Quantitative System Evaluation with Java Modeling Tools (Tutorial Paper)

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ABSTRACT

Java Modelling Tools (JMT) is a suite of open source applications for performance evaluation and workload characterization of computer and communication systems based on queueing networks. JMT includes tools for workload characterization (JWAT), solution of queueing networks with analytical algorithms (JMVA), simulation of general-purpose queueing models (JSIM), bottleneck identification (JABA), and teaching support for Markov chain models underlying queueing systems (JMCH). This tutorial summarizes the main features of the tools that compose the suite. Furthermore, using a composite case study, we provide intuition on the versatility of JMT in dealing with the different aspects of quality-of-service (QoS) evaluation, what-if analysis, and software performance tuning.

Categories and Subject Descriptors

C.4 [**Performance of Systems**]: Modeling Techniques; D.2.8 [**Software Engineering**]: Metrics—*complexity measures, performance measures*

General Terms

Performance

Keywords

Tools, Performance Evaluation, Modeling, Simulation, Load Balancing, Bottlenecks detection, Queueing Networks

1. INTRODUCTION

Ongoing work in the software performance modeling community has significantly stressed the importance of developing automated or semi-automated frameworks for performance optimization and management of complex applications [8,9]. This is especially important in the design phases of a large-scale software in order to avoid taking choices that result in poor quality of service (QoS).

The Java Modelling Tools suite (JMT) is here proposed as tool to visually help software and system performance engineers to predict the performance of a system and quickly answer *what-if* questions. JMT is released as an open source tool suite that can be downloaded free from `http://jmt.sourceforge.net`. Thanks to the availability of Java sources, JMT functionalities may be freely integrated or interfaced via XML with other tools, as done for example in Opedo [1].

JMT consists of six applications that communicate using XML with a core algorithmic module composed by the simulation engine (*JSIMengine*) and by a library of analytical functions for performance model evaluation.

- *JSIMgraph* is a graphical design environment for queueing network models which is tightly coupled to the JSIMengine for running discrete-event simulation. JSIMwiz replaces the graphical framework of JSIMgraph with a set of wizards that guide the user through the definition of a queueing model. The tools generate XML specifications of simulation models, pretty-print visualization of complex networks, automatic model debugging, support for what-if analyses, and dynamical presentation of simulation state, performance metrics estimates and related confidence intervals. JSIMengine supports the evaluation of the most popular types of queueing models and several constructs that cannot be solved with exact analytical techniques like multiclass queueing networks with blocking, priorities, fork-and-join elements, burstiness, and state-dependent routing schemes.
- *JMVA* is a graphical user interfaces for the analytical evaluation of queueing network models. The tool relies on an implementation of the Mean value Analysis (MVA) algorithm for closed networks, together with its extensions for open and mixed networks.
- *JABA* is an analytical tool for automatic identification of the bottlenecks in multiclass closed queueing networks. The tool receives in input a set of service demands specifying the speed of each server in processing requests of the different classes. JABA identifies the mixes of requests of the different classes that saturate concurrently more than one resource. It uses efficient convex-hull algorithms. This saves the computational costs of a long simulative analysis over different mixes of requests.
- *JWAT* tool supports the workload characterization process. Algorithms for data scaling, sample extraction, outlier filtering, k-means and fuzzy k-means clustering for

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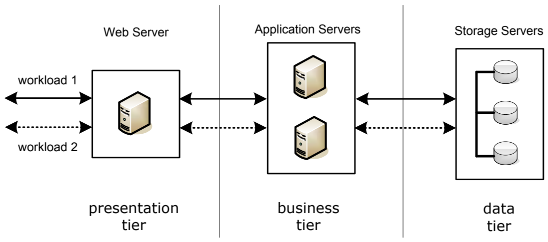

Figure 1: The topology of the example 3-tier system

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, number of I/Os, number of web pages accessed) that can be used for the workload parameterization. The characterization of time-varying workloads (e.g., burstiness analysis) and the fitting of input data with exponential and Pareto distributions are also supported.

- *JMCH* application is a graphical simulator of M/M/c and M/M/c/K queues. The simulation state is visualized both on the queue buffer and on a Markov model representing the system state.

2. LEARNING JMT BY EXAMPLE

In this section, we provide a case study to illustrate two applications of the JMT suite, namely JAVA and JMVA. The case study considers the performance analysis and optimization of the 3-tier enterprise system illustrated in Figure 1. This is composed by a Web Server (presentation tier), 2 Application Servers (business logic tier), and 3 Storage Servers (data tier) for DBs. The evaluation of performance metrics such as throughputs and response times is here obtained using the JMVA tool, which considers product-form queueing networks hence it implicitly takes assumptions regarding exponentiality of service times for first-come first-server queues and other properties of the queueing network model [3]. For systems where such assumptions are not satisfied, JMVA results can be equivalently replaced by the simulation-based estimated provided by JSIMgraph or JSIMwiz [4].

The workload of the system consists of two classes of applications which have different requirements in terms of the amount of resources requested. Furthermore, each application may be subject to a different QoS constraints. The two application classes are data intensive: data processing for the first class and data updating the second class. We assume that, for performance reasons, the maximum number of requests simultaneously in execution is limited to N, therefore we consider a closed queueing model. This is a convenient assumption to model load balancing based on admission control or to describe the performance of systems which use a finite number of software threads to serve requests. For the sake of illustration, let us set $N = N_1 + N_2 = 100$ as the constant number of requests in execution, where $N_1 \geq 0$ and $N_2 \geq 0$ are the number of requests in execution for the two application classes, respectively. The objectives of the case study are twofold:

*	Class1	Class2
Storage1	20.000000	90.000000
Storage2	80.000000	30.000000
Storage3	31.000000	33.000000
ApplServer1	14.000000	20.000000
ApplServer2	23.000000	14.000000
WebServer	12.000000	7.000000

Figure 2: Service demands of the requests of the two classes for the resources of the system.

- to study the performance behavior of the system as a function of the different mix of requests in concurrent execution;
- to determine the optimal load balancing of the system that maximizes the global application throughput while satisfying the QoS constraints.

In order to achieve these goals, we can follow a methodology that combines the features of JMVA and JABA. JMVA is used to estimate the performance of the system for a given parameter range. Conversely, JABA is used to drive in a computationally efficient manner the guessing of the optimal load balancing for the system. The main steps of the case study are:

1. Identify with JABA the bottlenecks of the system with respect to all the possible mixes of requests in execution. This allows to *quickly* identify what resources may limit the performance of the system under all possible workload mixes (N_1, N_2) under the assumption that $N = N_1 + N_1$ is asymptotically large.

2. Evaluate with JMVA the most important performance measures, e.g., throughput, response time, resource utilization, system power, per-class and at the system level with respect to all the possible mixes of requests in execution. This refines the information obtained in the previous step by considering the actual value $N = 100$ in place of the asymptotic one. For large models, it may be useful to restrict the range of analysis to a subset of workload mixes following the insights obtained from JABA.

3. Compute with JABA the optimal load balancing that maximizes the system throughput. JABA supports the dynamic re-evaluation of a system's asymptotic performance without the need of solving the models with a computationally intensive procedure as in JMVA. Hence, one could visually retune the system load balancing in order to obtain a more performing configuration.

4. Evaluate with JMVA the new performance metric values with respect to all the possible mixes of requests in execution. This validates for $N = 100$ the load balancing reconfigurations suggested by JABA.

To characterize the requests of the applications in terms of processing requirements a set of service demands, one for each resource and for each class, is used. The service demand of a request of class r at resource i, $D_{i,r}$, is the total amount of time the request requires at that resource in order to be completely executed. The service demand value is computed ignoring contention by other requests and may be estimated

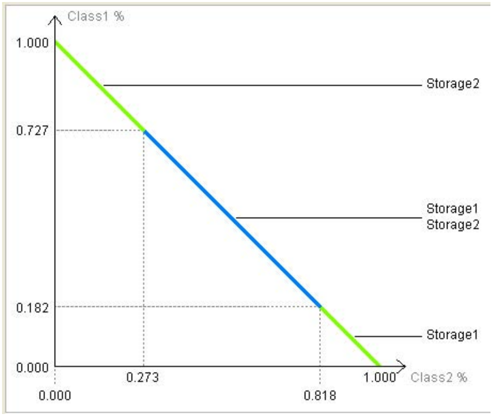

Figure 3: Bottleneck migration as a function of the fraction of requests of the two classes (population mix) in execution.

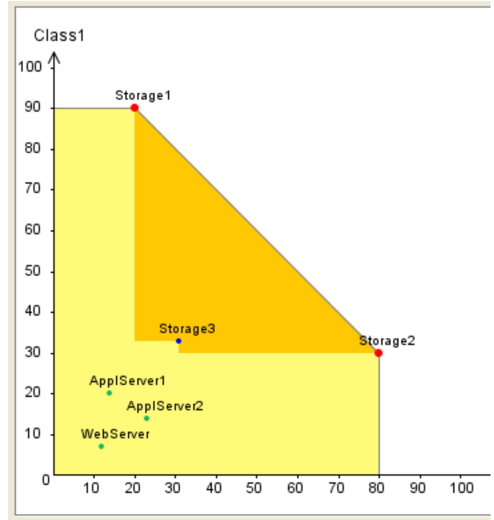

Figure 4: Visual representation of the service demands and identification of the bottlenecks as resources that lie on the convex hull.

directly from measured utilizations according to the relation $U_{i,r} = X_r D_{i,r}$, where X_r is the system throughput for workload class r and $U_{i,r}$ is its utilization at resource i. The parameters of our system, in ms, are shown in Fig. 2. The amount of work requested from the Web Server is much less demanding than the one requested from the Application and Storage Servers. The computations required by the business logic place a medium load on the Application Servers while the high number of data manipulated, uploaded and downloaded, generate a high load on the Storage Servers.

In the asymptotic analysis phase [2], JABA derives the set of bottlenecks as a function of all the possible mix of requests (see Fig. 3). Indeed, keeping the total population of the system constant, and large, and varying the population mix, we may observe a bottleneck migration phenomenon. When the fraction of *class 1* requests is between 18.2% and 72.7% of the total population, two resources, namely `StorageServer1` and `StorageServer2`, saturate concurrently. This is in contrast with the other segments of Fig. 3 where it is shown that some mixes of requests result in only `StorageServer1` or `StorageServer2` being saturated.

The identification of the interval of joint saturation for `StorageServer1` and `StorageServer2`, referred to as *common saturation sector*, is important in order to find the load of the system that satisfy the performance criteria related to the QoS. Indeed, it can be shown that the equiutilization point, i.e., the mix that causes the two bottlenecks to be equally utilized, lies into this interval and provides the maximum system throughput [10]. Furthermore, the existence of such saturation sectors, despite being derived under the assumptions of product-form theory, has been independently observed to exist in real-world multi-tier applications [7,11]. The graph of Fig. 4, generated by JABA, provides a visual representation of the resources that may become saturated as a function of the mix of requests.

In [5] it is shown that the potential bottlenecks lie on the convex hull of the service demands (`Storage1` and `Storage2` in this case). To evaluate the exact values of the performance metrics corresponding to all the possible population mix we used the What-if feature of JMVA varying from 100% to 0% the requests in execution of one class and the opposite (from 0% to 100%) the fraction of the other class. Fig. 5 shows the throughput X of the system, global and per-class. The x-axis represents the fraction of class 1 requests (referred to as β_1) with respect to the total number of requests in execution. It is evident that X is maximized for all the mixes of requests that belong to the common saturation sector while the per-class throughput is constant in the interval. Similarly, Fig. 6 illustrates the response time R, of the system and per class. As can be seen, the system response time R is constant for all the mixes of the common saturation sector. The response times of the two classes are identical when the two bottlenecks are equiloaded and it can be shown that the corresponding equiload mix lies inside the common saturation sector [10].

The utilizations of the three storage servers are shown in Fig. 7. As predicted, the `StorageServer1` and `Storage-Server2` saturate together for all the mixes of the common saturation sector while the utilization of `StorageServer3` is definitively lower, $U_{StoSer3} = 0.58$, since its service demands are smaller with respect to the ones of the two bottlenecks. In Fig. 8 the `Power` measures, at the system level and per-class, are shown. The `Power` measure, first introduced in [6], is an interesting metric that combines the throughput X and the response time R. This metric is the ratio $\Phi = X/R$ of throughput and response time and captures the level of efficiency in executing a workload. The maximum `Power` corresponds to the optimal operating point for the system, i.e., the point in which the throughput is maximized with the minimum response time. This concept is directly related with the one of QoS. JMVA plots the Power for the requests of each class and at the aggregate level. As shown in Fig. 8, the population mixes close to the extremes of the common saturation sector provides a better QoS to the requests of one class or of the other. When the fraction of requests of class 1 is about 0.21 the QoS of class 1 is maximized, while with a fraction of about 0.69 the QoS of class 2 is maximized.

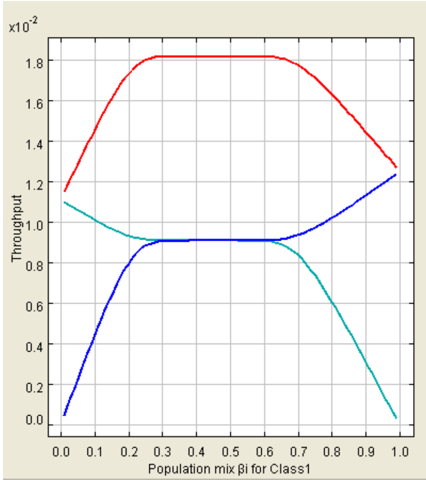

Figure 5: *Throughput* of the system (red curve) and per-class (blue curve for class 1 and light blue for class 2), as a function of the fraction of requests of the two classes in execution.

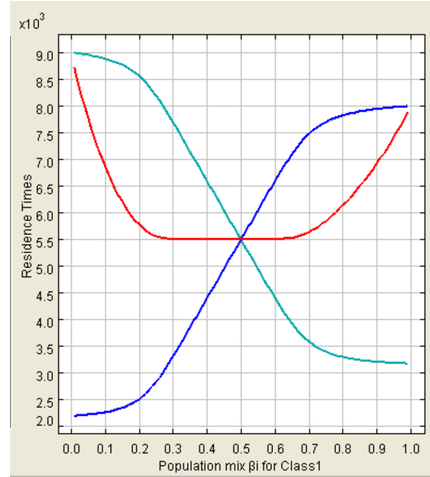

Figure 6: *Response time* of the system (red curve) and per-class (blue curve for class 1 and light blue for class 2), as a function of the mix of requests in execution.

To enhance the performance of the system we need to take into consideration the most heavily loaded servers, namely `StorageServer1` and `StorageServer2`, since reducing the service demands at resources other than the bottlenecks produces only marginal improvements. The total load on the two `StorageServers 1` and `2` is well balanced, $D_{Sto1} = \sum_{r=1}^{2} D_{Sto1,r} = 110ms$, $D_{Sto2} = \sum_{r=1}^{2} D_{Sto2,r} = 110ms$, while the load of the third server is much smaller, 64s. We want to assess the effect of alleviating the bottlenecks, balancing the load of the three storage servers. Thus, we assume that it is possible to move data across them, more precisely from `Storage1` and `Storage2` to `Storage3`, in order to have their total service demands similar. This is possible since shifting some data from one resource to another may alter the time that a request takes to access it, e.g., due to use of different hardware technologies (flash memories, larger caches, different disk drives, etc). Let us remark that the global service demand to all the three servers must remain the same as the one of the original workload, namely $D = 284ms$. Fig. 9 shows the new service demands.

Fig. 10 shows the convex hull of the optimized system. Since the load of the three storage servers is balanced, the points corresponding to their service demands lie on the same edge of the convex hull. This configuration denotes perfect balancing since the load equally loads all resources and no server is underutilized.

Fig. 11 shows the utilization of the three storage servers. By comparing their behavior with the ones obtained by the original system (see Fig. 7) it is evident that their values are maximized. The point in which the utilizations of the three storage servers are equal, i.e., the *equiutilization* point, lies inside the common saturation sector [10]. The corresponding load, consisting of the fraction $\beta_1 = 0.48$ of *class 1* requests, represents the optimal operating point since it maximizes the sum of the utilizations and thus the system throughput. The maximum throughput of the original system with the mix $\beta_1 = 0.48$ was $X_{max\ Orig} = 0.0181 req/ms$ while the one obtained after the balancing action (see Fig. 12) is $X_{max\ Bal} = 0.0209 req/ms$, with an improvement of about 15%. The minimum system response times corresponding to the same mix were $R_{min\ Orig} = 5.5s$ and $R_{min\ Bal} = 4.78s$ with a reduction of about 13%. The behavior of the residence times of the three storage servers is shown in Fig. 13. The residence time of `StorageServer3`, the lower one in the graph, clearly emphasizes the set of mixes, close to $\beta_1 = 0.48$, that utilize all the three servers similarly.

Summarizing, the above case study shows that the combined application of tools such as JABA and JMVA may help gaining qualitative understanding on the best configuration decisions for a system. Indeed, due to the open source nature of JMT, it would be possible to automize the above methodology by reusing in an external application the Java library functions offered by JABA and JMVA to estimate asymptotic performance, systems bottlenecks, and performance measures for finite population sizes.

3. CONCLUSIONS

In this paper, we have illustrated the application of JMT to a basic QoS optimization problem. The study aimed at the bottleneck identification, performance evaluation and optimization of an enterprise system and proves the simplicity of studying a system's performance in a graphical way by means of JMT. Further examples and case studies are provided in the bibliography section of the JMT websites at `http://jmt.sourceforge.net`.

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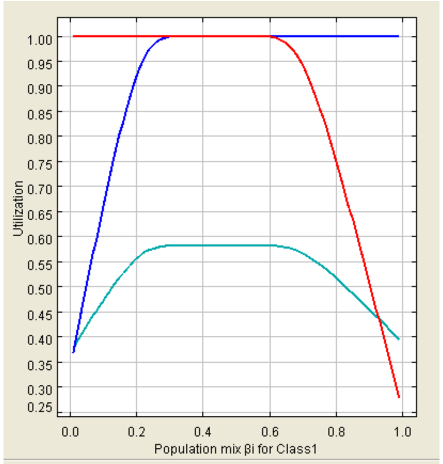

Figure 7: *Utilization* of the three storage servers (red curve for Storage 1, blue curve for Storage 2, and light blue curve for Storage 3) as a function of the mix of requests in execution.

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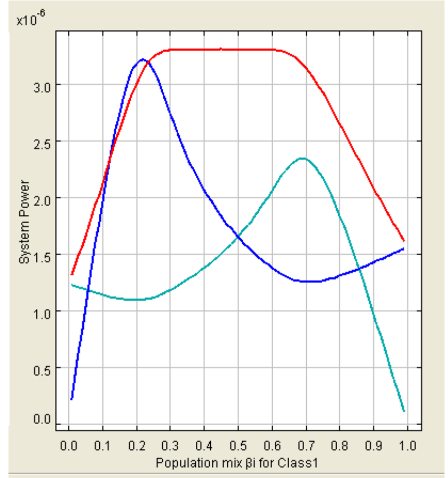

Figure 8: Behavior of the *Power* (the ratio of X to R) at the system level (red curve) and per-class (blue curve for class 1 and light blue for class 2).

*	Class1	Class2
Storage1	20.500000	74.000000
Storage2	70.000000	25.000000
Storage3	41.000000	53.500000
ApplServer1	14.000000	20.000000
ApplServer2	23.000000	14.000000
WebServer	12.000000	7.000000

Figure 9: Service demands of the optimized system

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Figure 10: Identification of the bottlenecks in the optimized system. The load of the three Storage Servers is balanced.

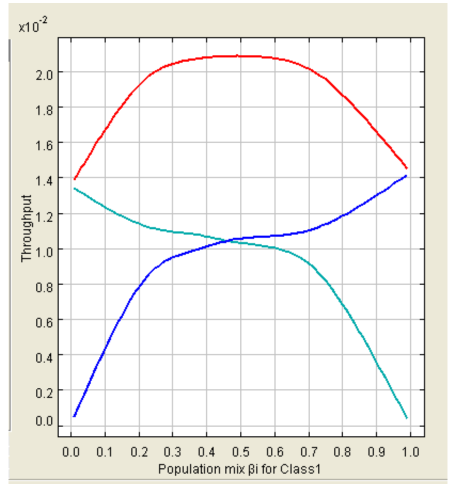

Figure 12: *Throughput* behavior of the optimized system (red curve for system throughput, blue curve for class 1 and light blue for class 2).

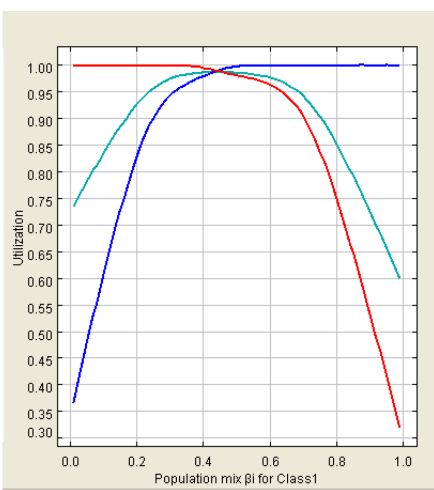

Figure 11: *Utilization* of the storage servers (red curve for Storage 1, blue curve for Storage 2, and light blue curve for Storage 3) with the balanced load

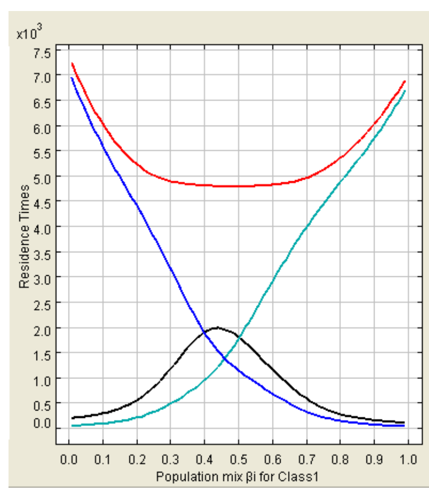

Figure 13: *Response time* of the system (red curve) and residence times of the three storage servers (light blue curve for Storage 1, blue curve for Storage 2, and black curve for Storage 3).