QPME 2.0 - A Tool for Stochastic Modeling and Analysis using Queueing Petri Nets

Samuel Kounev, Simon Spinner and Philipp Meier

Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
kounev@kit.edu, simon.spinner@gmail.com

Abstract Queueing Petri nets are a powerful formalism that can be exploited for modeling distributed systems and analyzing their performance and scalability. By combining the modeling power and expressiveness of queueing networks and stochastic Petri nets, queueing Petri nets provide a number of advantages. In this paper, we present Version 2.0 of our tool QPME (Queueing Petri net Modeling Environment) for modeling and analysis of systems using queueing Petri nets. The development of the tool was initiated by Samuel Kounev in 2003 at the Technische Universität Darmstadt in the group of Prof. Alejandro Buchmann. Since then the tool has been distributed to more than 100 organizations worldwide. QPME provides an Eclipse-based editor for building queueing Petri net models and a powerful simulation engine for analyzing the models. After presenting the tool, we discuss ongoing work on the QPME project and the planned future enhancements of the tool.

1 Introduction

QPME (Queueing Petri net Modeling Environment) [20] is a modeling and analysis tool based on the Queueing Petri Net (QPN) modeling formalism. The tool is developed and maintained by the Descartes Research Group [7] at Karlsruhe Institute of Technology (KIT). Introduced in 1993 by Falko Bause [1], the QPN formalism has a number of advantages over conventional modeling formalisms such as queueing networks and stochastic Petri nets. By combining the modeling power and expressiveness of queueing networks and stochastic Petri nets, QPNs enable the integration of hardware and software aspects of system behavior into the same model. In addition to hardware contention and scheduling strategies, QPNs make it easy to model simultaneous resource possession, synchronization, asynchronous processing and software contention. These aspects have significant impact on the performance of modern enterprise systems.

Another advantage of QPNs is that they can be used to combine qualitative and quantitative system analysis. A number of efficient techniques from Petri net theory can be exploited to verify some important qualitative properties of QPNs. The latter not only help to gain insight into the behavior of the system, but are also essential preconditions for a successful quantitative analysis [3]. Last but not least, QPN models have an intuitive graphical representation that facilitates model development. In [11], we showed how QPNs can be used for modeling

distributed e-business applications. Building on this work, we have developed a methodology for performance modeling of distributed component-based systems using QPNs [9]. The methodology has been applied to model a number of systems ranging from simple systems to systems of realistic size and complexity. It can be used as a powerful tool for performance and scalability analysis. Some examples of modeling studies based on QPNs can be found in [14, 15, 18, 21]. These studies consider different types of systems including distributed component-based systems, event-based systems and Grid computing environments.

In this paper, we present QPME 2.0 (Queueing Petri net Modeling Environment) - a tool for stochastic modeling and analysis of systems using queueing Petri nets. The paper is an updated and extended version of [13] where we presented version 1.0 of the tool. QPME is made of two major components, a QPN Editor (QPE) and a Simulator for QPNs (SimQPN). In this paper, we present an overview of these components. Further details on their internal architecture and implementation can be found in [8, 10, 12, 24]. QPME is available free-of-charge for non-profit use (see [7]) and has been distributed to more than 100 universities and research organizations worldwide. The current license is closed-source, however, there are plans to make the tool open-source in the near future.

The most important new features introduced in Version 2.0 of the tool are the following:

- Central queue management and support for having multiple queueing places that share the same underlying physical queue.
- Advanced query engine for processing and visualization of simulation results.
- Support for simulating hierarchical QPNs using SimQPN.
- Support for defining probes that specify metrics of interest for which data should be collected.
- Support for two additional simulation output data analysis techniques: spectral analysis and standardized time series.
- Support for empirical and deterministic distributions.
- Improved performance and scalability of the simulation engine (SimQPN).
- Automatic detection of infinitely growing queues (model instability).
- A number of features improving user friendliness (e.g., simulation progress bar and "stop simulation" button).

The rest of this paper is organized as follows: We start with a brief introduction to QPNs in Section 2. Sections 3 and 4 provide an overview of the QPN editor and the simulation engine, respectively. Section 5 presents the framework for processing and visualization of the simulation results. Finally, Section 6 summarizes the ongoing and future work on QPME and the paper is wrapped up with some concluding remarks in Section 7.

2 Queueing Petri Nets

The main idea behind the QPN formalism was to add queueing and timing aspects to the places of Colored Generalized Stochastic Petri Nets (CGSPNs) [1].

This is done by allowing queues (service stations) to be integrated into places of CGSPNs. A place of a CGSPN that has an integrated queue is called a *queueing place* and consists of two components, the *queue* and a *depository* for tokens which have completed their service at the queue. The behavior of the net is as follows: tokens, when fired into a queueing place by any of its input transitions, are inserted into the queue according to the queue's scheduling strategy. Tokens in the queue are not available for output transitions of the place. After completion of its service, a token is immediately moved to the depository, where it becomes available for output transitions of the place. This type of queueing place is called *timed* queueing place. In addition to timed queueing places, QPNs also introduce *immediate* queueing places, which allow pure scheduling aspects to be described. Tokens in immediate queueing places can be viewed as being served immediately. Scheduling in such places has priority over scheduling/service in timed queueing places and firing of timed transitions. The rest of the net behaves like a normal CGSPN. A formal definition of a QPN follows [1]:

Definition 1. *A QPN is an 8-tuple* $QPN = (P, T, C, I^-, I^+, M_0, Q, W)$ *where:*

1. $P = \{p_1, p_2, ..., p_n\}$ *is a finite and non-empty set of* places,
2. $T = \{t_1, t_2, ..., t_m\}$ *is a finite and non-empty set of* transitions, $P \cap T = \emptyset$,
3. C *is a* color function *that assigns a finite and non-empty set of* colors *to each place and a finite and non-empty set of* modes *to each transition.*
4. I^- *and* I^+ *are the backward and forward* incidence functions *defined on* $P \times T$*, such that* $I^-(p,t), I^+(p,t) \in [C(t) \to C(p)_{MS}]$, $\forall (p,t) \in P \times T$[1]
5. M_0 *is a function defined on* P *describing the* initial marking *such that* $M_0(p) \in C(p)_{MS}$.
6. $Q = (\tilde{Q_1}, \tilde{Q_2}, (q_1, ..., q_{|P|}))$ *where*
   - $\tilde{Q_1} \subseteq P$ *is the set of timed queueing places,*
   - $\tilde{Q_2} \subseteq P$ *is the set of immediate queueing places,* $\tilde{Q_1} \cap \tilde{Q_2} = \emptyset$ *and*
   - q_i *denotes the description of a queue*[2] *taking all colors of* $C(p_i)$ *into consideration, if* p_i *is a queueing place or equals the keyword 'null', if* p_i *is an ordinary place.*
7. $W = (\tilde{W_1}, \tilde{W_2}, (w_1, ..., w_{|T|}))$ *where*
   - $\tilde{W_1} \subseteq T$ *is the set of timed transitions,*
   - $\tilde{W_2} \subseteq T$ *is the set of immediate transitions,* $\tilde{W_1} \cap \tilde{W_2} = \emptyset$, $\tilde{W_1} \cup \tilde{W_2} = T$ *and*

[1] The subscript MS denotes multisets. $C(p)_{MS}$ denotes the set of all finite multisets of $C(p)$.

[2] In the most general definition of QPNs, queues are defined in a very generic way allowing the specification of arbitrarily complex scheduling strategies taking into account the state of both the queue and the depository of the queueing place [1]. In QPME, we use conventional queues as defined in queueing network theory.

– $w_i \in [C(t_i) \longmapsto \mathbb{R}^+]$ *such that* $\forall c \in C(t_i)$:
$w_i(c) \in \mathbb{R}^+$ *is interpreted as a rate of a negative exponential distribution specifying the firing delay due to color c, if* $t_i \in \tilde{W}_1$ *or a firing weight specifying the relative firing frequency due to color c, if* $t_i \in \tilde{W}_2$.

For a more detailed introduction to the QPN modeling formalism, the reader is referred to [1, 3]. To illustrate the above definition, we present an example QPN model of a simple Java EE system. The model was taken from [11] and is shown in Figure 1.

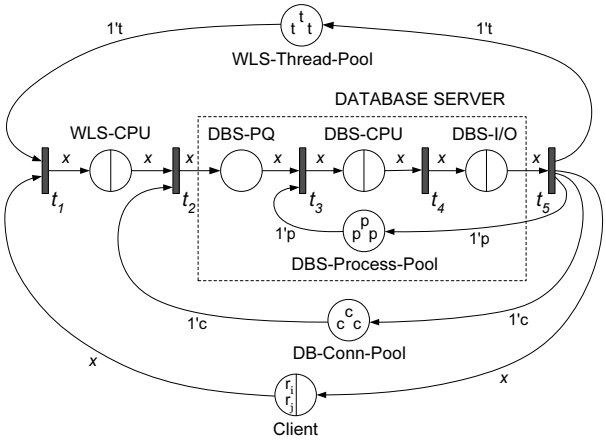


Figure 1. QPN Model of a Java EE System [11]

The system modeled is an e-business application running in a Java EE environment consisting of a WebLogic Server (Java EE application server) hosting the application components and a backend database server used for persisting business data. In the following, we describe the places of the model:

`Client` Queueing place with IS scheduling strategy used to represent clients sending requests to the system. Time spent at the queue of this place corresponds to the client think time, i.e., the service time of the queue is equal to the average client think time.

`WLS-CPU` Queueing place with PS scheduling strategy used to represent the CPU of the *WebLogic Server (WLS)*.

`DBS-CPU` Queueing place with PS scheduling strategy used to represent the CPU of the *database server (DBS)*.

`DBS-I/O` Queueing place with FCFS scheduling strategy used to represent the disk subsystem of the DBS.

`WLS-Thread-Pool` Ordinary place used to represent the thread pool of the WLS. Each token in this place represents a WLS thread.

`DB-Conn-Pool` Ordinary place used to represent the database connection pool of the WLS. Tokens in this place represent database connections to the DBS.

`DBS-Process-Pool` Ordinary place used to represent the process pool of the DBS. Tokens in this place represent database processes.

`DBS-PQ` Ordinary place used to hold incoming requests at the DBS while they wait for a server process to be allocated to them.

The following types of tokens (token colors) are used in the model:

Token 'r_i' represents a request sent by a client for execution of a transaction of class i. For each request class a separate token color is used (e.g., 'r_1', 'r_2', 'r_3',...). Tokens of these colors can be contained only in places `Client`, `WLS-CPU`, `DBS-PQ`, `DBS-CPU` and `DBS-I/O`.

Token 't' represents a WLS thread. Tokens of this color can be contained only in place `WLS-Thread-Pool`.

Token 'p' represents a DBS process. Tokens of this color can be contained only in place `DBS-Process-Pool`.

Token 'c' represents a database connection to the DBS. Tokens of this color can be contained only in place `DB-Conn-Pool`.

We now take a look at the life-cycle of a client request in our system model. Every request (modeled by a token of color 'r_i' for some i) is initially at the queue of place `Client` where it waits for a user-specified think time. After the think time elapses, the request moves to the `Client` depository where it waits for a WLS thread to be allocated to it before its processing can begin. Once a thread is allocated (modeled by taking a token of color 't' from place `WLS-Thread-Pool`), the request moves to the queue of place `WLS-CPU`, where it receives service from the CPU of the WLS. It then moves to the depository of the place and waits for a database connection to be allocated to it. The database connection (modeled by token 'c') is used to connect to the database and make any updates required by the respective transaction. A request sent to the database server arrives at place `DBS-PQ` (DBS Process Queue) where it waits for a server process (modeled by token 'p') to be allocated to it. Once this is done, the request receives service first at the CPU and then at the disk subsystem of the database server. This completes the processing of the request, which is then sent back to place `Client` releasing the held DBS process, database connection and WLS thread.

3 QPE - Queueing Petri net Editor

QPE (Queueing Petri net Editor), the first major component of QPME, provides a graphical tool for building QPN models [8]. It offers a user-friendly interface enabling the user to quickly and easily construct QPN models. QPE is based on the Eclipse Rich Content Platform (RCP) and the Graphical Editing Framework (GEF) [23]. The latter is an open source framework dedicated to providing a rich, consistent graphical editing environment for applications on the Eclipse platform. As a GEF application, QPE is written in pure Java and runs as a standalone RCP application on all operating systems officially supported by the Eclipse platform. This includes Windows, Linux, Solaris, HP-UX, IBM AIX and

Apple Mac OS among others, making QPE widely accessible. The only thing required is a Java Runtime Environment (JRE) 6.0. It is recommended to run QPE on Windows since this is the platform it has been tested on.

Being a GEF application, QPE is based on the model-view-controller (MVC) architecture. The model in our case is the QPN being defined, the views provide graphical representations of the QPN, and finally the controller connects the model with the views, managing the interactions among them. QPN models created with QPE can be stored on disk as XML documents. QPE uses its own XML schema based on the Petri Net Markup Language (PNML) [4] with some changes and extensions to support the additional constructs available in QPN models. Figure 2 shows the QPE main window which is comprised of four views: Main Editor View, Outline View, Properties View and Console View. The Main Editor View contains a Net Editor, Palette and Color Editor. The Net Editor displays the graphical representation of the currently edited QPN, the Palette displays the set of QPN elements that are used to build QPN models and the Color Editor, shown in Figure 3, is used to define the token colors available for use in the places of the QPN. The Properties View enables the user to edit the properties of the currently selected element in the Net Editor. Finally, the Console View is used to display output from QPE extensions and plug-ins.

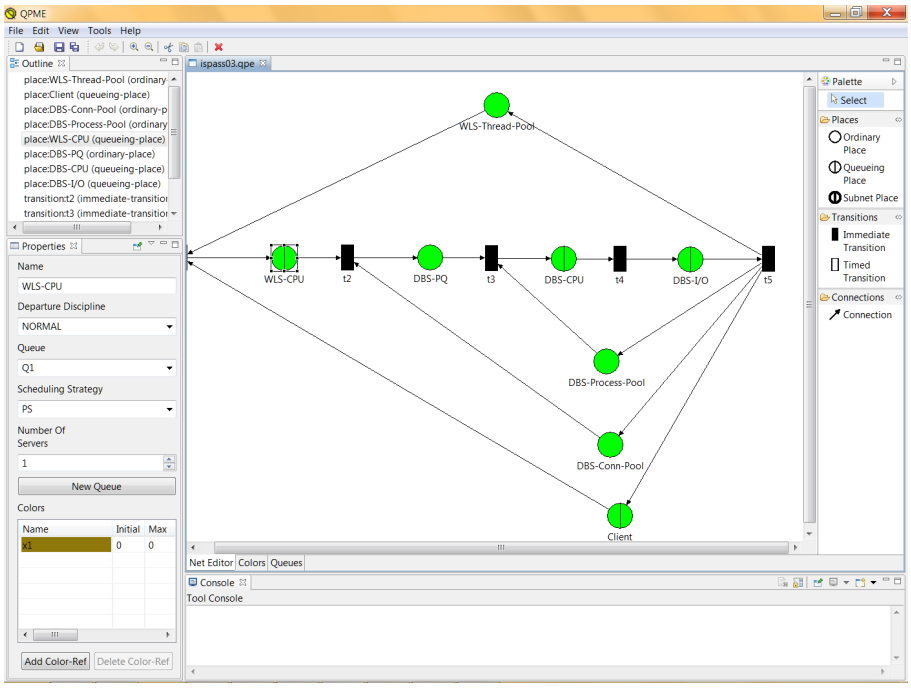


Figure 2. QPE Main Window

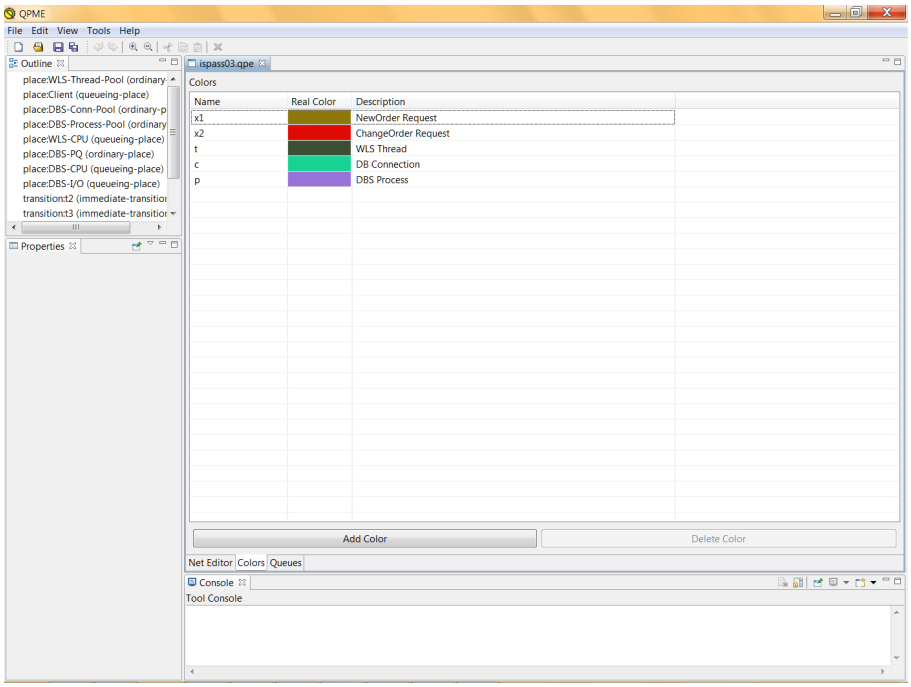


Figure 3. QPE Color Editor

A characterizing feature of QPE is that it allows token colors to be defined globally for the whole QPN instead of on a per place basis. This feature was motivated by the fact that in QPNs typically the same token color (type) is used in multiple places. Instead of having to define the color multiple times, the user can define it one time and then reference it in all places where it is used. This saves time, makes the model definition more compact, and last but not least, it makes the modeling process less error-prone since references to the same token color are specified explicitly.

Another characterizing feature of QPE, not supported in standard QPN models [21], is the ability to have multiple queueing places configured to share the same underlying physical queue[3]. In QPE, queues are defined centrally (similar to token colors) and once defined they can be referenced from inside multiple queueing places. This allows to use queueing places to represent software entities, e.g., software components, which can then be mapped to different hardware resources modeled as queues [21]. This feature of QPE, combined with the support for hierarchical QPNs, allows to build multi-layered models of software architectures similar to the way this is done in layered queueing networks, however,

[3] While the same effect can be achieved by using multiple subnet places mapped to a nested QPN containing a single queueing place, this would require expanding tokens that enter the nested QPN with a *tag* to keep track of their origin as explained in [2].

with the advantage that QPNs enjoy all the benefits of Petri nets for modeling synchronization aspects.

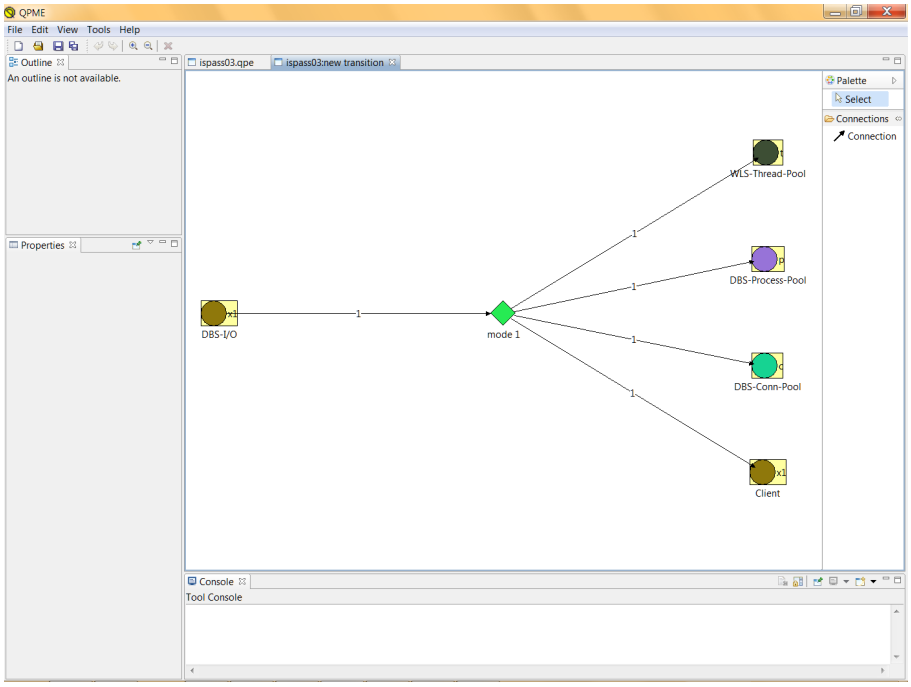


Figure 4. QPE Incidence Function Editor

Figure 4 shows the Incidence Function Editor. The incidence function specifies the behavior of the transition for each of its firing modes in terms of tokens destroyed and/or created in the places of the QPN. Once opened the Incidence Function Editor displays the transition input places on the left, the transition modes in the middle and the transition output places on the right. Each place (input or output) is displayed as a rectangle containing a separate circle for each token color allowed in the place. The user can create connections from token colors of input places to modes or from modes to token colors of output places. If a connection is created between a token color of a place and a mode, this means that when the transition fires in this mode, tokens of the respective color are removed from the place. Similarly, if a connection is created between a mode and a token color of an output place, this means that when the transition fires in this mode, tokens of the respective color are deposited in the place. Each connection can be assigned a weight interpreted as the number of tokens removed/deposited in the place when the transition fires in the respective mode.

Further details on the implementation of QPE can be found in [8, 24].

4 SimQPN - Simulator for Queueing Petri Nets

The second major component of QPME is SimQPN - a discrete-event simulation engine specialized for QPNs. It is very light-weight and has been implemented 100% in Java to ensure portability and platform-independence. SimQPN can be run either as Eclipse plugin in QPE or as a standalone Java application. Thus, even though QPE is limited to Eclipse-supported platforms, SimQPN can be run on any platform on which Java SE 5.0 is available. This makes it possible to design a model on one platform (e.g., Windows) using QPE and then analyze it on another platform (e.g., Linux) using SimQPN. SimQPN configuration parameters are stored as metadata inside the XML file containing the QPN model.

SimQPN simulates QPNs using a sequential algorithm based on the event-scheduling approach for simulation modeling. Being specialized for QPNs, it simulates QPN models directly and has been designed to exploit the knowledge of the structure and behavior of QPNs to improve the efficiency of the simulation. Therefore, SimQPN provides much better performance than a general purpose simulator would provide, both in terms of the speed of simulation and the quality of output data provided.

SimQPN currently supports most, but not all of the QPN features that are supported in QPE. The reason for not limiting QPE to only those features supported by SimQPN is that QPE is meant as a general purpose QPN editor and as such the QPN features it offers should not be limited to any particular analysis method. SimQPN currently supports three different scheduling strategies for queues inside queueing places: Processor-Sharing (PS), Infinite Server (IS) and First-Come-First-Served (FCFS). A wide range of service time distributions are supported including Beta, BreitWigner, ChiSquare, Gamma, Hyperbolic, Exponential, ExponentialPower, Logarithmic, Normal, StudentT, Uniform and VonMises as well as deterministic and empirical distributions. Empirical distributions are supported in the following way. The user is expected to provide a probability distribution function (PDF), specified as an array of positive real numbers (histogram) read from an external text file. A cumulative distribution function (CDF) is constructed from the PDF and inverted using a binary search for the nearest bin boundary and a linear interpolation within the bin (resulting in a constant density within each bin).

Timed transitions are currently not supported, however, in most cases a timed transition can be approximated by a serial network consisting of an immediate transition, a queueing place and a second immediate transition. The spectrum of scheduling strategies and service time distributions supported by SimQPN will be extended. Support for timed transitions and immediate queueing places is also planned and will be included in a future release.

4.1 Probes and Data Collection Modes

SimQPN offers the ability to configure what data exactly to collect during the simulation and what statistics to provide at the end of the run. This can be

specified on a per *location* basis where location is defined to have one of the following five types:

1. Ordinary place.
2. Queue of a queueing place (considered from the perspective of the place).
3. Depository of a queueing place.
4. Queue (considered from the perspective of all places it is part of).
5. Probe.

A probe is a tool to specify a region of interest for which data should be collected during simulation. The region of a probe includes one or more places and is defined by one start and one end place. The goal is to evaluate the time tokens spend in the region when moving between its begin and end place. The probe starts its measurements for each token entering its region at the start place and updates the statistics when the token leaves at the end place. It can be specified whether the measurements start when the token enters the start place or when the token leaves it. The same can be specified for the end place. Each probe references a subset of the colors defined in the QPN. A probe only collects data for tokens of the referenced colors.

Currently, probes allow to gather statistics for the residence time of a token in a region of interest. For example, in the model shown in Figure 1, a probe can be used to measure the time spent at the database server, which consists of places `DBS-PQ`, `DBS-CPU` and `DBS-I/O`. In this case, the probe starts at place `DBS-PQ` (on entry) and ends at place `DBS-I/O` (on exit). For each transaction of type i for which data should be collected, a reference to color 'r_i' is defined in the probe. As a result, the user is provided with the mean residence time of requests in the database server including the associated confidence interval and distribution.

The probes are realized by attaching timestamps to individual tokens. In the start place a probe adds the current simulation time as a timestamp to all tokens of colors it is interested in. A token can carry timestamps from different probes. Thus intersecting regions of several probes in a QPN are supported. Firing transitions collect all timestamps from input tokens and copy the timestamps to the output tokens. For each output token only the timestamps of probes interested in the token color are passed on. In some models, e.g. with a synchronous fork/join, it is possible that a transition gets tokens with different timestamps from the same probe. In this case, a warning is issued and only the minimal timestamp is passed on. The other timestamps are discarded. In the end place of a probe, its timestamp is removed and its statistics are updated.

For each location the user can choose between six modes of data collection (called `stats-levels`). The higher the mode, the more information is collected and the more statistics are provided. Since collecting data costs CPU time, the more data is collected, the slower the simulation would progress. Therefore, by configuring data collection modes, the user can speed up the simulation by making sure that no time is wasted collecting unnecessary data. The six data collection modes (stats-levels) are defined as follows:

Mode 0 In this mode no statistics are collected.

Mode 1 This mode considers only token throughput data, i.e., for each location the token arrival and departure rates are estimated for each color.

Mode 2 This mode adds token population, token occupancy and queue utilization data, i.e., for each location the following data is provided:
- Token occupancy (for locations of type 1 or 3): fraction of time in which there is a token inside the location.
- Queue utilization (for locations of type 2 or 4): proportion of the queue's server resources used by tokens arriving through the respective location.
- For each token color of the respective location:
  - Minimum/maximum number of tokens observed in the location.
  - Average number of tokens in the location.
  - Token color occupancy: fraction of time in which there is a token of the respective color inside the location.

Mode 3 This mode adds token residence time data, i.e., for each location the following additional data is provided on a per-color basis:
- Minimum/maximum observed token residence time.
- Mean and standard deviation of observed token residence times.
- Estimated steady state mean token residence time.
- Confidence interval (c.i.) for the steady state mean token residence time at a user-specified significance level.

Mode 4 This mode adds a histogram of observed token residence times.

Mode 5 This mode additionally dumps token residence times to a file for further analysis.

Since probes currently only support residence time statistics, mode 1 and 2 do not apply to them.

4.2 Steady State Analysis

SimQPN supports the following four methods for estimation of the steady state mean residence times of tokens inside the various locations of the QPN:

1. Method of independent replications (replication/deletion approach).
2. Method of non-overlapping batch means (NOMB).
3. Spectral analysis.
4. Standardized time series.

We refer the reader to [16, 19] for an introduction to these methods. All of them can be used to provide point and interval estimates of the steady state mean token residence time. Details on the way these methods were implemented in SimQPN can be found in [12]. For users that would like to use different methods for steady state analysis (for example ASAP [22]), SimQPN can be configured to output observed token residence times to files (mode 5), which can then be used as input to external analysis tools. SimQPN utilizes the *Colt* open source library for high performance scientific and technical computing in Java, developed at CERN [6]. In SimQPN, Colt is primarily used for random number generation

and, in particular, its implementation of the Mersenne Twister random number generator is employed [17].

We have validated the analysis algorithms implemented in SimQPN by subjecting them to a rigorous experimental analysis and evaluating the quality of point and interval estimates [12]. In particular, the variability of point estimates provided by SimQPN and the coverage of confidence intervals reported were quantified. A number of different models of realistic size and complexity were considered. Our analysis showed that data reported by SimQPN is very accurate and stable. Even for residence time, the metric with highest variation, the standard deviation of point estimates did not exceed 2.5% of the mean value. In all cases, the estimated coverage of confidence intervals was less than 2% below the nominal value (higher than 88% for 90% confidence intervals and higher than 93% for 95% confidence intervals). For FCFS queues, SimQPN also supports *indirect estimation* of the steady state token residence times according to the variance-reduction technique in [5].

SimQPN includes an implementation of the method of Welch for determining the length of the initial transient (warm-up period). We have followed the rules in [16] for choosing the number of replications, their length and the window size. SimQPN allows the user to configure the first two parameters and then automatically plots the moving averages for different window sizes. Simulation experiments with SimQPN usually comprise two stages: stage 1 during which the length of the initial transient is determined, and stage 2 during which the steady-state behavior of the system is simulated and analyzed. Again, if the user prefers to use another method for elimination of the initialization bias, this can be achieved by dumping collected data to files (mode 4) and feeding it into respective analysis tools.

4.3 Departure Disciplines

A novel feature of SimQPN is the introduction of the so-called *departure disciplines*. This is an extension of the QPN modeling formalism introduced to address a common drawback of QPN models (and of Petri nets in general), i.e., tokens inside ordinary places and depositories are not distinguished in terms of their order of arrival. Departure disciplines are defined for ordinary places or depositories and determine the order in which arriving tokens become available for output transitions. We define two departure disciplines, Normal (used by default) and First-In-First-Out (FIFO). The former implies that tokens become available for output transitions immediately upon arrival just like in conventional QPN models. The latter implies that tokens become available for output transitions in the order of their arrival, i.e., a token can leave the place/depository only after all tokens that have arrived before it have left, hence the term FIFO. For an example of how this feature can be exploited and the benefits it provides we refer the reader to [9]. An alternative approach to introduce token ordering in an ordinary place is to replace the place with an immediate queueing place containing a FCFS queue. The generalized queue definition from [1] can be exploited to define the scheduling strategy of the queue in such a way that tokens are served

immediately according to FCFS, but only if the depository is empty [3]. If there is a token in the depository, all tokens are blocked in their current position until the depository becomes free. However, the generalized queue definition from [1], while theoretically powerful, is impractical to implement, so, in practice, it is rarely used and queues in QPNs are usually treated as conventional queues from queueing network theory.

5 Processing and Visualization of Simulation Results

After a successful simulation run, SimQPN saves the results from the simulation in an XML file with a `.simqpn` extension which is stored in the configured output directory. In addition, a summary of the results in text format is printed on the console and stored in a separate file with a `.log` extension.

QPE provides an advanced query engine for processing and visualization of the simulation results. The query engine allows to define queries on the simulation results in order to filter, aggregate and visualize performance data for multiple places, queues and colors of the QPN. The results from the queries can be displayed in textual or graphical form. QPE provides two editors that can be used as a front-end to the query engine: "Simple Query Editor" and "Advanced Query Editor".

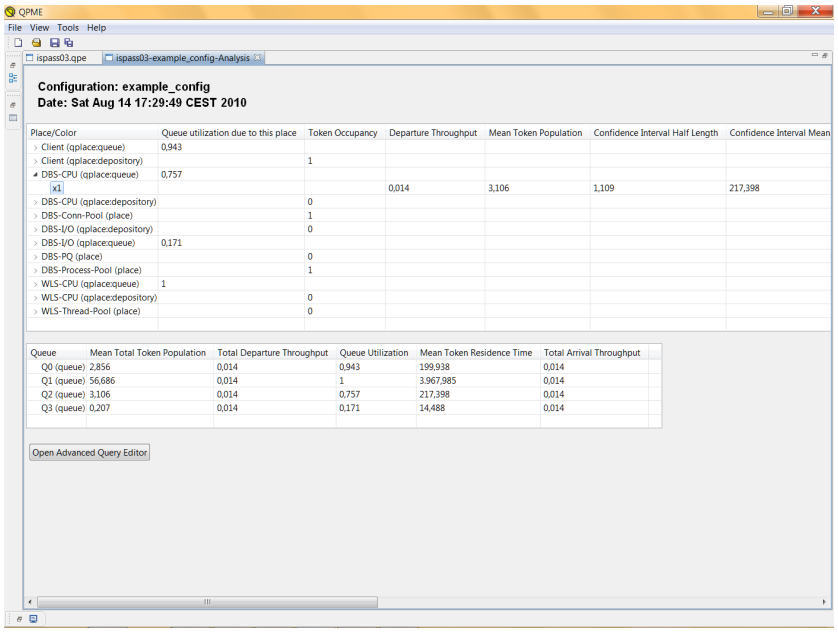


Figure 5. Basic Query Editor

5.1 Simple Query Editor

The "Simple Query Editor", shown in Figure 5, is displayed when opening the `.simqpn` file containing the results from the simulation. The editor displays the collected statistics for the various places and queues of the QPN. Statistics are reported on a per *location* basis where location is defined as in Sect. 4.1). The five location types are denoted as follows:

1. "place" - ordinary place.
2. "qplace:queue" - queue of a queueing place considered from the perspective of the place.
3. "qplace:depository" - depository of a queueing place.
4. "queue" - queue considered from the perspective of all places it is part of.
5. "probe".

The statistics for the various locations are presented in two tables. The first table contains the statistics for locations of type "place", "qplace:queue", "qplace:depository" and "probe", while the second one contains the statistics for locations of type "queue". Depending on the configured data collection modes (see Sect. 4.1), the set of available performance metrics for the various locations may vary.

By clicking on multiple locations while holding "Ctrl", the user can select a set of locations and respective token colors. A right click on a selection opens the context menu (see Figure 6) in which the user can choose which metric should be visualized for the selected set of locations and token colors. After choosing a metric, the user can select the form in which the results should be presented. Currently, three options are available: "Pie Chart", "Bar Chart" and "Console Output". Figure 7 shows an example of a pie chart and bar chart for the metric mean token residence time.

The "Simple Query Editor" is intended for simple filtering and visualization of the simulation results and does not provide any means to aggregate metrics over multiple locations and token colors. Queries involving aggregation are supported by the "Advanced Query Editor".

5.2 Advanced Query Editor

The "Advanced Query Editor" is opened by clicking on the respective button at the bottom of the "Simple Query Editor". Using this editor the user can define complex queries on the simulation results involving both filtering and aggregation of performance metrics from multiple places, probes and queues of the QPN. An example of such a query is shown in Figure 8.

A query is defined by first selecting a set of locations and a set of colors using the combo boxes and the +/- buttons at the top of the editor. The selected locations and colors specify a filter on the data that should be considered as part of the query. Using the table at the bottom of the editor, the user can select the specific performance metrics of interest and how data should be aggregated with respect to the considered locations and colors. Three options for aggregating data are available:

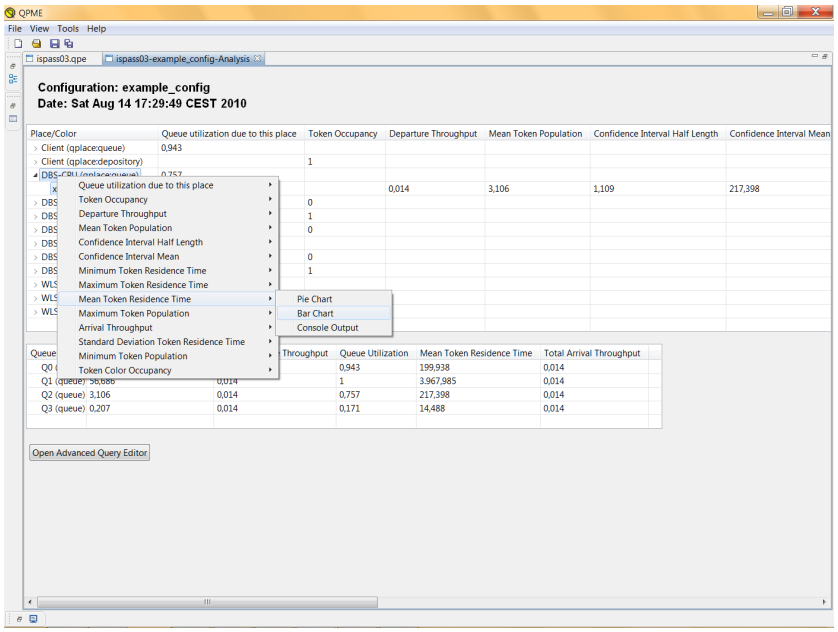
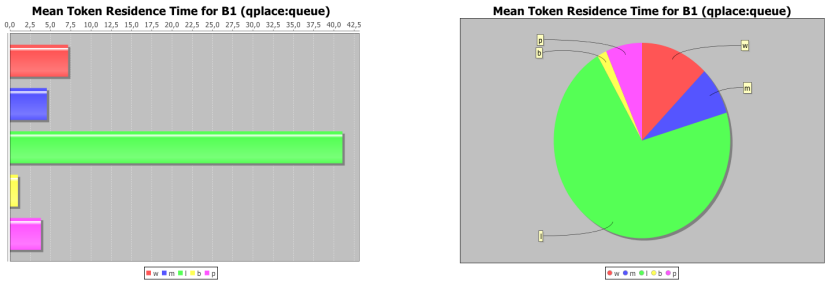


Figure 6. Context Menu in Basic Query Editor



(a) Bar Chart (b) Pie Chart

Figure 7. Example Diagrams

- "For each" - no aggregation is applied and performance metrics are considered separately for each location/color.
- "Average" - the average over the selected locations/colors is computed.
- "Sum" - the sum over the selected locations/colors is computed.

Two "Aggregation" fields are available, the left one is applied to the set of locations, while the right one is applied to the set of colors. Similarly, two "Visualization" fields are available, one applied to the set of locations, the other

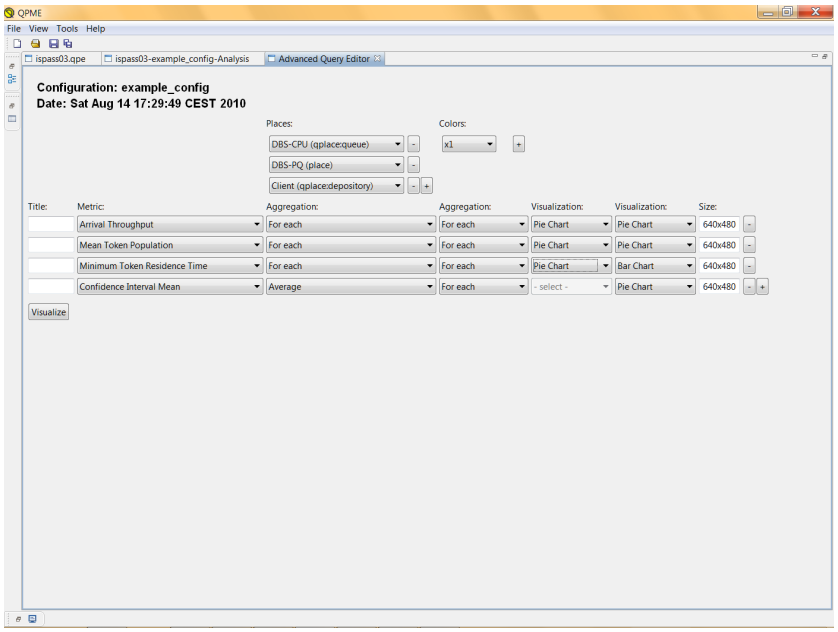


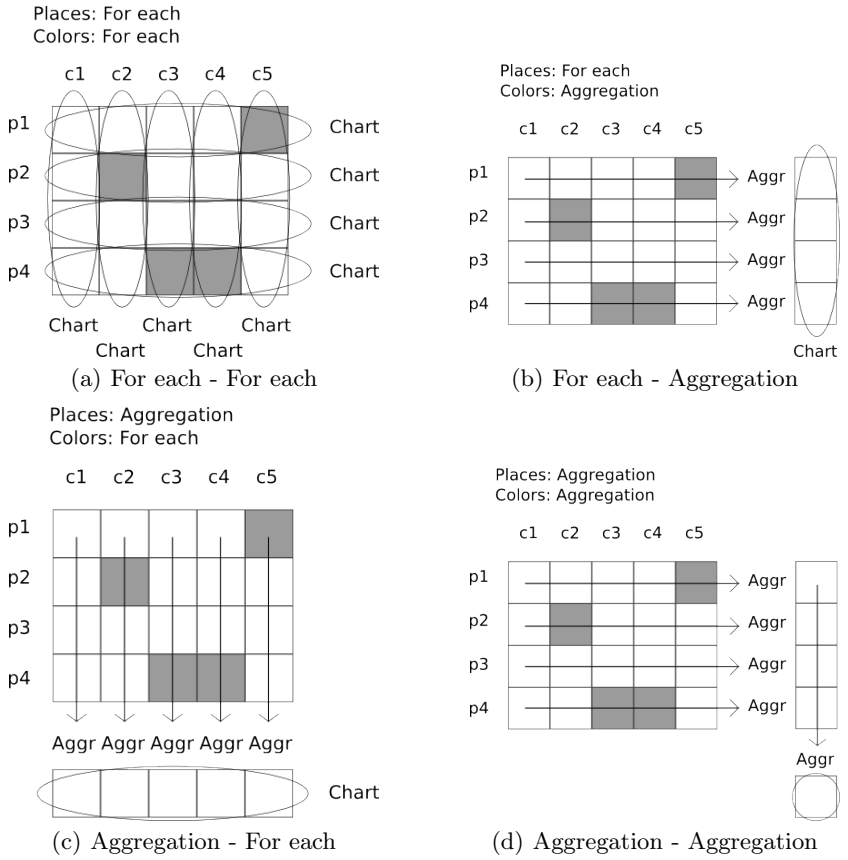
Figure 8. Advanced Query Editor

one to the set of colors. QPE currently offers three visualization options: "Bar Chart", "Pie Chart" and "Console Output".

Depending on the selected aggregation options, there are four possible scenarios: a) no aggregation, b) aggregation over colors, c) aggregation over locations, d) aggregation over both colors and locations. The four scenarios are depicted in Figure 9 illustrating how performance metrics are aggregated and used to produce a set of charts capturing the results from the respective query. Assuming that the user has selected a set of locations $p_1, p_2, ..., p_m$ and a set of colors $c_1, c_2, ..., c_n$, a matrix is generated that contains the values of the selected performance metric for each combination of location and color. Some of the cells of the matrix could be empty (denoted in grey in Figure 9). This could happen if the metric is not available in the configured data collection mode or if the considered color is not defined for the respective location. The number of charts generated depends on the selected aggregation options. In case no aggregation is selected, $m + n$ charts are generated. In the case of aggregation over the set of colors or locations, one chart is generated. Finally, in the case of aggregation over both colors and locations, the result of the query is a single value.

6 Ongoing and Future Work

As part of our ongoing and future work on QPME, enhancements along three different dimensions are envisioned: i) user friendliness, ii) model expressiveness



(a) For each - For each (b) For each - Aggregation

(c) Aggregation - For each (d) Aggregation - Aggregation

Figure 9. Aggregation Scenarios

and iii) model analysis methods. In the following, we outline the major enhancements that have been planned.

Improve User Friendliness Support for the following features will be added:

- Introduce modeling templates (e.g., for modeling common types of resources and workloads) to facilitate model reuse.
- Introduce automated support for sensitivity analysis.

Improve Model Expressiveness Support for the following features will be added:

- Load-dependent service times (resource demands).
- Further scheduling strategies for queues, e.g., GPS, priority scheduling.
- Timed transitions.
- Transition priorities and inhibitor arcs.

Improve Model Analysis Methods Support for the following features will be added:

- Support for parallel/distributed simulation to take advantage of multi-core processors.
- Support for analytical model solution techniques (structured analysis techniques, product-form solution techniques, approximation techniques).
- Further methods for determining the length of the simulation warm-up period.

7 Summary

In this paper, we presented QPME 2.0, our tool for modeling and analysis using queueing Petri nets. QPME provides a user-friendly graphical interface enabling the user to quickly and easily construct QPN models. It offers a highly optimized simulation engine that can be used to analyze models of realistically-sized systems. In addition, being implemented in Java, QPME runs on all major platforms and is widely accessible. QPME provides a robust and powerful tool for performance analysis making it possible to exploit the modeling power and expressiveness of queueing Petri nets to their full potential. The tool is available free-of-charge for non-profit use and there are plans to make it open-source in the near future. Further information can be found at the QPME homepage [20].

8 Acknowledgements

This work was funded by the German Research Foundation (DFG) under grant No. KO 3445/6-1. We acknowledge the support of Frederik Zipp and Ana Aleksieva from KIT.

References

1. F. Bause. Queueing Petri Nets - A formalism for the combined qualitative and quantitative analysis of systems. In *Proc. of 5th Intl. Workshop on Petri Nets and Perf. Models, Toulouse, France, Oct. 19-22*, 1993.
2. F. Bause, P. Buchholz, and P. Kemper. Integrating Software and Hardware Performance Models Using Hierarchical Queueing Petri Nets. In *Proc. of the 9. ITG / GI - Fachtagung Messung, Modellierung und Bewertung von Rechen- und Kommunikationssystemen, Freiberg, Germany*, 1997.
3. F. Bause and F. Kritzinger. *Stochastic Petri Nets - An Introduction to the Theory.* Vieweg Verlag, 2002.
4. J. Billington, S. Christensen, K. van Hee, E. Kindler, O. Kummer, L. Petrucci, R. Post, C. Stehno, and M. Weber. The Petri Net Markup Language: Concepts, Technology, and Tools. In *Proc. of 24th Intl. Conf. on Application and Theory of Petri Nets, June 23-27, Eindhoven, Holland*, 2003.
5. J. Carson and A. Law. Conservation Equations and Variance Reduction in Queueing Simulations. *Operations Research*, 28, 1980.
6. CERN - European Organisation for Nuclear Research. The Colt Distribution - Open Source Libraries for High Performance Scientific and Technical Computing in Java, 2004. `http://dsd.lbl.gov/~hoschek/colt/`.

7. Descartes Research Group. http://www.descartes-research.net, August 2010.
8. C. Dutz. QPE - A Graphical Editor for Modeling using Queueing Petri Nets. Master thesis, Technische Universität Darmstadt, Apr. 2006.
9. S. Kounev. Performance Modeling and Evaluation of Distributed Component-Based Systems using Queueing Petri Nets. *IEEE Transactions on Software Engineering*, 32(7):486–502, July 2006.
10. S. Kounev. *QPME 2.0 User's Guide*. Descartes Research Group, Karlsruhe Institute of Technology (KIT), Aug. 2010.
11. S. Kounev and A. Buchmann. Performance Modelling of Distributed E-Business Applications using Queuing Petri Nets. In *Proc. of the 2003 IEEE Intl. Symposium on Performance Analysis of Systems and Software, Austin, USA, March 20-22*, 2003.
12. S. Kounev and A. Buchmann. SimQPN - a tool and methodology for analyzing queueing Petri net models by means of simulation. *Performance Evaluation*, 63(4-5):364–394, May 2006.
13. S. Kounev and C. Dutz. QPME - A Performance Modeling Tool Based on Queueing Petri Nets. *ACM SIGMETRICS Performance Evaluation Review (PER), Special Issue on Tools for Computer Performance Modeling and Reliability Analysis*, 36(4):46–51, Mar. 2009.
14. S. Kounev, R. Nou, and J. Torres. Autonomic QoS-Aware Resource Management in Grid Computing using Online Performance Models. In *Proc. of 2nd Intl. Conf. on Perf. Evaluation Methodologies and Tools - VALUETOOLS, Oct. 23-25, Nantes, France*, 2007.
15. S. Kounev, K. Sachs, J. Bacon, and A. Buchmann. A Methodology for Performance Modeling of Distributed Event-Based Systems. In *Proc. of 11th IEEE Intl. Symp. on Object/Comp./Service-oriented Real-time Distr. Computing (ISORC), Orlando, USA*, May 2008.
16. A. Law and D. W. Kelton. *Simulation Modeling and Analysis*. Mc Graw Hill Companies,˜Inc., third edition, 2000.
17. M. Matsumoto and T. Nishimura. Mersenne Twister: A 623-Dimensionally Equidistributed Uniform Pseudo-Random Number Generator. *ACM Trans. on Modeling and Comp. Simulation*, 8(1):3–30, 1998.
18. R. Nou, S. Kounev, F. Julia, and J. Torres. Autonomic QoS control in enterprise Grid environments using online simulation. *Journal of Systems and Software*, 82(3):486–502, Mar. 2009.
19. K. Pawlikowski. Steady-State Simulation of Queueing Processes: A Survey of Problems and Solutions. *ACM Computing Surveys*, 22(2):123–170, 1990.
20. QPME Homepage. http://descartes.ipd.kit.edu/projects/qpme/, August 2010.
21. K. Sachs. *Performance Modeling and Benchmarking of Event-based Systems*. PhD thesis, TU Darmstadt, 2010.
22. N. Steiger, E. Lada, J. Wilson, J. Joines, C. Alexopoulos, and D. Goldsman. ASAP3: a batch means procedure for steady-state simulation analysis. *ACM Transactions on Modeling and Computer Simulation*, 15(1):39–73, 2005.
23. The Eclipse Foundation. Graphical Editing Framework (GEF). `http://www.eclipse.org/gef/`, 2006.
24. F. Zipp. Study Thesis (in German): Filterung, Aggregation und Visualisierung von QPN-Analyseergebnissen. Descartes Research Group, Karlsruhe Institute of Technology (KIT), May 2009.