions of the application. All the operations that can be performed on the input data are shown in four navigable tabs: input, statistics, clustering, clustering information (Figure 7.4).



Figure 7.4: Tabs selector

- **Navigation buttons:** used for navigate between panels. The buttons are enabled and disabled automatically depending on the operations to be performed in the actual step (Figure 7.5).

In the following sections the utilization of the panels will be described in detail together with the available options.

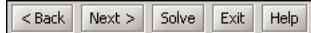


Figure 7.5: Navigation buttons

7.1.1 A workload characterization study

In this section the main operations to be performed in a workload characterization study are described. The definition of the *workload basic components*, that is, the identification of the smallest level of detail that is to be considered and of the set of variables to be used for their description, is among the first operations to be performed. Depending on the intended use of the study, as workload basic components one may select interactive commands, database queries and updates, web site requests, web downloads, programs, scripts, servlets, applets, traffic intensity, source level instructions, etc. In the following we will refer to a workload basic component as an *observation* (i.e., an item in the input file) and to the parameters that describe each component as *variables*.

1. The first step consists of the selection of the file containing the data that are to be considered as input, of the variables to load and of their format (see section 7.1.2). Let us remark that each observation may be described in the input file by n variables but that the number of variables that are considered in the actual statistical analysis may be less than n . It is also possible to decrease the number of observations of the original input file (decrease its size) that will be loaded (considered) in the characterization study. Several filtering criteria for the construction of a sample of data are available: random selection of a given number of observations, selection of the observations that belong to a given interval of their sequence number. At the end of the data loading a panel describing the errors found in the data is shown. A user may decide to stop the analysis and verify the input data or may continue with the following steps.
2. Computation and visualization for each variable of the descriptive statistics univariate and bivariate, of the frequency graphs, of the scatter plots, and of the QQ-plot compared to a normal or exponential distribution (section 7.1.4).

It is important to observe that usually the variables are expressed in nonhomogeneous units. To make them comparable a *scale change* must be performed. The following statistical analysis of the original data, especially of the histograms of their parameters, allows us to determine when it would be useful to apply to them a logarithmic or another transformation. Very often the density functions of some variables are highly positively skewed and have high values of kurtosis too. Applying a logarithmic transformation of highly skewed variable densities it is possible to avoid or to reduce correlations among means and variances of the clusters that will be identified. Several *transformations* may be applied to the numeric variables (attention, *ONLY* to the numeric variables).

A *sample* may be extracted from input file by using different criteria. The distributions of two variables may be compared through QQ-plots and scatter plots selected in the corresponding matrix.

3. Selection of the clustering algorithm to apply and of the variables to be considered in the cluster analysis (see section 7.1.5). The basic idea is to partition the given set of observations into classes of components having homogeneous characteristics. Among the various clustering algorithms the most commonly applied to workload characterization problems belong to the non-hierarchical k-means family. The algorithm produces a number of classes ranging from 1 to k , where k is a parameter that must be specified by the user. The observations are assigned to a class so that the sum of the distances between all the elements and the centroid of the class is minimized. A set of representative components will then be selected from the classes according to some extraction criteria (usually the centroids of the clusters) and used in the construction of the workload model.
4. A panel is available for the visualization of the results of the clustering analysis. Several graphics and tables are reported in order to describe the clusters composition and the goodness of a partition. Scatter plots are available for all the variables considered (see section 7.1.6).

7.1.2 Input definition

The panel for the description of the input data (Figure 7.2) is a very important one since it allows the selection of the input file that contains the data to be analyzed and the description of their structure. In such a way we may take into consideration the log files generated by different systems and tools. The format definition structure of the input file is described in detail in Section subsection 7.1.3.

Input file selection

To select the input file use the panel shown in Figure 7.6. The *Browse...* option for the selection of the input file is available (Figure 7.6). Once a file has been selected its name is added to the list of the files available for following analyses. A panel showing the number of observations loaded and the file name will automatically



Figure 7.6: Panel for the selection of the input file

appears (Figure 7.7).



Figure 7.7: Panel with information about the selected file

Format definition

The next operation consists of the definition of the data format. The format of the input data is required by the application:

- to recognize the number of variables that belongs to each observation
- to recognize the type (string, numeric or data) of each variable
- to the right interpretation of the meaning of each data element that belong to a single observation. For the definition of the elements regular expressions Perl5 (subsection 7.1.3) are used. The defined formats are stored in a library and can be browsed and reused.
- to select a subset of the variables of the observations that are in the original input file.

We will describe a very simple example of the format definition of an *observation*, i.e., a single element in the input log file. The considered log file contains several data, e.g., IP client address that submits the request for a resource to a web server, request timestamp, etc...) that are called *variables*.

After the selection of the input file, the format definition table is empty, see Figure 7.2, since no information regarding current format has already been defined.

Two types of format definition are available:

- Manual, that consists of the definition of the format of each single variable through relative table and relative commands
- Automatic, that load one of the predefined standard formats previously defined and loaded in files '*jwat-format*'.

Manual definition

At the beginning, the correct number of variables of each observation in the log file is to be set (use the spinner '*Number*'). By using the '*New var*' button a new variable is added to the format table. The same result is obtained using the spinner '*Number*' at the right top of the table (see Figure 7.8).

To remove one or more variables by a format table we can utilize:

- the button  at the end of each row of the table. The result is the deletion of the concerning variable
- turned arrow towards the bottom of the spinner. The result is the deletion of the last variable of the table
- the right button of the mouse on a single selected variable, or on a set, to delete them from the format table (Figure 7.9).

Once the correct number of variables in a observation is defined the next step is their description. The columns of the format table have the following meaning:

- *Name*: as default, to each new added variable it is assigned the standard name *Variable X*. In order to facilitate the analysis of the results it is recommended to change these names with new ones related with the meaning of the variables.

Name	Type	Select	Comment	Sep.	Perl5 Reg. Exp.	
Variable 0	Numeric	<input checked="" type="checkbox"/>			([+-])?\d+([.,]\d+)?	X
Variable 1	String	<input checked="" type="checkbox"/>	"		\w+	X
Variable 2	Date	<input checked="" type="checkbox"/>			\d\d/\w\w\w\w/\d\d\d\d:\d\d:\d\d:\d\d[\w^]+	X

Figure 7.8: Format table

Name	Type	Select	Comment	Sep.	Perl5 Reg. Exp.	
IP	String	<input checked="" type="checkbox"/>	IP Address		\d+\.\d+\.\d+\.\d+	X
Username etc	String	<input checked="" type="checkbox"/>	Only relevant ...		--	X
Timestamp	Date	<input checked="" type="checkbox"/>	Time stamp of ...		\d\d/\w\w\w\w/\d\d\d\d:\d\d:\d\d:\d\d[\w^]+	X
Access request	String	<input checked="" type="checkbox"/>	The request m...		".+"	X
Result status code	Numeric	<input checked="" type="checkbox"/>	The result			Delete selected variable Elimina
Bytes transferred	Numeric	<input checked="" type="checkbox"/>	The numb			Deselect all variables Ctrl-D
Referrer URL 1	String	<input checked="" type="checkbox"/>	The refer			X

Figure 7.9: Deletion of selected variables

- *Type*: it identifies the type of the variable. Possible choices are *number*, *string* and *data*. The type definition is fundamental for the right interpretation of the results.
- *Selection*: it allows to specify which of the variables of the observations registered in the input file will be effectively loaded. In any case, it is necessary to define all the variables of each observation, also if some of them will not be selected for the statistical analysis.
- *Comment*: it is allowed to add a string of comment to each variable.
- *Delimiter [Sep]*: it identifies the character used (if it exists) in the input file to delimit the field identified by the current variable. For example in the Apache server log file the variable "timestamp" is contained within square brackets.
- *Regular Expression* : definition of regular expression (Perl 5) that defines the variable. For example in case of IP variables a possible regular expression is: '\d+\.\d+\.\d+\.\d+'.
- *Delete*: the corresponding variable will be deleted.

In order to help the users for each of the types the tool sets automatically some of the fields (delimiter of field and regular expression) supplying standard settings as shown in Figure 7.8 where for the type *string* it is proposed " as delimiter and \w+ as regular expression.

A format definition may be saved by using the '*Save format*' button so that it may be reused in the future.

Format loading

If a standard log file (Apache, IIS) is used it is possible to load the corresponding format by using the combobox in the panel of Figure 7.10.

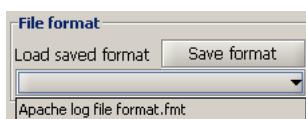


Figure 7.10: Panel for the loading of standard and previously saved format

For example, by selecting the option "Apache log file format", the format definition table of Figure 7.11 is automatically loaded. At this point, the user can select through the format table selection field the subset of variables to load.

Methods for extracting a sample

In order to process the data from real log files, that usually are constituted by a very large number of observations (e.g., several Gigabytes), by a cluster algorithm with a reasonable amount of processing time and storage dimensions, the size of the original data set has to be reduced. Thus, only a sample drawn from the original set of data is often submitted as input to the clustering algorithm.

After the definition of the data format it is possible through the panel *Workload sampling method* of Figure 7.12 to select one of the following extraction criteria:

- *Complete file*: all the observations of the input file are considered.
- *Random*: the number of observations to be loaded should be specified in the panel of Fig. Figure 7.13.

Name	Type	Select	Comment	Sep.	Perl5 Reg. Exp.	
IP	String	<input checked="" type="checkbox"/>	IP Address		\d+\.\d+\.\d+\.\d+	X
Username etc	String	<input checked="" type="checkbox"/>	Only relevant ...		--	X
Timestamp	Date	<input checked="" type="checkbox"/>	Time stamp of ...	[]	\d\d/\w\w\w\w/\d\d\d:\d\d:\d\d:\d\d[^:]+	X
Access request	String	<input checked="" type="checkbox"/>	The request m...	"	.+	X
Result status code	Numeric	<input checked="" type="checkbox"/>	The resulting s...		([-])?d+([,]d+)?	X
Bytes transferred	Numeric	<input checked="" type="checkbox"/>	The number of ...		([-])?d+([,]d+)?	X
Referrer URL 1	String	<input checked="" type="checkbox"/>	The referring p...		[^\s]+	X
Referrer URL 2	String	<input checked="" type="checkbox"/>	The referring p...	"	.+	X
User Agent	String	<input checked="" type="checkbox"/>	The user agent...	"	.+	X
Referrer URL 3	String	<input checked="" type="checkbox"/>	The referring p...	"	.+	X

Click or drag to select classes; to edit data single-click and start typing. Right-click for a list of available operations

Figure 7.11: Format definition table

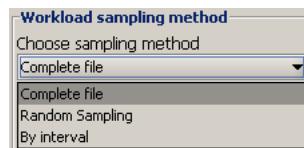


Figure 7.12: Extraction criteria for the sample construction

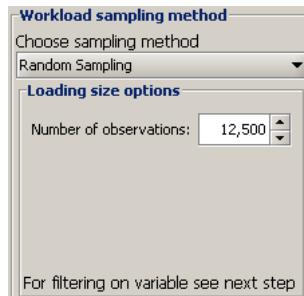


Figure 7.13: Random method for the construction of a sample

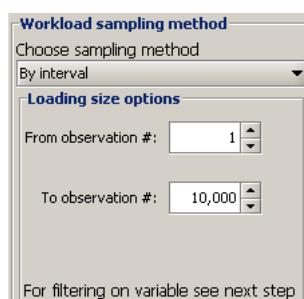


Figure 7.14: Interval method options

- *Interval*: the panel of Figure 7.14 that requires to specify the interval of observations (according to their id numbers) to load will be shown.

Loading of log file

After the definition of the input file the loading of the selected observations will be started. After pressing the ‘LOAD’ button (Figure 7.15) the loading window of Figure 7.16 will be opened. The percentage of loading completion, the number of processed observations and the number of observations discarded because not consistent with the specified format are shown. At the end of the load a window summarizing the total number



Figure 7.15: Button for the loading of the input data.

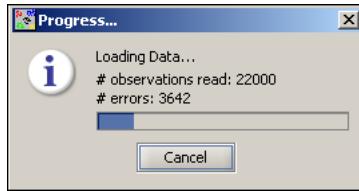


Figure 7.16: Window showing the loading progress

of observations loaded and the total number of observations loaded correctly (Figure 7.17) is shown. It is

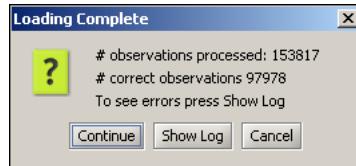


Figure 7.17: Loading phase results

possible to visualize the log file that contains the description of the errors found during the loading operation (Figure 7.18). The error messages that are contained in the log file are:

- *Error in row xx : Element y is wrong*: (if you defined separators) the element corresponding to the variable *y*, for the row *xx*, does not correspond to the defined regular expression.
- *Error in row xx : Line does not match format (element y not found)*: The element corresponding to the variable *y* is not present in the row (observation) *xx* of the input file.
- *Error in row xx : Too many fields* : the row *xx* contains elements in excess compared to the defined format. This may indicate with high probability that the format definition described by the user is not correct for the considered observation.

7.1.3 Format definition

In this section we will describe the format definition of the file in input to the application. We will introduce the basic concepts on which the format specific is based and then we will describe some examples with different files.

The application allows, by using regular expression, to utilize as input either log files of standard formats, as Apache and IIS, or log files modified by the user. The only important requirement on the input file structure is that every observation (i.e., the set of the variables that refer to one element/item considered) must end with ‘\n’ character (new line).

To allow the application to be able to process correctly a log file, the user must describe:

- the observation structure, that is the number of variables that compose it.
- and for each variable the name, the type and the ‘structure’.

These information are specified by the user through the input panel described in section 7.1.2.

Regarding the number of variables it is enough to insert in the format table a number of rows equal to the number of elements that compose the observation (see section 7.1.2). In Figure 7.19 the observation is composed of 6 variables.

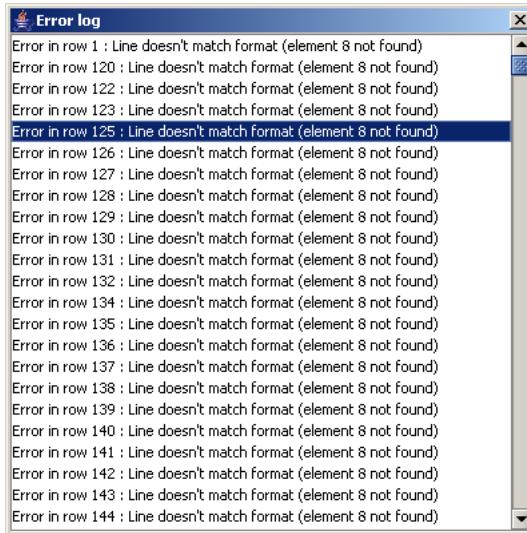


Figure 7.18: Example of error log in the loading phase

Name	Type	Select	Comment	Sep.	Perl5 Reg. Exp.	
Variable 0	Numeric ▾	<input checked="" type="checkbox"/>			([+-])?d+([.,])d+)?	X
Variable 1	Numeric ▾	<input checked="" type="checkbox"/>			([+-])?d+([.,])d+)?	X
Variable 2	Numeric ▾	<input checked="" type="checkbox"/>			([+-])?d+([.,])d+)?	X
Variable 3	Numeric ▾	<input checked="" type="checkbox"/>			([+-])?d+([.,])d+)?	X
Variable 4	Numeric ▾	<input checked="" type="checkbox"/>			([+-])?d+([.,])d+)?	X
Variable 5	Numeric ▾	<input checked="" type="checkbox"/>			([+-])?d+([.,])d+)?	X

Figure 7.19: Format table after the insertion of the number of variables

The definition of the single variable requires, in addition to the name, a comment, its selection in order to be considered in the analysis or not, its type, the description of the possible delimiter (Separator) and of the regular expression that characterizes it.

The type has to be chosen among the *numeric*, *string o data*. The delimiter defines (if it exists) the character or the characters that delimit the variable's value. The regular expression (Perl 5) defines the format with which the variable value is recorded in the log file.

A concise description of the format used for the regular expressions (Perl 5) follows. The purpose of the definition of the regular expression is to specify the pattern that the variable values must have and therefore (together with selected type) to allow the application to process correctly its value. For a complete description of the regular expressions see a Mastering regular expressions book. In this section we will describe some options useful to define in a simple way the pattern of the variables values. A list of operators follows:

- + : it indicates that there are one or more instances of the preceding character (a+ ⇒ a,aa,aaa,...)
- []: it defines a pattern that allows to utilize as match element one of the values within square brackets (a[bcd]e ⇒ abe, ace, ade)
- * : it indicates that there are zero or more instances of the preceding character (ba* ⇒ b,ba,baa,baaa,...)
- ? : it indicates that there are zero or one instance of the preceding character (ba? ⇒ b,ba)
- ^ : it has two different meanings depending on the use. The former permits to require that a pattern starts with a particular character (^abc ⇒ abcdef,abc fg,...). If it is utilized within square brackets as first character, it allows to match any character that doesn't belong to the defined group ([^a] ⇒ bcd,wedfgr,...)
- () : it defines a pattern that permits to use as match element the string that is contained between brackets ((ab)+ ⇒ ab,abab,ababab,...).

A list of *Escape Sequences* used to identify intervals of characters follows:

- \d : it identifies whichever number [0-9].
- \D : it identifies whichever thing except a number [^0-9].
- \w : it identifies whichever character or number [0-9a-zA-Z].
- \W : it identifies whichever thing except a character or a number [^0-9a-zA-Z].
- \s : it identifies a *white space* character [\t\n\r\f].

\S : it identifies whichever thing except a *white space* character [^\t\n\r\f].

. : it identifies whichever character except the *new line* character '\n'.

Combining in an opportune way the characters, the options and the *Escape Sequences* it is possible to define correctly the regular expression for each variable.

In the specific of regular expressions in Perl 5 there are some characters that are considered *metacharacters*. Some of them are the same operators defined before. In this case, to use such characters as elements in the expression is enough to precede them with the \ character.

The delimiter identifies one or more characters that delimit the value of a variable. In the log file of the Apache format the page URL requested by the user contains characters and spaces and is delimited by ". ". A simple definition of the \w+ type regular expression could produce a wrong result because the value recovered by application would finish at the first met space and not at the closure ". ". To avoid this problem it is possible to utilize the delimiters so that by using the expression .+ and specifying as delimiter " " the result will be correct.

Concerning the Apache log file, and more precisely the *timestamp* field, it is possible to show another use of the delimiter. The value is contained between characters '[' e ']' (e.g. [12/Dec/2001:00:00:03 +0100]) and by using the field delimiter it is possible to specify as regular expression the following:

```
\d\d/\w\w\w/ \d\d\d\d:\d\d:\d\d:\d\d:\d\d
```

This expression doesn't specify the last part of the field (+0100) but it is correct in any case because specifying the delimiters it is possible to define the regular expression in order to match only a part of the variable value.

Example of a format definition

Let's consider a file to be analyzed with the following structure of the observations:

```
String without spaces 1000 0.0876 -12.663 "String with spaces" [12/Dec/2001:00:00:03 +0100]
```

The variables are 6 and their definition (Figure 7.20) is the following:

String without spaces : we can define the regular expression in different ways, as for example /a-zA-Z/+ if the string doesn't contain numbers or \w+ to indicate whichever string of numbers and characters.

Integer number : we define the regular expression as a sequence of one or more numbers and therefore as \d+.

Positive decimal : in this case there is the possibility to have decimal digits so that we define the regular expression as a sequence of one or more digits (\d+) that may have the decimal separator and a further succession of one or more digits. The result is therefore \d+(\.\.\d+)?.

Decimal with sign : in this case in comparison to the previous case there is the possibility that at the beginning of the number there is a sign +, - or no sign. Therefore it is enough to add at the beginning of the regular expression ([+-])?.

String with spaces : if we utilize the regular expression previously defined \w+ we would have a problem because the value recovered from the log file would be "String that is not correct. The best solution is to utilize the delimiter, in this case ", and to utilize therefore the definition .+.

Date : even in this case by using the delimiter (//) we can define the following regular expression \d\d/\w\w\w/ \d\d\d\d\d:\d\d:\d\d:\d\d:\d\d that may be used to recover the only information "12/Dec/2001:00:00:03" leaving out the remaining part.

Name	Type	Select	Comment	Sep.	Perl5 Reg. Exp.	
Stringa senza spazi	String	<input checked="" type="checkbox"/>			\w+	
Numero intero	Numeric	<input checked="" type="checkbox"/>			\d+	
Numero Reale	Numeric	<input checked="" type="checkbox"/>			\d+(\.\.\d+)?	
Reale con segno	Numeric	<input checked="" type="checkbox"/>			([+-])?\d+(\.\.\d+)?	
Stringa con spazi	String	<input checked="" type="checkbox"/>			(\w+\[\s\]+)+	
Data	Date	<input checked="" type="checkbox"/>		[]	\d\d/\w\w\w/\d\d\d\d\d:\d\d:\d\d:\d\d:\d\d:\d\d:[^\\]+	

Figure 7.20: Example of the definition of a file format

Example of the definition of the Apache log

Now we will describe the format of the Apache log. Each observation has the following structure:

```
151.29.12.105 - - [12/Dec/2001:00:00:10 +0100] "GET /mappe HTTP/1.1" 200 313 www.polimi.it "http://www.polimi.it/"  
"Mozilla/4.0 (compatible; MSIE 5.0; Windows 98; DigExt)" "-"
```

A brief explanation of the regular expressions used (Figure 7.21) follows:

1. for the Ip address of the request we define a sequence of one or more digits separated by a point and therefore the regular expression is `\d+\.\d+\.\d+\.\d+`.
2. in most cases no value is set, and therefore it is possible to define exactly the string that we want to recover from the file through `- -` (it is advisable not to select this variable at the moment of loading).
3. for the date we use the same definition described in the previous example or more simply by selecting the date type in the concerning box, the application supplies a default definition that is correct too.
4. it is a string, delimited by `"`, that can contains within some spaces characters and numbers. The best definition uses the delimiter and the regular expression `.+`.
5. it is an integer number and as we have seen before we can utilize a more simple regular expression `\d+ o ([+-])?\d+([.,]\d+)?`.
6. even in this case it is an integer number and as we have seen before we can utilize the regular expression `\d+ o ([+-])?\d+([.,]\d+)?`.
7. in this case the string is not delimited by any particular character and it doesn't contain any spaces so that we can utilize a simple regular expression `\w+` or ones little bit different as `[^\s]+`.
8. these last three strings are all delimited by the character `"` and they can contain some spaces, characters or numbers and therefore we must utilize the regular expression `.+`.

Name	Type	Select	Comment	Sep.	Perl5 Reg. Exp.	
IP	String	<input checked="" type="checkbox"/>	IP Address		<code>\d+\.\d+\.\d+\.\d+</code>	X
Username etc	String	<input checked="" type="checkbox"/>	Only relevant ...		--	X
Timestamp	Date	<input checked="" type="checkbox"/>	Time stamp of ...	[]	<code>\d\d/\w\w\w\w/\d\d\d\d:\d\d:\d\d:\d\d[\^\]]+</code>	X
Access request	String	<input checked="" type="checkbox"/>	The request m...	"	<code>.+</code>	X
Result status code	Numeric	<input checked="" type="checkbox"/>	The resulting s...		<code>([+-])?\d+([.,]\d+)?</code>	X
Bytes transferred	Numeric	<input checked="" type="checkbox"/>	The number of ...		<code>([+-])?\d+([.,]\d+)?</code>	X
Referrer URL 1	String	<input checked="" type="checkbox"/>	The referring p...		<code>[^\s]+</code>	X
Referrer URL 2	String	<input checked="" type="checkbox"/>	The referring p...	"	<code>.+</code>	X
User Agent	String	<input checked="" type="checkbox"/>	The user agent...	"	<code>.+</code>	X
Referrer URL 3	String	<input checked="" type="checkbox"/>	The referring p...	"	<code>.+</code>	X

Figure 7.21: Apache log file format definition

7.1.4 Data processing

A tabs substructure (Figure 7.22) shows the groups of the various statistics available:

Univariate: descriptive statistics, graphs and transformations.

Sample construction: methods of sample construction and data filtering.

Bivariate: bivariate statistics.

QQ-plot matrix: QQ-plots of the variables for comparison with normal and exponential distributions

Scatter plot matrix: Scatter plots of all the variables.



Figure 7.22: Tabs structure for the processing of the data

Variable	Mean	Variance	Std. Dev.	Coeff. of var.	Minimum	Maximum	Range	Median	Kurtosis	Skewness	Num. Obs.
IP	330.431E0	687.347E2	262.173E0	793.426E-3	000.000E0	908.000E0	908.000E0	164.000E0	-880.929E-3	713.959E-3	358.380E2
Timestamp	100.839E10	225.805E12	150.268E5	149.018E-7	100.837E10	100.841E10	417.500E5	100.839E10	-166.636E-2	-180.260E-4	358.380E2
Access request	333.612E1	185.306E5	430.471E1	129.034E-2	000.000E0	142.380E2	142.380E2	735.000E0	-441.802E-4	116.237E-2	358.380E2
Result status...	202.568E0	390.938E0	197.722E-1	976.073E-4	100.000E-2	404.000E0	403.000E0	200.000E0	748.764E-1	820.835E-2	358.380E2
Bytes transfe...	492.681E1	381.579E6	195.340E2	396.485E-2	000.000E0	103.972E4	103.972E4	956.000E0	646.421E0	200.840E-1	358.380E2
Referrer URL 1	195.323E-6	418.524E-6	204.579E-4	104.738E0	000.000E0	300.000E-2	300.000E-2	000.000E0	157.631E2	120.562E0	358.380E2

Figure 7.23: Descriptive statistics of the variables

	IP	Timestamp	Access request	Result status code	Bytes transferred
IP		402.181E-13	193.853E-9	124.385E-7	191.049E-10
Timestamp	402.181E-13		717.968E-14	487.647E-12	723.455E-15
Access request	193.853E-9	717.968E-14		584.537E-8	718.559E-11
Result status code	124.385E-7	487.647E-12	584.537E-8		136.254E-8
Bytes transferred	191.049E-10	723.455E-15	718.559E-11	136.254E-8	

Figure 7.24: Correlation coefficients of the variables

Statistics

The univariate and bivariate panels show respectively several statistical indexes concerning each variable of the observations (Figure 7.23) and the correlation coefficients of the variables (Figure 7.24).

The univariate panel shows also the following two types of graphs:

- a histogram, or frequency graph, preview for each variable, that can be magnified with a double click on the preview (Figure 7.25).

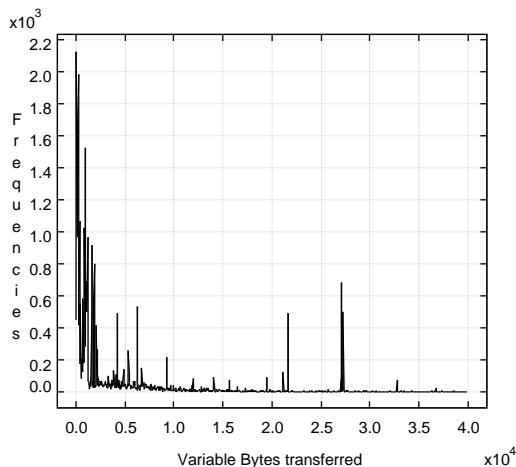


Figure 7.25: Histogram, or frequency graph, of the variable "Bytes transferred"

- a preview of the QQ-plot graph of the variable quantiles compared with the normal distribution quantiles with the same average and variance or the exponential distribution with the same average. Also this preview can be magnified with a double click (Figure 7.26).

Both magnified graphs can be saved in *eps* (Encapsulated PostScript) and *png* (Portable Network Graphics) formats.

Transformations and sample extraction

The panel of univariate statistics allows also to perform some variables transformations. To apply a transformation select the variable in the table of Figure 7.23; if it is of a numeric type the panel of Figure 7.27 that allows the selection of the type of transformation (logarithmic, min-max and standard deviation) will be shown and press the '*Apply transformation*' button. It is possible to undo the last transformation by pressing the '*Undo transformation*' button. The list of the variables with the transformations applied is reported in the table. If the selected variable is not numeric, the following message is shown: "*This variable could not be transformed since it is not numeric*".

To extract a sample from the original input file press on tab '*Sample construction*'. The panel of Figure 7.28 shows the possible criteria that can be applied to the loaded variables that depends on the selected method and on the type of the variables.

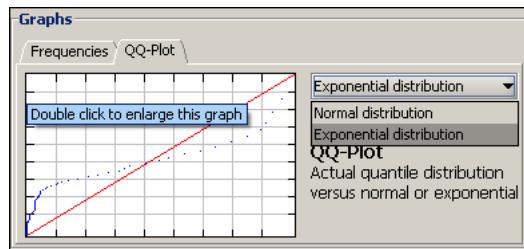


Figure 7.26: QQ-plot preview for the comparison of a given distribution with an exponential or a normal ones.



Figure 7.27: Selection of the transformation to apply to the original data

Sampling methods	Variables
Trimming	IP
Random	Username etc
Observ. # interval	Timestamp
Interval	Access request
	Result status code
	Bytes transferred
	Referrer URL 1
	Referrer URL 2
	User Agent
	Referrer URL 3

Figure 7.28: Sampling extraction criteria that can be applied on the selected variables

- *Random* and *Observe. # interval* methods are similar to those available in input window and allow to select randomly n observations from the input file or to extract the observations whose numerical identifiers are included into the interval defined by the user.
- *Trimming* : the outliers, i.e., those values of a variable that are too distant from the other values of the same variable, may distort the transformation and the statistical analysis by causing the other observations to be assigned too much or too little weight should be removed. To filter a variable distribution (trimming operation) the percentiles that should be removed can be specified (Figure 7.29).

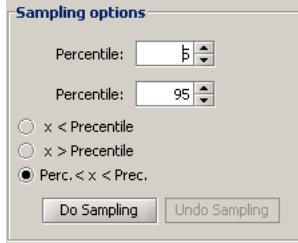


Figure 7.29: Filter of the percentiles of a variable (trimming of the distribution)

- *Interval* operation applies a filter on a variable's values. Depending on the type of the variable different options panels will be shown. If the selected variable is *numeric* the panel is similar to that of Figure 7.30: the minimum and maximum values of the variable should be specified. If the selected variable is of *data* type the panel is similar to that of Figure 7.31: the dates of start and end of observations should be specified. If the variable is of *string* type, it is possible to specify a substring that has to be contained in the selected observations.

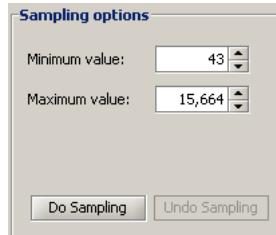


Figure 7.30: Filter on the values of a numeric variable

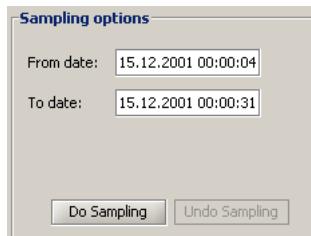


Figure 7.31: Filter on the values of a data variable

The operation of '*Undo sampling*' is available.

Graphs

The last two panels of the statistics tab concern a preview of QQ-plot graphs and of scatter plots for all the variables, respectively. Both allow to save graphs in the most common formats (.png, .eps). Previews can be magnified with a left double click of the mouse. Several functions are available for the graphs: portions zoom, points dimension, by clicking the right button of the mouse on a graph various formats are available for export the graph as image.

7.1.5 Clustering algorithms

The next step of the characterization process is the choice of the clustering algorithm to be used ad of the options available. Two clustering algorithms are actually implemented in the tool (k-Means and Fuzzy k-Means), see

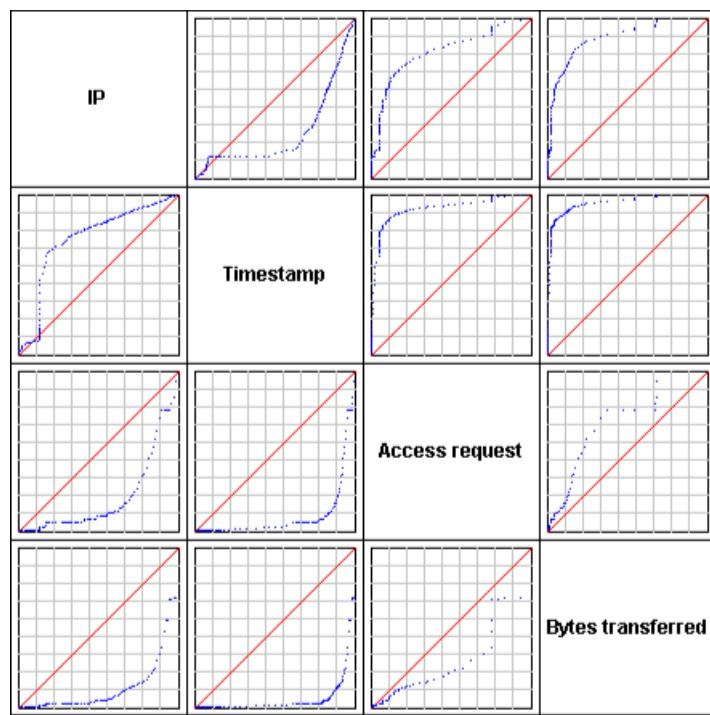


Figure 7.32: QQ-plot matrix for the comparison of the distributions of two variables

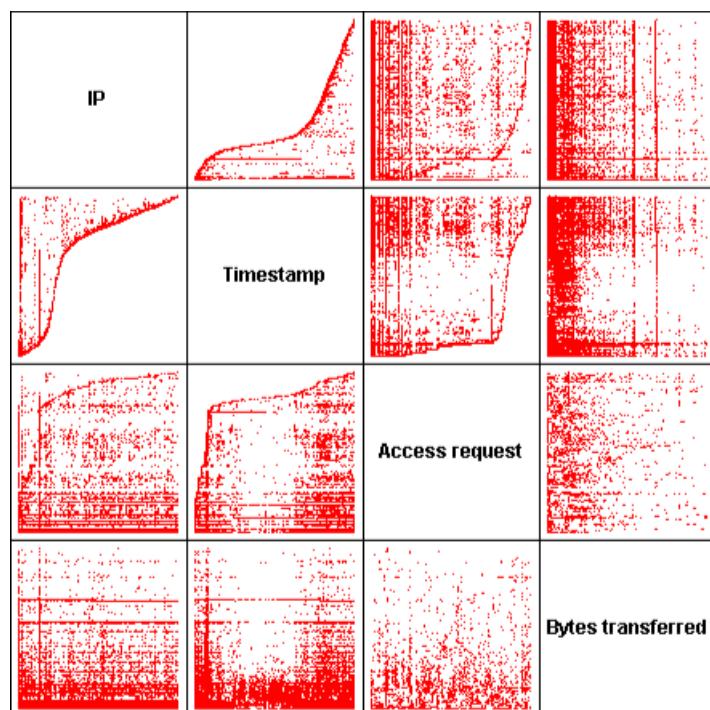


Figure 7.33: Scatter matrix

Figure 7.34. Depending on the selected algorithm, in the right panel of tab the available options are listed.

The execution of a clustering algorithm will start when the buttons ‘*Solve*’ or ➤ are pressed. During the execution, the window of Figure 7.35 that report the progress state and allows to interrupt the execution is shown.

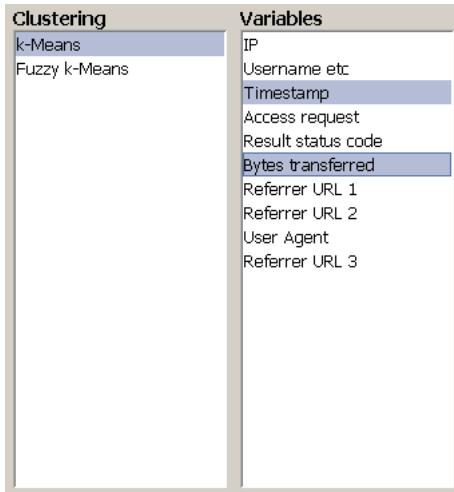


Figure 7.34: Clustering algorithm used and variables selected that will be considered in the analysis.



Figure 7.35: Clustering progress panel

K-Means algorithm

The non-hierarchical k-Means algorithm implemented in the tool requires the specification of the following parameters, Figure 7.36:

- *the maximum number k of clusters* that the algorithm has to produce. Note that the algorithm produces the results for all partitions from 1 to k clusters
- *the maximum number of iterations* to perform in order to find the optimal partition. The initial subdivision into k clusters is iteratively improved by shifting, based on the selected criterion (in this case the Euclidean distance), the elements of a cluster to another and computing after each assignment the new center of mass of the clusters. The optimum configuration is obtained when points can no longer be reassigned. The selected value is an upper limit of the number of interactions for each partition. Experiences suggest the value of 4 interactions as a reasonable choice: the results are obtained in a short time and are enough accurate. To obtain more accurate results higher values should be used, this involves a higher computation time
- *the transformation type* to apply to selected variables (if needed). Transformations of the values are applied before the execution of the algorithm and at the end of the execution the results can be transformed back to their original values. The transformation of the values is often required since the variables are usually expressed in different units and their ranges are very different. Since the algorithm uses the Euclidean distance function as comparison metric to determine if an observation belongs to a cluster, the results could be not reliable if the values differ of one or more order of magnitude.

Fuzzy k-Means algorithm

The fuzzy k-Means algorithm implemented in the tool requires the following parameters, Figure 7.37:

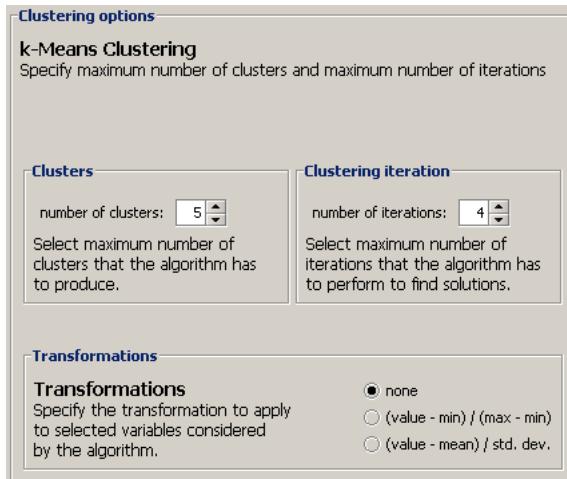


Figure 7.36: Parameters of the clustering algorithm k-Means

- *the maximum number k of clusters* that the algorithm has to produce. The results for all the partitions from two to the selected maximum value will be provided. The higher is this value the higher is the execution time of the algorithm
- *the maximum number of iterations* to perform in order to find the optimal partition. Four is a suggested value. See the comments reported above for the K-means algorithm.
- *the fuzziness level* to apply during the algorithm execution. It is the value used by algorithm to determine the fuzziness degree of final solution. It ranges from 2 to 100
- *the transformation type* to apply to selected variables (if needed). See the comments reported above for the K-means algorithm.

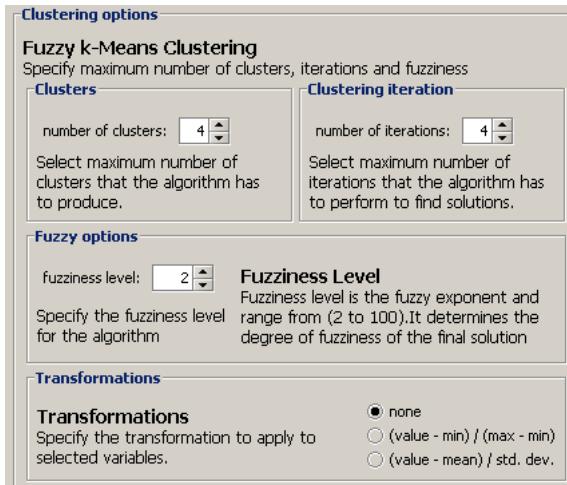


Figure 7.37: Parameters of the clustering algorithm Fuzzy k-Means

7.1.6 The results of a clustering execution

At the end of the execution of a clustering algorithm the tab that allows the analysis of the results is shown. The main panel shows the table in Figure 7.38 that contains the algorithm(s) executed and the maximum number of clusters identified. It is possible to delete the results of an execution by clicking the button in the last column.

Depending on the selected clustering algorithm different results panels are shown in the results table.

K-Means algorithm results

When the $k - M e a n s$ algorithm results are selected, a table reporting the indices concerning the goodness of the partitions is shown, Figure 7.39.

Clusterings		
Clustering	Cl.	
k-Means	8	✗
Fuzzy k-Means	8	✗
k-Means	4	✗

Figure 7.38: List of executed clustering algorithms

To estimate the optimal number k of clusters in which the given set of observations will be subdivided two indicators of the goodness of a partition are used. For each variable the *Overall Mean Square Ratio*, *OMSR*, i.e., a measure of the reduction of within-cluster variance between partitions in k and in $k + 1$ clusters, and the *ratio* of the variance among the clusters and the within-cluster variance have been used. Large values of the *OMSR* justify increasing the number of clusters from k to $k + 1$. An optimal partition should also be characterized by values greater than 1 of the *ratios* of the variances among the clusters and within the clusters for each variable.

A visual indication of the goodness of a partition is given with the icons and representing good and bad results respectively. The values of OMSR and of the *ratio* are also reported in the table.

By selecting one of the rows of the table in Figure 7.39 the panel is updated and in the right side a tabs structure concerning the visualization of the results is shown. Three main panels are available (Figure 7.40):

Num. of clusters			
Cl	G	OMSR	Ratio
2	✗	648.856E2	112.239E-2
3	✗	578.101E2	788.943E-3
4	✓	732.755E2	258.719E-2
5	✗	283.224E2	130.698E-2
6	✓	216.702E2	271.445E-2
7	✗	798.327E1	129.406E-2
8	✗	616.915E1	000.000E0

Figure 7.39: Indicators of the goodness of a partition (*Overall Mean Square Ratio* and *ratio* indices) for the K-Means algorithm

- *Clustering Info:* It shows some statistical information concerning the clusters. For each cluster the number of its components and its weight with respect to the total population are reported. Pie-charts are also used to visualize these data. The panel at the bottom shows for each variable the distribution (in %) of its values among the clusters.

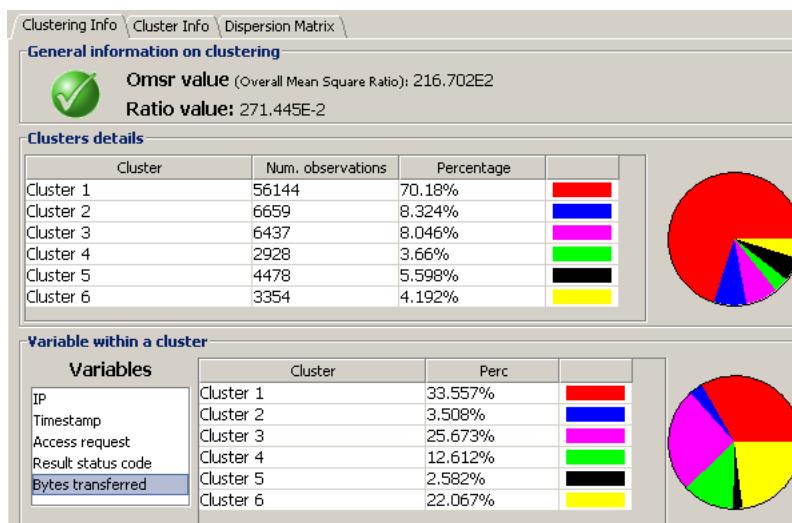


Figure 7.40: Characterization of the clusters

- *Clusters Info:* It shows statistics concerning the clusters (Figure 7.41). Besides the classic descriptive univariate statistics, the *ISC*, that indicates which variables have been used for the clustering, and the *center* values, that refer to the centroid coordinates of each cluster, are reported. The panel at the bottom shows a preview (it can be magnified by a left double click of the mouse) of the graph concerning the comparisons of the distributions of the variables used in each cluster. It is also possible to visualize the list of observations that belong to a cluster through the ‘*Show Observations*’ button (attention! this operation may require several minutes).

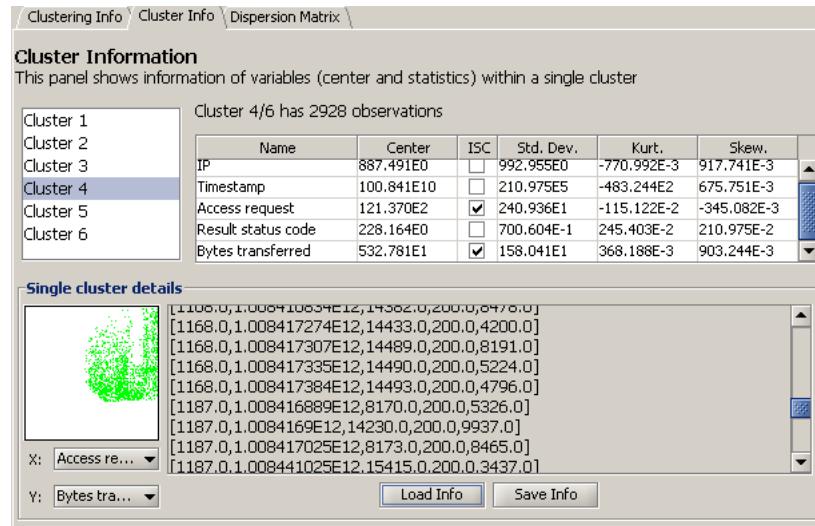


Figure 7.41: Descriptive statistics of the clusters obtained with the k-means algorithm and their visual characterization through the dispersion matrix

- *Dispersion Matrix:* this panel shows the matrix of all the possible variable *vs* variable scatter plots (Figure 7.42). These graphs allow a visual interpretation of the compositions of the clusters since the observations are represented with the color corresponding to the cluster it is assigned. With a left double click of the mouse on a preview, the graph is magnified and several options can be selected with a right click on the graph.

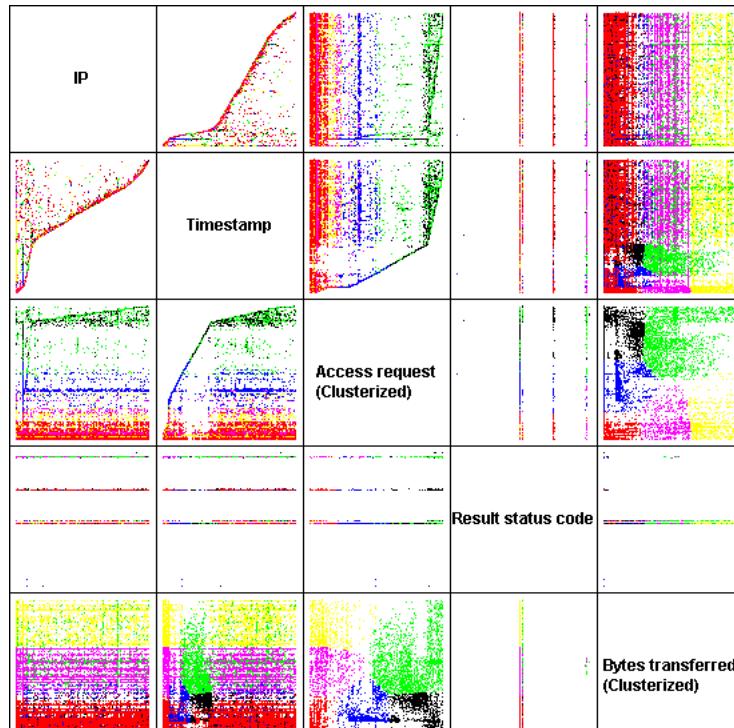


Figure 7.42: K-Means scatter plots matrix. Each observation is represented with the color corresponding to the cluster it is assigned.

Fuzzy K-Means algorithm results

When the fuzzy k-Means results are selected, the panel is uploaded and in the table of Figure 7.38 a new table containing a row for each partition identified is shown (Figure 7.39). The number of clusters, the *Entropy* index and the *ratio* are shown. By selecting one of the rows of table in Figure 7.43 the panel is updated and appears in the right side a tabs structure that permits to visualize information concerning results, by grouping them in three main panels:

Num. of clusters		
Cl	Entropy	Ratio
2	254.017E-3	-
3	435.116E-3	171.294E-2
4	610.374E-3	140.278E-2
5	736.876E-3	120.725E-2
6	912.391E-3	123.819E-2
7	101.505E-2	111.252E-2
8	108.480E-2	106.872E-2

Figure 7.43: Results of a fuzzy k-Means algorithm execution

- *Clustering Info:* It shows the clusters that have been identified and the entropy values (Figure 7.44). The error value used to identify a partition should be set by the user and can be easily changed (error setting information are reported on the right). Pressing the ‘*Apply error*’ button the assignment of the observations in the current partitions will be changed according to the new error value and the table at the bottom showing the composition of each cluster (and the statistical and graphic information) of the following panels will be updated. Note that the sum of the percentages could be *greater* than 100% because of the multiple assignments of the fuzzy algorithm.

/ Clustering Info \ Cluster Info \ Dispersion Matrix \		
CLUSTERING INFORMATION		
This clustering has been performed searching 4 clusters and the entropy for this result is 610.374E-3		
Select the error:	0.35	<input type="button" value="Apply error"/>
ERROR SETTING INFORMATION You can select which error to use to create each single cluster according to Fuzzy K-Means clustering results		
Cluster	Num. observations	Percentage
Cluster 1	11133	13.916%
Cluster 2	5916	7.395%
Cluster 3	6303	7.879%
Cluster 4	57324	71.655%
Not assigned	3624	4.53%

Figure 7.44: Results of a fuzzy k-means algorithm execution

- *Clusters Info:* It shows statistical information concerning the selected cluster (Figure 7.45). See the comments reported above for the cluster info of the k-means algorithm.
- *Dispersion Matrix:* this last panel shows the matrix of all the possible variable vs. variable scatter plots (Figure 7.46). See the comments reported above for the dispersion matrix of the k-means algorithm.

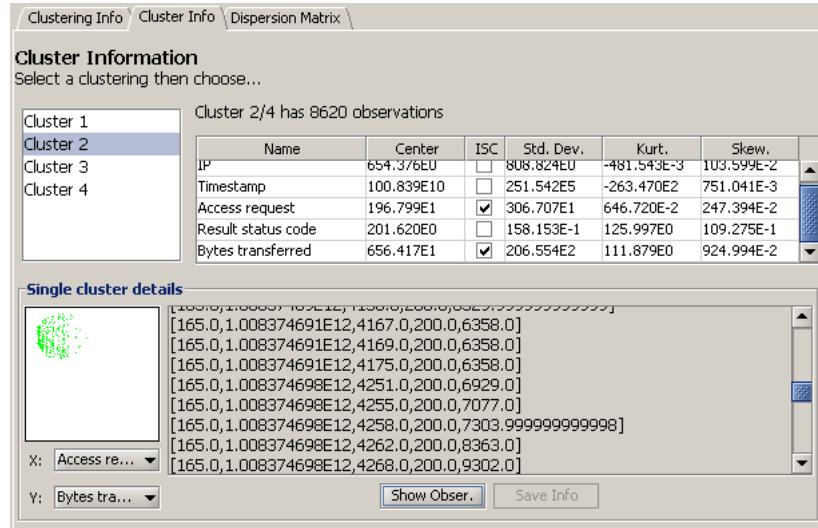


Figure 7.45: Descriptive statistics of the clusters obtained with the fuzzy k-means algorithm and their visual characterization through the dispersion matrix

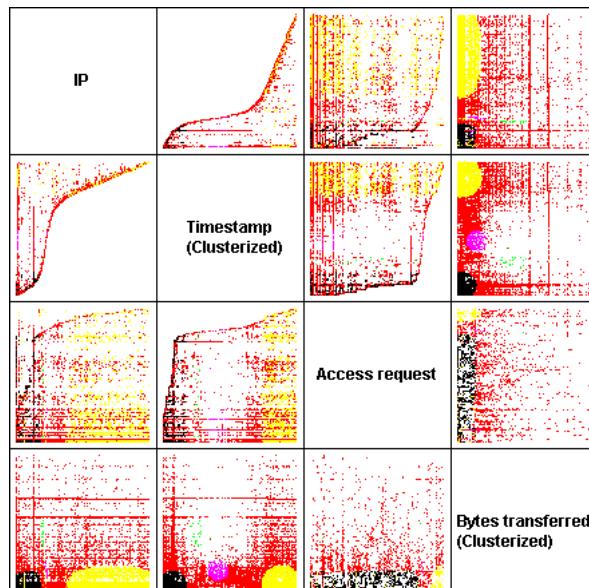


Figure 7.46: Fuzzy k-Means scatter plot matrix. Each observation is represented with the color corresponding to the cluster it is assigned

7.1.7 An example of a web log analysis

In this section we will describe an example of application of the JWAT tool for a workload analysis. The analyzed set of data consists of observations stored in the log file of a web server of a university site. The input file *Demo1Data.jwat* and its format *Demo1Format.jwatformat* can be found in the subfolders *Examples* and *jwatFormats*, respectively, of the Java Modelling Tools folder installed with the JMT tools.

Step 1 - Input panel

146.48.13.191 15/Dec/2001:00:00:04 "GET /homepage/homepage.php" 3914
146.48.13.191 15/Dec/2001:00:00:05 "GET /homepage/homepage.php" 7825
151.29.12.105 15/Dec/2001:00:00:06 "GET /images2000/home/ombrasnussoliv2.gif" 223
151.29.12.105 15/Dec/2001:00:00:06 "GET /images2000/home/ombraliv2.gif" 131
151.29.12.105 15/Dec/2001:00:00:06 "GET /images2000/home/spacer.gif" 43

Figure 7.47: Example of observations in the input file considered.

Name	Type	Select	Comment	Sep.	Perl5 Reg. Exp.	Def.	Rep.
IP	String	<input checked="" type="checkbox"/>	IP Address		\d+\.\d+\.\d+\.\d+		<input checked="" type="checkbox"/>
Timestamp	Date	<input checked="" type="checkbox"/>	Timestamp of the visit as s...		\d\d/\w\w\w/\d\d...		<input checked="" type="checkbox"/>
Access request	String	<input checked="" type="checkbox"/>	The request made	"	.+		<input checked="" type="checkbox"/>
Bytes transferred	Numeric	<input checked="" type="checkbox"/>	The number of bytes trans...		([+-])?\d+([.]\d+)?		<input checked="" type="checkbox"/>

Figure 7.48: Input format example

Each observation consists of the values of 4 variables described in Figure 7.48:

- *IP*: String type variable that defines IP address of the request.
- *Timestamp*: Date type variable that defines the timestamp of the request, the regular expression "`\d\d/\w\w\w/\d\d\d:\d\d:\d\d:\d\d`" identifies that the data will be in the format dd/mmm/yyyy:hh:mm:ss (e.g., 12/Jun/2000:12:21:45).
- *Access request*: String type variable that identifies the object that is the target of the request. The definition through delimiter " and regular expression ".*" allows the reading of all the string that is contained between quotation marks; if it is necessary it is possible to modify the expression ".*" to read only a part of the string between quotation marks.
- *Bytes transferred*: Numeric type variable that identifies the quantity of bytes transferred due to the execution of the request submitted.

Step 2 - Descriptive statistics and sample extraction

Before the execution of the cluster analysis the size of the input data set has been reduced executing the filter *Interval* to the values of the variable *Bytes transferred* setting a maximum value of 20000 and a minimum value of 0. The purpose of this filtering operation is to obtain a data set more compact but still representative of the original one. In Tables Figure 7.49 and Figure 7.50 the descriptive statistics before and after applying the filter on the input data are shown, respectively. Scatter plot matrix of the filtered data are shown in Figure 7.51.

Variable	Mean	Variance	Std. Dev.	Coeff. of v...	Minimum	Maximum	Range	Median	Kurtosis	Skewness	Num. Obs.
IP	516.057E0	144.585E3	380.244E0	736.825E-3	000.000E0	124.800E1	124.800E1	473.000E0	-123.437E-2	312.164E-3	376.140E2
Timestamp	100.840E10	271.278E12	164.705E5	163.333E-7	100.837E10	100.842E10	477.690E5	100.841E10	-123.961E-2	-642.748E-3	376.140E2
Access request	384.799E0	312.824E3	559.306E0	145.350E-2	000.000E0	232.000E1	232.000E1	131.000E0	212.949E-2	182.649E-2	376.140E2
Bytes transferred	397.872E1	465.577E5	682.332E1	171.495E-2	000.000E0	398.790E2	398.790E2	111.100E1	598.435E-2	255.522E-2	376.140E2

Figure 7.49: Descriptive statistics of the original data before applying the filter on the "Bytes transferred" variable

About 2500 observations have been dropped due to the filtering action, reducing considerably the variance.

Step 3 - Clustering panel

The k-Means algorithm and the variables *timestamp* and *Bytes transferred* have been selected in the clustering panel together with the following options: number of clusters 7, interactions 50 and transformation *Max-Min*. The clustering results panel is opened automatically. Through the 'Back' button we went back to the previous panel to execute a new clustering algorithm. The fuzzy k-Means algorithm and the variables *timestamp* and *Bytes transferred* have been selected together with the following options: number of clusters 6, interactions 20, fuzziness level 2.0.

Variable	Mean	Variance	Std. Dev.	Coeff. of v...	Minimum	Maximum	Range	Median	Kurtosis	Skewness	Num. Obs.
IP	513.059E0	144.963E3	380.740E0	742.098E-3	000.000E0	124.600E1	124.600E1	466.000E0	-123.152E-2	326.854E-3	351.270E2
Timestamp	100.840E10	271.088E12	164.647E5	163.276E-7	100.837E10	100.842E10	477.690E5	100.841E10	-125.431E-2	-628.080E-3	351.270E2
Access request	389.184E0	312.667E3	559.166E0	143.677E-2	000.000E0	232.000E1	232.000E1	141.000E0	201.294E-2	179.578E-2	351.270E2
Bytes transferred	241.119E1	117.579E5	342.898E1	142.211E-2	000.000E0	199.800E2	199.800E2	100.200E1	610.155E-2	237.149E-2	351.270E2

Figure 7.50: Descriptive statistics of the original data after applying the filter on the "Bytes transferred" variable

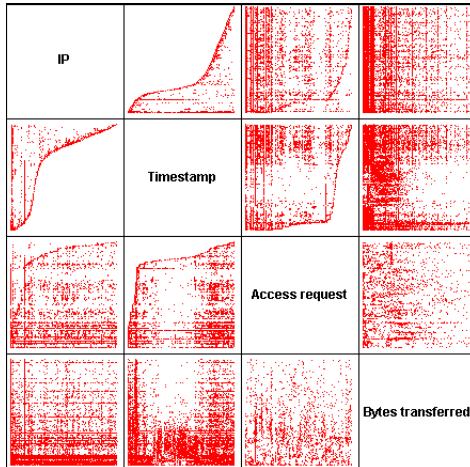


Figure 7.51: Scatters matrix on the data set after applying the filter on the "Bytes transferred" variable.

Step 4 - Results panel

The results concerning the goodness of the partitions obtained with the two clustering algorithms are reported in the following tables:

Clustering	Cl.	
k-Means	7	✗
Fuzzy k-Means	6	✗

Clustering algorithms

Cl	G	OMSR	Rat
2	✓	876.308E2	893.69%
3	✗	980.541E1	564.59%
4	✗	173.673E2	114.89%
5	✓	151.157E2	238.12%
6	✗	634.773E1	961.66%
7	✗	660.077E1	000.00%

k-Means

Cl	Entropy	Ratio
2	200.614E-3	-
3	433.346E-3	216.009E-2
4	552.932E-3	127.596E-2
5	651.680E-3	117.859E-2
6	674.182E-3	103.453E-2

Fuzzy k-Means

We have visualized different statistics for each algorithm by varying the number of clusters, in particular we show the scatter plots matrix for the partition with 5 clusters (as can be seen from the OMSR values this partition has been evaluated as a good one).

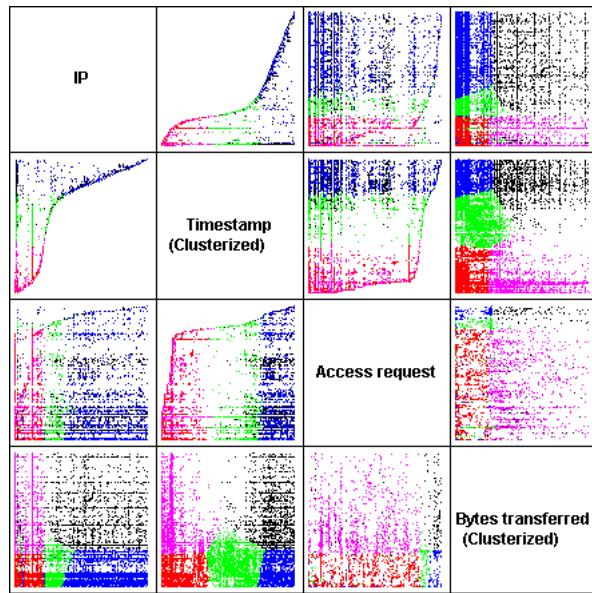


Figure 7.52: K-Means algorithm scatter plots matrix

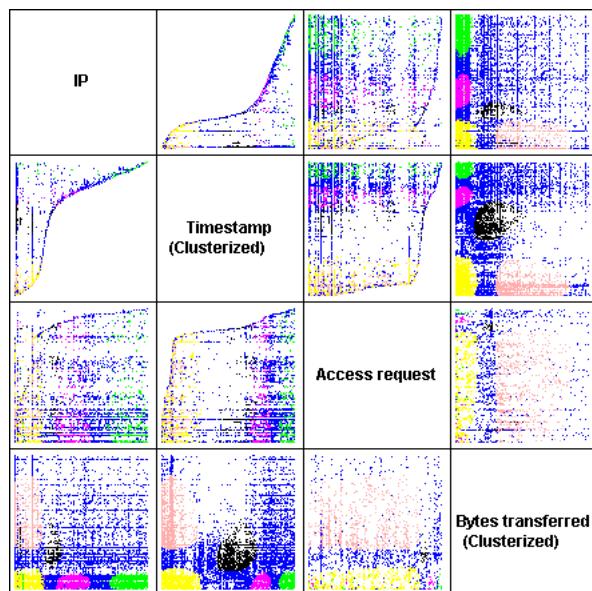


Figure 7.53: Fuzzy k-Means algorithm scatter plots matrix

7.1.8 Menus description

File

New Use this command to start a new analysis selecting a new log file.



Shortcut on Toolbar:

Accelerator Key: CTRL+N

Exit

Use this command to terminate the JWAT current session. It is possible to utilize ‘Exit’ button in the buttons bar of application. If the session has been modified after its creation or after its last saving, a popup window asks confirmation to save session.

Accelerator Key: CTRL+Q

Action

Solve Use this command, when enabled, to start the algorithm selected in the clustering panel. It is possible to obtain the same result by using ‘Solve’ button in the buttons bar of the application.



Shortcut on Toolbar:

Accelerator Key: CTRL+L

Help

JWAT Help Use this command to visualize the help. Suggestions concerning the single tab in the application are also available by using the ‘Help’ button in the buttons bar of application.



Shortcut on Toolbar:

Accelerator Key: CTRL+Q

About

Use this command to visualize information concerning JWAT application.

7.1.9 Demo

In order to show the functionality of the workload analysis program, a demo has been realized. It can be accessed using the button in the main JWAT panel (see Figure 7.1). Once the demo panel has been opened it is sufficient to click on Load demo button (see Figure Figure 7.54) to launch the workload analysis algorithms on the file Demo_WAData.jwat present in the folder examples of the JMT installation directory.

7.2 Fitting

To start a fitting session press the button in the JWAT window and the window of Figure 7.55 will appear. This application helps the user to assess whether a sequence of experimental data fits a known distribution through the application of statistical hypothesis algorithms. In case the experimental data fits one of the available known distributions the parameter values to be used to reproduce the original sequence of data will be shown. Graphs will also be produced. With the current JWAT release only the Pareto and exponential distributions are available, more will be added in the future. The main components of the fitting window are:

- *Menu and Toolbar*: the functioning of these two parts of the window is the same of the one of the Workload Analysis application, so the reader is invited to see the introduction of Section 7.1.
- *Tabbed pane*: It concerns the main functions of the application. All the operations and results obtained during the fitting procedure are shown in three navigable tabs: input, Pareto and exponential (see Figure 7.56).
- *Navigation buttons*: this part aims at providing an alternative method of navigation through the tabbed pane (other than clicking on the tab themselves), using the next and previous buttons. For a detailed description see Section 7.1.

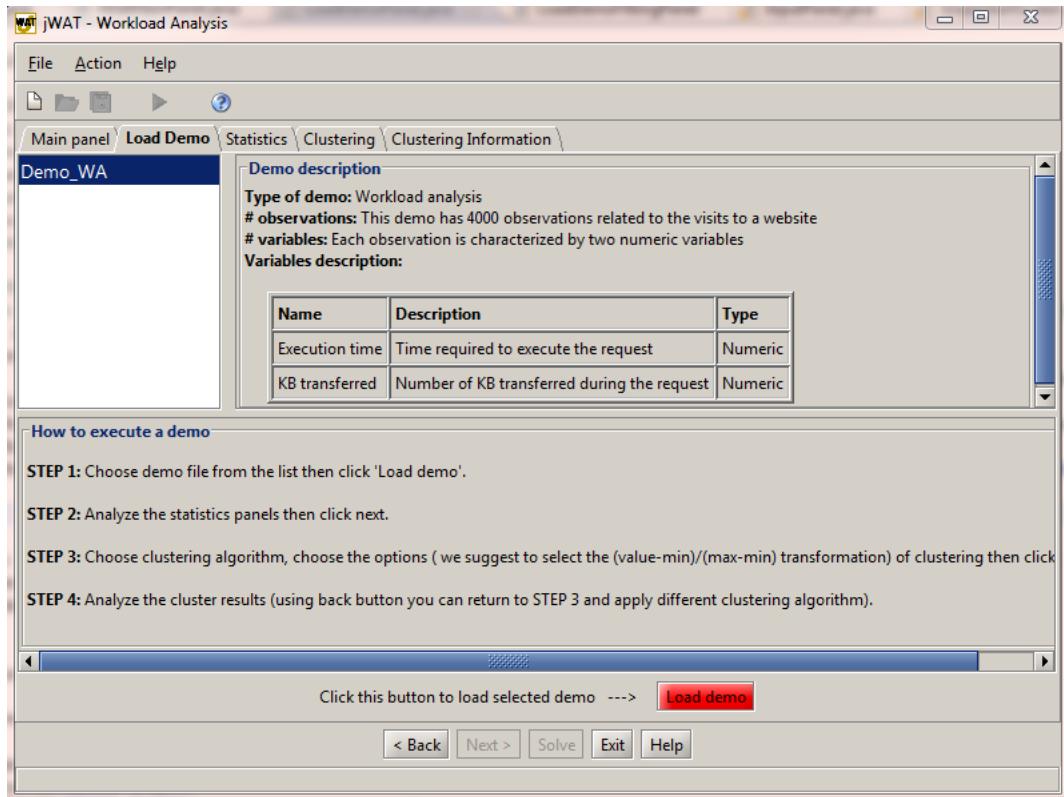


Figure 7.54: Demo Panel of the workload analysis tool

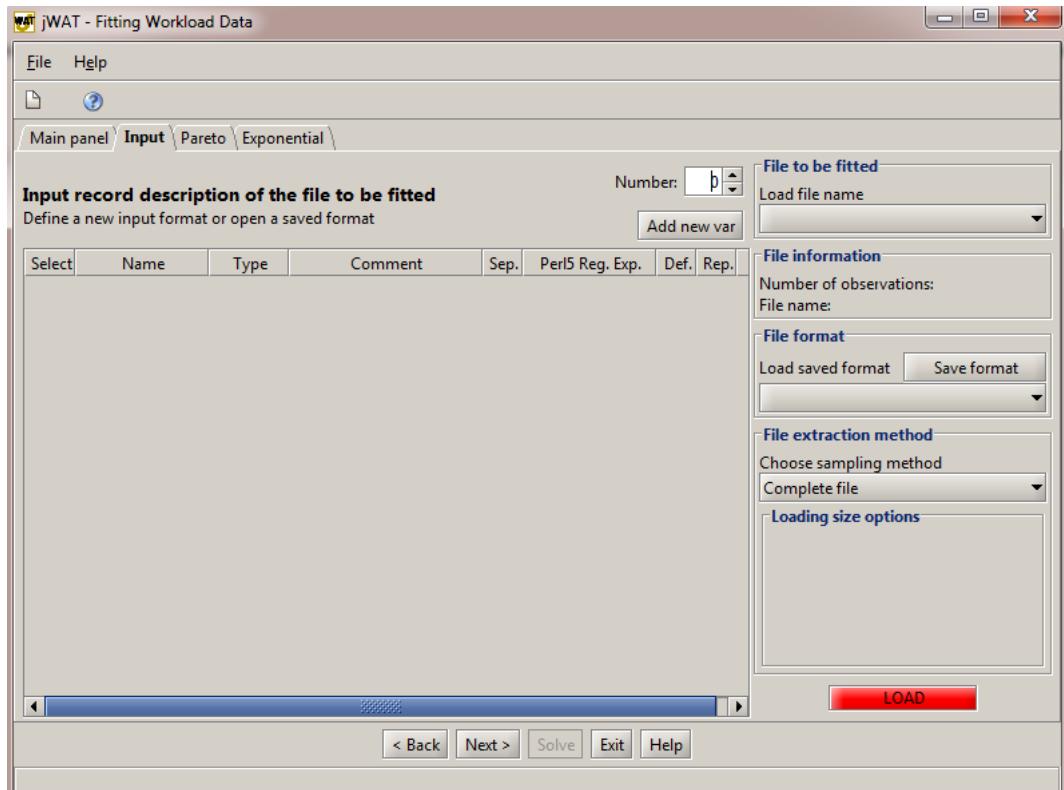


Figure 7.55: Main window of the Fitting application



Figure 7.56: Tabs selector

In the following sections the utilization of the panels of the fitting application will be described in detail.

7.2.1 Input definition

The definition of the input is similar to the one of Workload Analysis described in Section 7.1.2. In this step it is necessary to specify only one numeric variable in order to apply the fitting function. If more than one numeric variable should be fitted it is necessary to reload each time the log specifying a different Numeric field.

7.2.2 Pareto and Exponential panels

The Pareto and Exponential panels show the result of the application of the fitting function to the data provided in the Input definition, together with some graphical representations of statistical functions. The operation performed by the application can be subdivided into three steps, that are performed automatically:

- *Application of hypothesis tests*: two goodness-of-fit tests are applied to the data. In particular, the Pareto distribution is tested using the algorithm described in [?] while the exponential distribution using the one in [?]. Note that these tests have a good statistical power function in the presence of a consistent number of observations, thus for a reliable result use at least 50 or 100 observations for both tests.
- *Estimation of the parameters*: if a test gives a positive outcome then the parameters are estimated using a Maximum Likelihood Estimator. The estimators of the scale (k) and shape (α) parameters for the Pareto distribution are provided in [?] while the unique parameter λ of the exponential is simply the inverse of the empirical mean.
- *Construction of the graphs*: this step builds three graphs for each of the two panels: a QQ-Plot, an empirical Cumulative Function (CDF) and an empirical density function (pdf). The graphs are useful to make a visual assessment of the fitting of the data to the particular distribution, beyond the result of the goodness-of-fit test itself. Each of the graphs can be enlarged double clicking on it (see Figure 7.59). It is also possible to zoom-in and zoom-out the graphs, and also to save the plot in both `png` and `eps` formats.

Let us make an example of the behavior of the fitting application analyzing a sequence of data that will result to follow a Pareto distribution. The data associated with this example can be found in the directory `example` under the name `pareto_example.jwat` and loading the format `pareto_format.jwat`.

The Pareto panel in Figure 7.57 shows the results of the fitting with respect to the Pareto distribution. The upper part of the panel contains the message that the test applied with a significance of 0.05 produced a positive outcome. After that, the estimation of the parameters of the distribution are provided, in particular α (shape parameter) and k (scale parameter).

Finally, three typical statistical indicators are showed: the mean μ , the variance σ^2 and the coefficient of variation σ/μ . The lower part of the panel contains three graphs. The first one on the left is the QQ-Plot, which displays the comparison between the data (x-axis) and the quantiles of the Pareto distribution having the estimated parameters. The 45 degree line represents a reference for the points of the QQ-Plot, and it's the place where the data would lie if they followed perfectly a distribution with the estimated parameters. If the data are Pareto distributed, the points should lie close to the continuous red line. The graph in the middle is the CDF of the analyzed sequence of data, and it is constructed incrementing the value of the y-axis of $1/n$ every time a point of the dataset is encountered. The last graph is the empirical pdf of the analyzed data, which is essentially a frequency graph obtained dividing the x-axis in a number of buckets proportional to number n of observations, and counting the percentage of points that falls in each bucket.

Figure 7.58 shows the results of the exponential fitting on the same sequence of data. As it can be seen, the message says now that the data are not exponentially distributed. The mean, variance and coefficient of variation of the analyzed data are showed. The QQ-Plot in the lower-left part confirms that the data is not exponentially distributed, since the majority of the points lie far away from the 45 degree line.

7.2.3 Demo

In order to show the functionality of the fitting program, a demo has been realized. It can be accessed using the button in the main JWAT panel (see Figure 7.1). Once the demo panel has been opened it is sufficient to click on `Load demo` button (see Figure Figure 7.60) to read and fit automatically the file `DemoFittingPareto.jwat` present in the folder `examples` of the JMT installation directory. As the name suggests, this demo shows the fitting procedure applied to a dataset that is Pareto distributed.

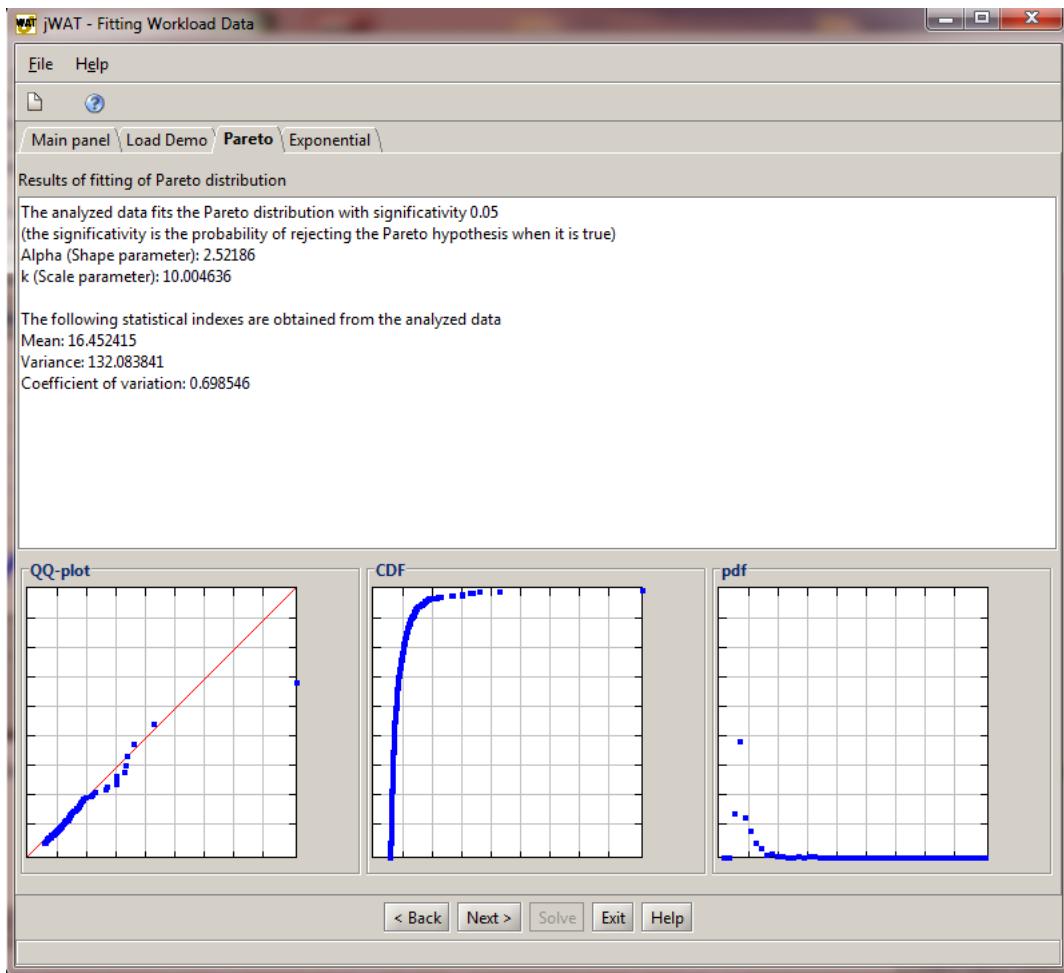


Figure 7.57: Results of the fitting on the Pareto panel when the program is fed with Pareto-distributed data

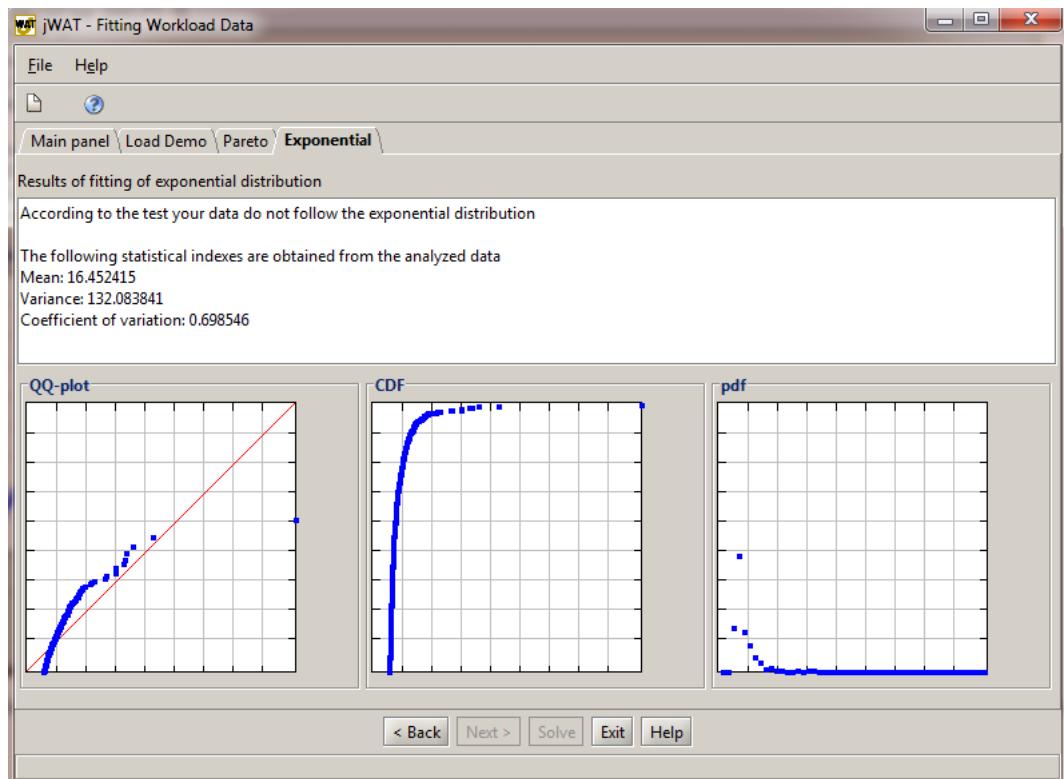


Figure 7.58: Results of the fitting on the exponential panel when the program is fed with Pareto-distributed data

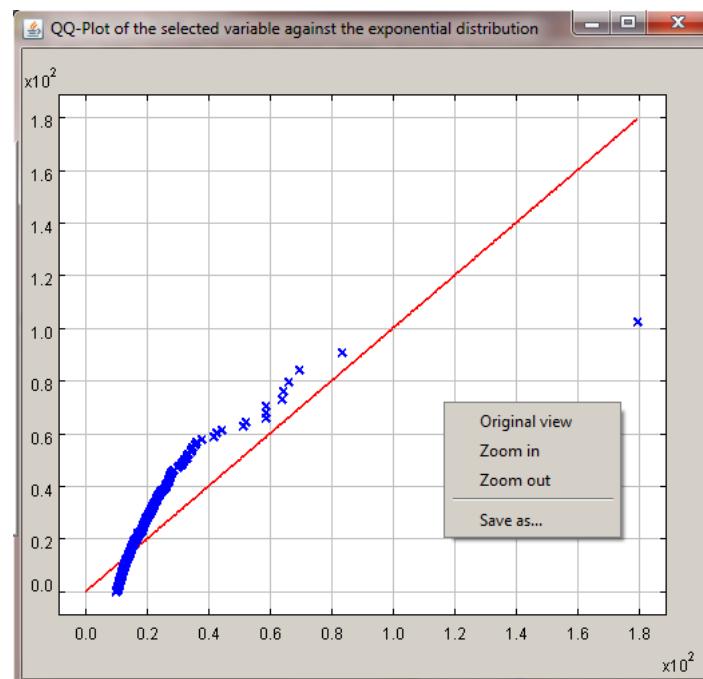


Figure 7.59: Enlarged QQ-Plot

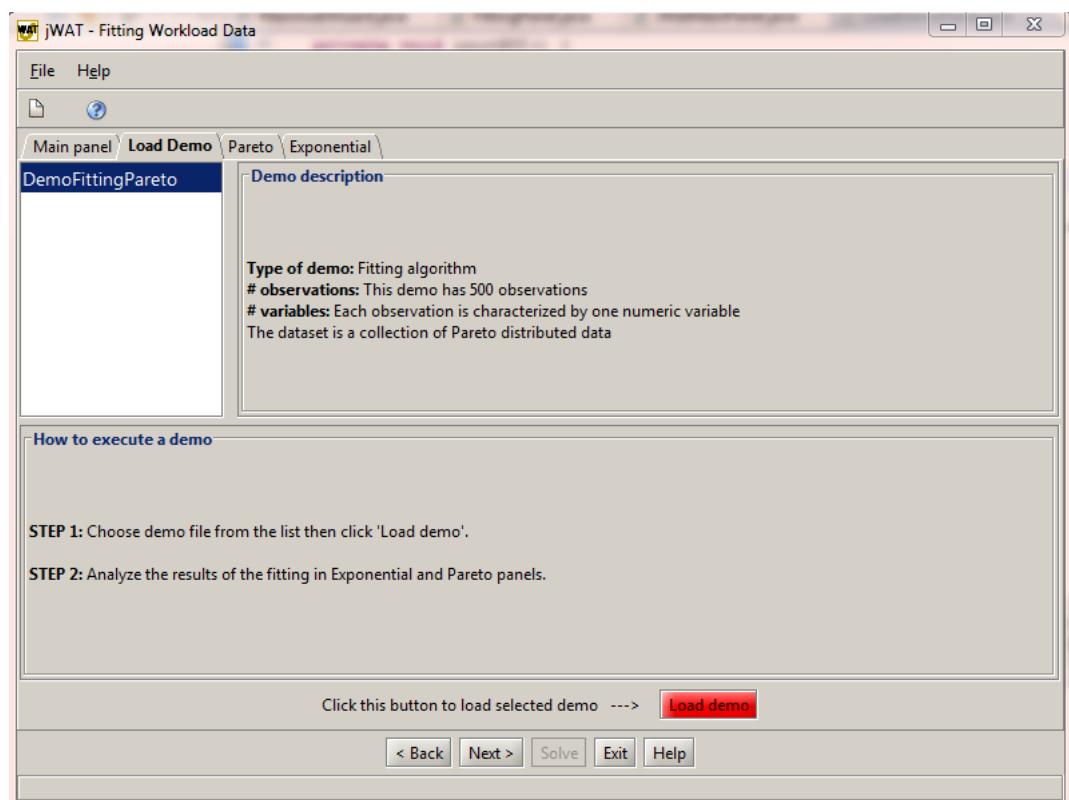


Figure 7.60: Demo Panel of the fitting tool

Appendix A

Basic Definitions

Approximate Mean Value Analysis (AMVA). Algorithms for computing approximate solutions of multi-class closed queuing networks providing significant time and space reduction by substituting non-recursive approximations for queue lengths (per resource r and per class c) seen by an arriving customer $A_{r,c}(\vec{N})$.

Arrival Rate (λ). Rate at which customers of an open class arrive to the system.

Batch workload. Closed workload class composed of customers that do not require interactions with users during their execution (i.e., the users think time is zero).

Bottleneck Station. The station with the highest utilization in the system.

Class of customers. A group of customers with service demands on the different stations statistically equal. Open classes are specified by the *arrival rate* λ (job/s), closed classes consist of a constant number of jobs N specified as the *population size* (job).

Class Switch. A *class switch* station allows the customers to change class according to the probabilities described in a *class switch matrix*.

Closed Class. Workload class in which customers that have completed service leave the system and are instantaneously replaced by a new customer. A closed model has a fixed population of requests.

Customer or Job or Transaction or Request. It is the element that will require service to stations. For example, it can be an http request, a database query, a ftp download command, or an I/O request.

Delay station. Customers at a delay station are each (logically) allocated their own server, so there is no competition for service (no queue). The time spent by a customer at a delay station is exactly its service demand. In delay stations, for consistency with Little's law, the *utilization* is computed as the *average number of customers* in the station, and thus it may be *greater than 1*.

Dominated Stations. A station S is dominated if exist at least one station Q whose service demands for each class of customer are highest or equal (but at least one highest) than those of S .

Interactive workload (terminal workload). Its intensity is specified by two parameters: the number of active terminals (customers), and the average length of time that customers use terminals ("think time") between interactions.

Load Dependent Resource (station). A load dependent service station can be thought of as a service station whose service rate (the reciprocal of its service time) is a function of the customer population in its queue.

Load Independent Resource (station). A load independent service station is a station whose service time S is *independent* of the actual load of the station (i.e., of the number of customers in the station).

Masked-off Stations. a station that is not a Potential Bottleneck or a Dominated station. A Masked-off station may exhibit the largest queue-length and hence the highest response time.

Mean Value Analysis (MVA). Iterative technique used to evaluate closed queuing networks.

Multiple class models. Models with several customer classes, each of which has its own workload intensity and its own service demand at each center. Within each class, the customers are indistinguishable.

Number of customers (N_r) . Average number of customers at station r , either waiting in queue *and* receiving service.

Number of customers in the system. It is the aggregate measure of the *Number of customers* over all the stations.

Number of visits. The average number of visits that a customer makes to each resource during a complete execution.

Open Class or Transaction Workload. Workload class in which there is an external source with an arbitrary number of customers that are sent to the system according to a given distribution. The number of customers in the model varies over time and can be arbitrarily large depending on the congestion level of the resources and on the arrival process.

Global Population (N). Constant number of requests belonging to a closed class.

Population Mix (β_i). The ratio between N_i , the *number of customers* of closed class i , and the total number of customers in the system: $\beta_i = N_i / \sum_k N_k$. It can be defined either for open and closed models.

Potential Bottleneck Station. A station that can become bottleneck for some feasible population mixes.

Queueing network model. A network of queues is a collection of service resources, which represent system resources, and customers, which represent users or transactions.

Queueing station. A resource consisting of two components: queue and server. Customers at a queueing resource compete for the use of the server. The time spent by a customer at a queueing resource has *two* components: time spent waiting in queue and time spent receiving service.

Reference Station. User-specified station where a customer flow through when it has completed its execution, i.e., it has performed an entire cycle of service in the system. The system throughput, system response time, and the visits V_k are computed with respect to the visits at the reference station (*usually* assumed as 1).

Residence Time (W_k). Average time that a customer spent at station k during its complete execution. It includes time spent queueing and time spent receiving service. It does not correspond to *Response Time* R_k of a station since $W_k = R_k * V_k$.

Response Time (R_k). Average time required by a customer to flow through a station k (includes queue time and service time).

Response Time per Sink. average time spent in system by a customer before dropping at the selected sink.

Saturated Resource. When the arrival rate at a resource is greater than or equal to the maximum service rate, the resource is said to be saturated (i. e., its utilization is equal to 1).

Saturation Sector. A set of Population Mixes (i.e., fraction of customers of the different classes that are in execution) in which *two or more* stations are *saturated concurrently*, i.e., are *bottlenecks*.

Server Utilization (U). The utilization of a queuing center is the proportion of time the resource is busy or, equivalently, the average number of customers in service there (definition valid also for delay centers).

Service Demand (D_k). average service requirement of a customer, that is the total amount of service required by a complete execution at resource k . In the model it is necessary to provide separate service demand for each pair service center-class. It is given by $D_k = V_k * S_k$.

Service Time (S_k). Average service requirement of a request of a given class per visit at resource k .

Station or Service Center or Resource. It represents an element of the network. Customers arrive at the station and then, if necessary, wait in queue, receive service from server, and depart from the station.

System Power (ϕ). It is a performance metric that allows to take into consideration *both* the system throughput X and the system response time R [Kle79]. It is defined as X/R . A system is in the optimal operational point when the value of the power is maximized. For a station c of an open model consisting of a single queue station that works in the optimal operational point it will be: $\lambda_c = 0.5 S$, $U_c = 0.5$, $N_c = 1$.

System Response Time (R). Correspond to the intuitive notion of response time perceived by users, that is, the time interval between the instant of the submission of a request to a system and the instant the corresponding reply arrives completely at the user. It is the aggregate measure of *Residence Times*: $R = \sum_k W_k$.

System Throughput (X). Rate at which customers perform an entire interaction with the system (i.e., a complete execution). It is the throughput observed at a user-defined *reference station*.

Throughput (X_r). Rate at which customers are executed by station r accounting also periods where the server is idle. That is, X_r is the mean number of completions in a time unit from stationr.

Throughput per Sink. rate at which customers departs from the system with respect to the selected sink, i.e., the number of requests completed in a time unit that reach a given sink.

Utilization (U_r). Proportion of time in which the station r is busy or, in the case of a *delay* station, it may be interpreted as the average number of customers in the station (see Little Law [Lit61]).

Visit (number of -) (V_k). Average number of visits that a customer makes at station k during a complete execution; it is computed as the ratio of the number of completions at resource k to the number of system completions as observed at a user-defined reference station. If resource k is a delay center representing the users, usually it is assigned a unitary value to the number of visits to this station.

Appendix B

List of Symbols

- λ_c arrival rate of class c
 N global population of a model
 β_c population mix $\beta_c = N_c / \sum_k N_k$, fraction of class- c customers
 N_k number of customers at station k
 V_k average number of visits at station k
 W_k average residence time at station k , $W_k = R_k V_k$
 R_k response time of station k
 U_k utilization of station k , $U_k = X_k S_k = X_0 V_k S_k = X_0 D_k$
 D_k service demand at station k (single class)
 $D_{k,c}$ service demand at station k of class c customer
 R response time of the system, $R = \sum_k W_k$
 X system throughput
 X_k throughput at station k
 ϕ system power ($\phi = X/R$)

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