



#### Introduction to Queueing Petri Nets: Modeling Formalism, Tool Support and Case Studies

Samuel Kounev, Simon Spinner and Philipp Meier Tutorial presented at ICPE 2012, Boston, USA, April 22, 2012

#### DESCARTES RESEARCH GROUP INSTITUTE FOR PROGRAM STRUCTURES AND DATA ORGANIZATION, FACULTY OF INFORMATICS



#### **References: Foundations**



- Modeling Formalism and Modeling Methodology
  - F. Bause and F. Kritzinger. Stochastic Petri Nets An Introduction to the Theory. Vieweg Verlag, 2002.
  - F. Bause. Queueing Petri Nets A formalism for the combined qualitative and quantitative analysis of systems. In Proceedings of the 5th International Workshop on Petri Nets and Performance Models, Toulouse, France, October 19-22, pp. 14-23, Washington, DC, USA, 1993. IEEE Computer Society.
  - F. Bause, P. Buchholz, and P. Kemper. Hierarchically Combined Queueing Petri Nets. In Proceedings of the 11th International Conference on Analysis and Optimization of Systems, Discrete Event Systems, Sophie-Antipolis, France, number 199 in LNCI 199, pages 176-182, Heidelberg, Germany, June 1994. Springer.
  - 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.
  - S. Kounev. Performance Engineering of Distributed Component-Based Systems Benchmarking, Modeling and Performance Prediction, Ph.D. Thesis, Technische Universität Darmstadt, Germany, 2005. Shaker Verlag. Download as PDF from http://www.descartes-research.net
- Analytical and simulation-based solution techniques
  - F. Bause, Peter Buchholz. Queueing Petri Nets with Product Form Solution. Performance Evaluation, 32(4): 265-299 (1998). Implemented as part of the HiQPN-Tool from TU Dortmund: http://ls4-www.cs.tu-dortmund.de/QPN/
  - 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. Implemented as part of the Queueing Petri net Modeling Environment (QPME): http://qpme.sourceforge.net
- Model-to-Model Transformations / QPNs as Intermediate Abstraction
  - P. Meier, S. Kounev, and H. Koziolek. Automated Transformation of Palladio Component Models to Queueing Petri Nets. In In 19th IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS 2011), Singapore, July 25-27 2011.
  - S. Becker, S. Kounev, A. Koziolek, H. Koziolek, P. Meier. Quantitative Evaluation of Model-Driven Performance Analysis, Simulation, and Prototyping of Component-based Architectures. Under review, IEEE TSE, 2012.

*Note:* Most papers listed here can be downloaded from http://www.descartes-research.net

#### **References: Selected Case Studies**



#### Java EE Applications

- 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.
- S. Kounev and A. Buchmann. Performance Modeling of Distributed E-Business Applications using Queueing Petri Nets. In Proc. of the 2003 IEEE Intl. Symposium on Performance Analysis of Systems and Software (ISPASS 2003), Austin, USA, March 6-8, 2003, pages 143-155. Best-Paper-Award.

#### Enterprise Grid Environments

- R. Nou, S. Kounev, F. Julia and J. Torres. Autonomic QoS control in enterprise Grid environments using online simulation. In Elsevier Journal of Systems and Software, Vol. 82, No. 3, pp. 486-502, doi:10.1016/j.jss.2008.07.048, March 2009.
- S. Kounev, R. Nou and J. Torres. Autonomic QoS-Aware Resource Management in Grid Computing using Online Performance Models. In Proc. of the 2nd International Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS 2007), Nantes, France, October 23-25, 2007.
- R. Nou, S. Kounev and J. Torres. Building Online Performance Models of Grid Middleware with Fine-Grained Load-Balancing: A Globus Toolkit Case Study. In Proc. of the 4th European Performance Engineering Workshop (EPEW 2007), Springer LNCS 4748/2007, Berlin, Germany, September 27-28, 2007.

#### Enterprise Data Fabrics

S. Kounev, K. Bender, F. Brosig, N. Huber, and R. Okamoto. Automated Simulation-Based Capacity Planning for Enterprise Data Fabrics. In 4th Intl. ICST Conference on Simulation Tools and Techniques (SimuTools 2012), Barcelona, Spain, 2011. Best Paper Award.

#### Message-oriented Event-driven Systems

- K. Sachs, S. Kounev and A. Buchmann. Performance Modeling and Analysis of Message-oriented Event-driven Systems. In Journal of Software and Systems Modeling (SoSyM), Springer Verlag, ISSN 1619-1366, DOI: 10.1007/s10270-012-0228-1, February 2012.
- S. Kounev and K. Sachs. Benchmarking and Performance Modeling of Event-Based Systems. In "it Information Technology" Heft 5 / 2009, Oldenbourg Wissenschaftsverlag, Munich, Germany, September 2009.
- S. Kounev, K. Sachs, J. Bacon and A. Buchmann. A Methodology for Performance Modeling of Distributed Event-Based Systems. In Proceedings of the 11th IEEE International Symposium on Object/ Component/Service-oriented Real-time Distributed Computing (ISORC 2008), Orlando, Florida, USA, May 5-7, 2008.

#### **References: Tools & Further Resources**



- Queueing Petri net Modeling Environment (QPME): http://qpme.sourceforge.net
  - S. Spinner, S. Kounev and P. Meier. Stochastic Modeling and Analysis using QPME:Queueing Petri Net Modeling Environment v2.0. In Proceedings of the 33rd International Conference on Application and Theory of Petri Nets and Concurrency (Petri Nets 2012), Hamburg, Germany, June 25-29, 2012.
  - S. Kounev, S. Spinner, and P. Meier. QPME 2.0 A Tool for Stochastic Modeling and Analysis using Queueing Petri Nets. In K. Sachs, I. Petrov and P. Guerrero (Eds.) From Active Data Management to Event-Based Systems and More, Springer LNCS, Vol. 6462, ISBN: 978-3-642-17225-0, November 2010.
  - S. Kounev and C. Dutz. QPME A Performance Modeling Tool Based on Queueing Petri Nets. In ACM SIGMETRICS Performance Evaluation Review (PER), Special Issue on Tools for Computer Performance Modeling and Reliability Analysis, Vol. 36, No. 4, pp. 46-51, March 2009.
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#### HiQPN-Tool: http://ls4-www.cs.tu-dortmund.de/QPN/

- F. Bause, P. Kemper. QPN-Tool for Qualitative and Quantitative Analysis of Queueing Petri Nets. In Proceedings of 7th Intl. Conf. on Modelling Techniques and Tools for Computer Performance Evaluation, Vienna (Austria), May 3-6. 1994, pp. 321-334. Springer LNCS 794, ISBN 3-540-58021-2.
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- F. Bause, P. Buchholz, P. Kemper. QPN-Tool for the Specification and Analysis of Hierarchically Combined Queueing Petri Nets. In Proceedings of 8th GI/ITG Conference on Measuring, Modeling and Evaluating Computing and Communication Systems (MMB 1995), pp. 224-238, Heidelberg, Germany, September 20-22, 1995, Springer LNCS 977, ISBN 3-540-60300-X.

#### Further Resources

4

- QPNs at TU Dortmund: http://ls4-www.cs.tu-dortmund.de/QPN/
- QPNs at KIT:\_http://descartes.ipd.kit.edu/projects/qpme/
- QPN Bibliography: http://descartes.ipd.kit.edu/projects/qpme/qpn\_bibliography/

#### Roadmap



- Introduction to Petri Nets
- Extensions to ordinary Petri Nets
- Queueing Petri Nets (QPNs)
- Case Studies
- Tool support



#### **Recall: Queueing Networks QN**: Set of interconnected queues **Queue** = waiting area and servers Scheduling strategies(FCFS,PS,...) **p**<sub>1</sub> -DISK Arriving **p**<sub>2</sub> Single-class vs. multi-class Requests Waiting CPL Area **SERVICE STATION 2** Open, closed or mixed Servers Departing Requests SERVICE STATION 1

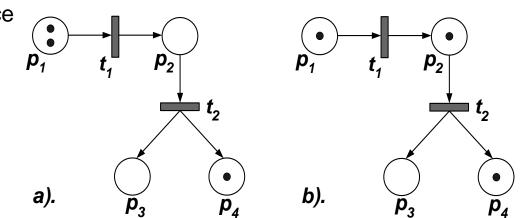
**PROS:** Very powerful for modelling **hardware contention** and scheduling strategies. Many efficient analysis techniques available.

**CONS:** Not as good for modelling software contention aspects such as blocking, synchronization and simultaneous resource possession. *Extended QNs* provide some limited support for the above, however, they are often restrictive and inaccurate.

# Petri Nets (PNs)



- Introduced in 1962 by Carl Adam Petri
- Ordinary Petri Net (Place-Transition Nets)
- Main concepts
  - Places
  - Tokens
  - Transitions
    - Input place, output place
    - Enabled transition
    - Transition firing
    - Firing weights
  - Incidence functions
  - Initial marking



An ordinary PN before and after firing transition t<sub>1</sub>.

### **Extensions to Petri Nets**



#### Colored PNs

- Entension introduced by Kurt Jensen
- Allow a type, i.e., a color, to be attached to a token
- Allow transitions to fire in different *modes (transition colors)*
- Stochastic PNs (SPNs)
  - Enabled transitions fire after a *firing delay* (exponential)
- Generalized Stochastic PNs (GSPNs)
  - Allow two types of transitions to be used: immediate and timed
- Colored Generalized Stochastic PNs (CGSPNs)
  - CPNs + GSPNs

### **CGSPNs: Pros and Cons**



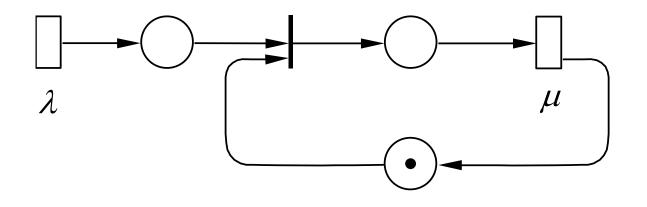
**PROS:** Suitable both for qualitative and quantitative analysis. Lend themselves very well to modelling blocking, synchronization, simultaneous resource possession and software contention.

**CONS:** No direct means for modelling scheduling strategies. Not as many algorithms/tools for efficient quantitative analysis are available as for Queueing Networks.

### **GSPN Models of Queueing Stations**



#### M/M/1-FCFS queue



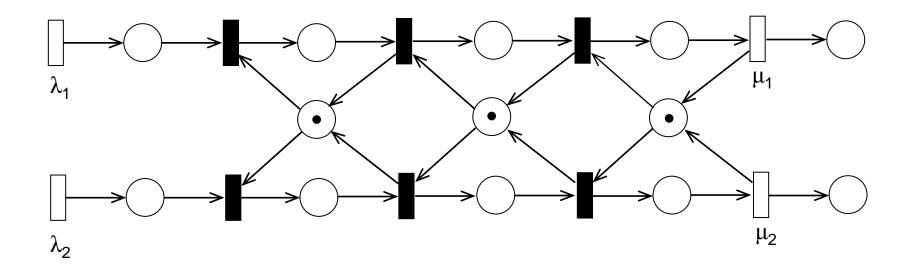
#### Assumptions

- Single token color (tokens undistinguishable)
- Exponentially-distributed service times

# **GSPN Models of Queueing Stations (2)**



Model of a M/M/1/3-FCFS queue with 2 token colors (have to encode the color of the token in each position of the queue):



- (4 + B + B\*NumColors) places needed for queue capacity B!
- For non-exponentially distributed firing delays or multiple servers, further places/transitions would be needed.

# **PS and IS Queues with Multiple Colors**

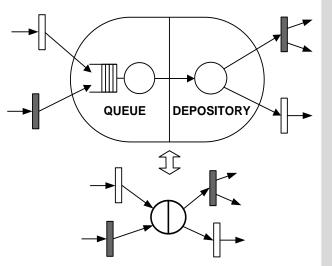


#### PS queues:

- Marking-dependent firing rates would be needed
- Problem: how to manage residual service times!
  - For queues with exponential service time distributions
  - For queues with general service time distributions
- IS queues:
  - Support for "IS server policy" would be needed

#### Queueing Petri Nets (QPNs = QNs + PNs)

- Introduced by Falko Bause in 1993.
- Combine queueing networks and Petri nets
- Allow integration of queues into places of PNs
- Ordinary vs. queueing places
- Queueing place = queue + depository



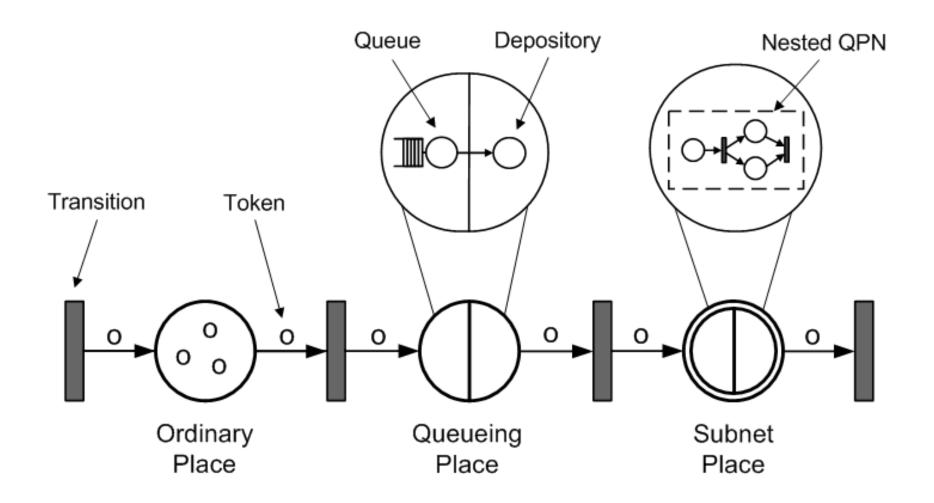
**PROS:** Combine the modelling power and expressiveness of QNs and PNs. Facilitate the modelling of both hardware and software aspects of system behavior in the same model.

**CONS:** Analysis suffers the **state space explosion** problem and this imposes a limit on the size of the models that are analyzable.



#### **Queueing Petri Nets**



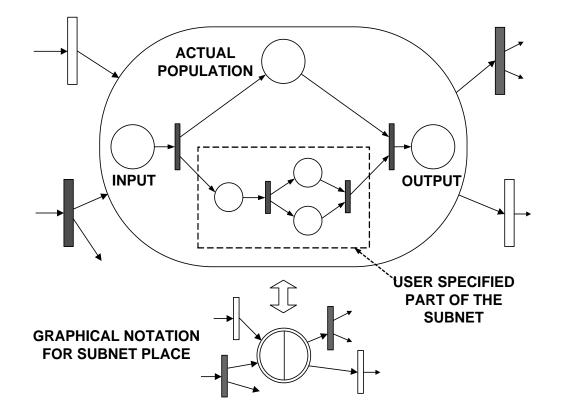


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#### **Hierarchical Queueing Petri Nets (HQPNs)**

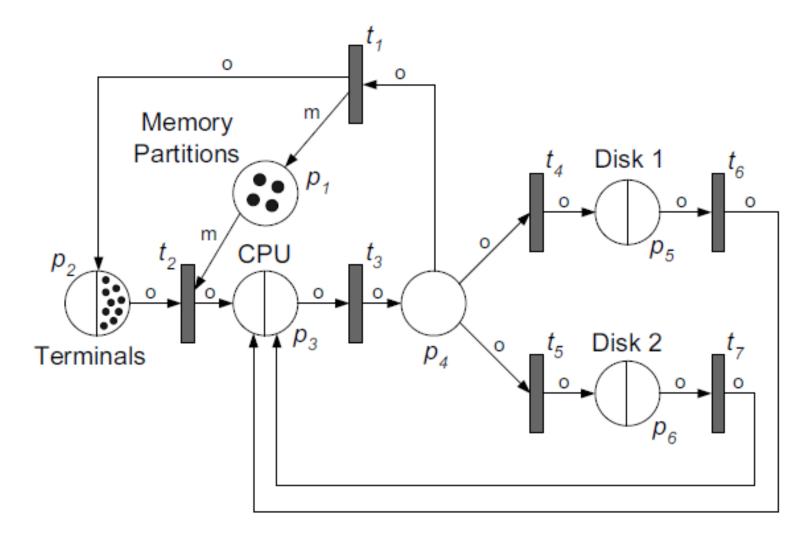


- Allow hierarchical model specification
- Subnet place: contains a nested QPN
- Structured analysis methods alleviate the state space explosion problem



#### **Example QPN**





### **Solution Techniques**



- Analytical solution techniques
  - Falko Bause, Peter Buchholz: Queueing Petri Nets with Product Form Solution. Performance Evaluation, 32(4): 265-299 (1998)
  - Implemented as part of the HiQPN-Tool from TU Dortmund: http://ls4-www.cs.tu-dortmund.de/QPN/
- Simulation-based techniques
  - SimQPN a tool and methodology for analyzing queueing Petri net models by means of simulation. Performance Evaluation, 63(4-5):364-394, May 2006.
  - Implemented as part of the Queueing Petri net Modeling Environment (QPME): http://qpme.sourceforge.net

## **Modeling Case Studies**



- Java EE applications
- Enterprise data fabrics
- Enterprise Grid environments
- Message-oriented systems
- Distributed event-based systems
- Component-based software architectures

## **Java EE Applications**



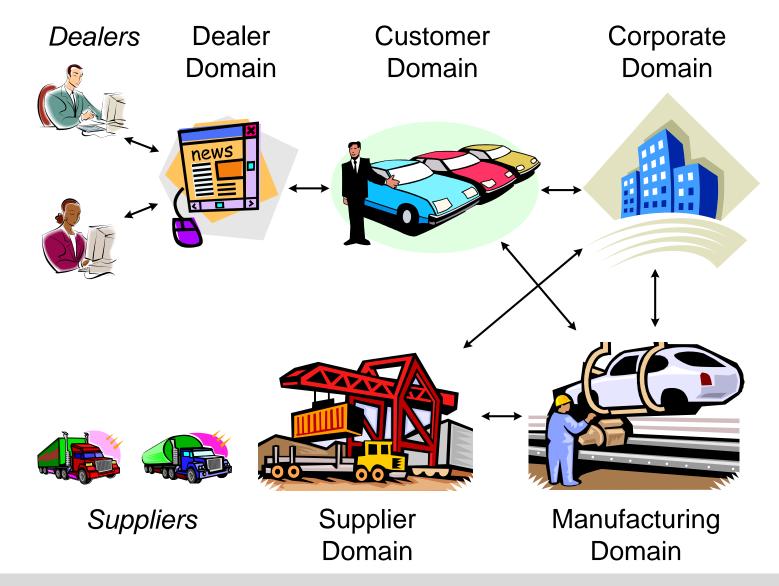
- Modeling methodology for distributed component systems
- Modeled SPECjAppServer2004 / SPECjEnterprise2010
- Extensive validation in a realistic environment
- Model accuracy for
  - throughput (+/- 5%)
  - utilization (+/- 10%)
  - response times (+/- 30%)

#### Further details in:

- 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.
- S. Kounev and A. Buchmann. Performance Modeling of Distributed E-Business Applications using Queueing Petri Nets. In Proceedings of the 2003 IEEE International Symposium on Performance Analysis of Systems and Software (ISPASS 2003), Austin, Texas, USA, March 6-8, 2003, pages 143-155, Washington, DC, USA, 2003. IEEE Computer Society. Best-Paper-Award.

## SPECjEnterprise2010 Business Model

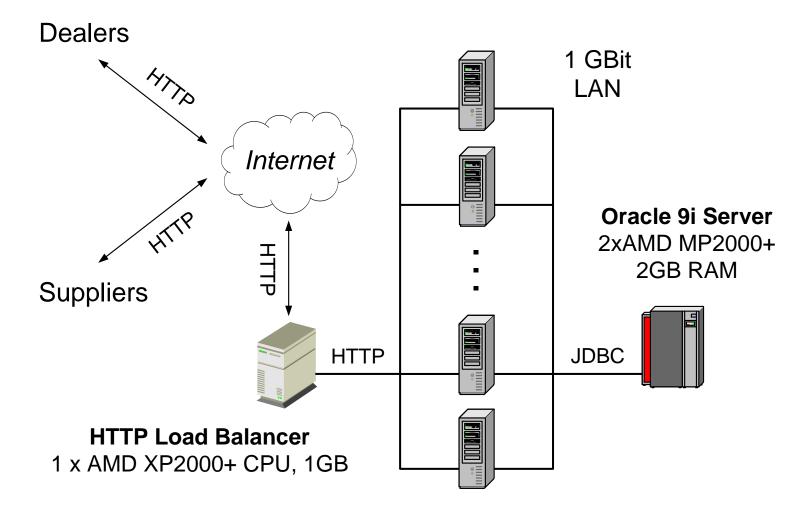




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# **Case Study - Deployment Environment**

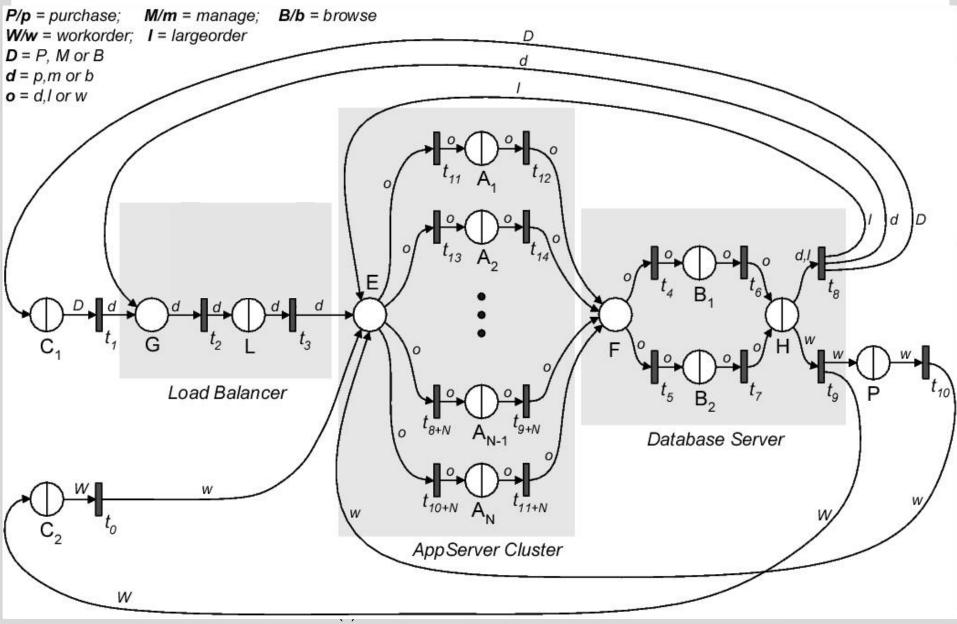




WebLogic 8.1 Cluster Each node with 1 x AMD XP2000+ CPU, 1GB

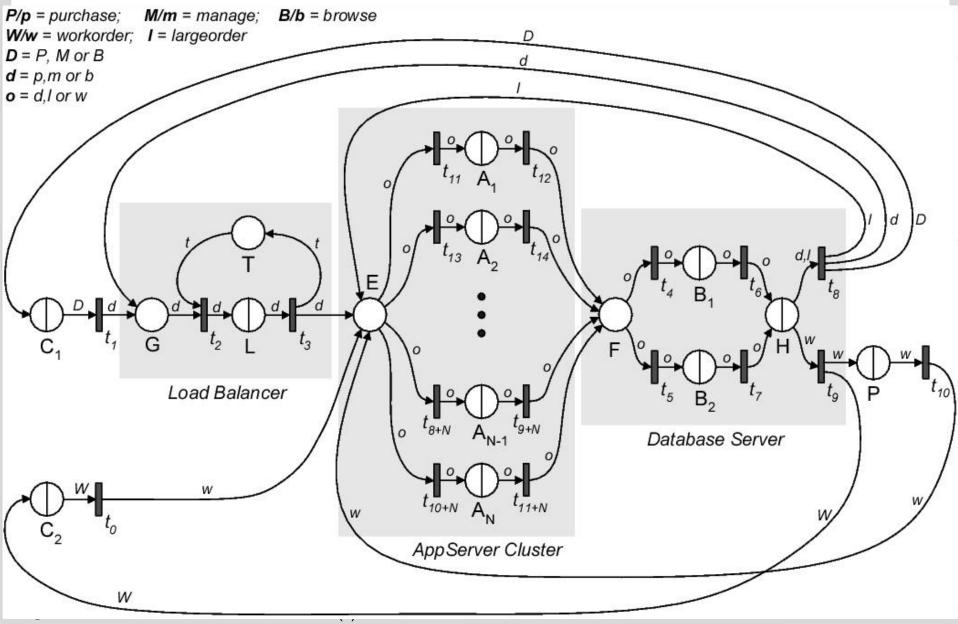
#### **QPN Model**





### **QPN Model (2)**



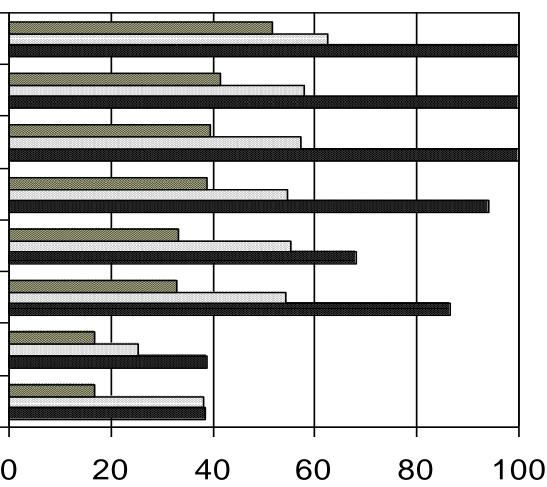


## **Summary Considered Scenarios**



■ LB-C ■ AS-C ■ DB-C

8AS / HEAVY 4 8AS / HEAVY 3 8AS / HEAVY 2 8AS / HEAVY 1 6AS/PEAK/UPG. LB 6AS / PEAK / ORIG. LB 6AS / NORMAL 4AS / NORMAL



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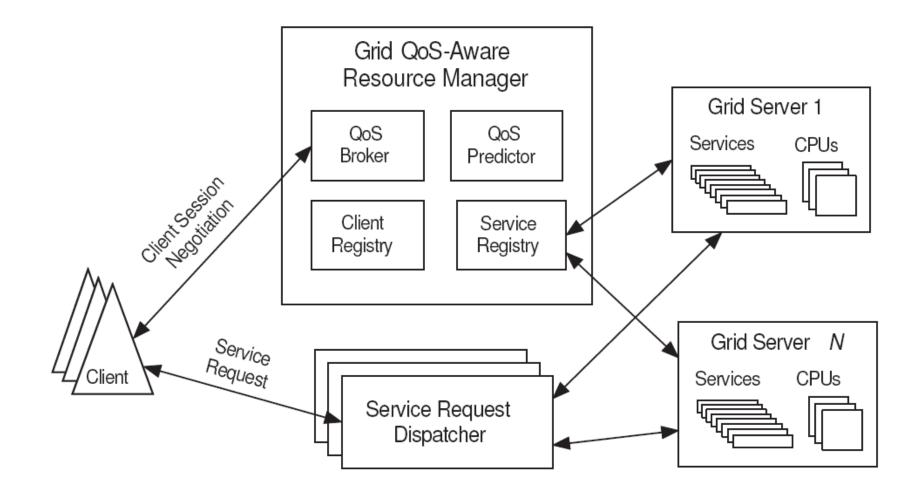


- QPN models used for online QoS Control
- Autonomic workload characterization on-the-fly
- Dynamic deployment of Grid servers on demand
- Dynamic system reconfiguration after a server failure

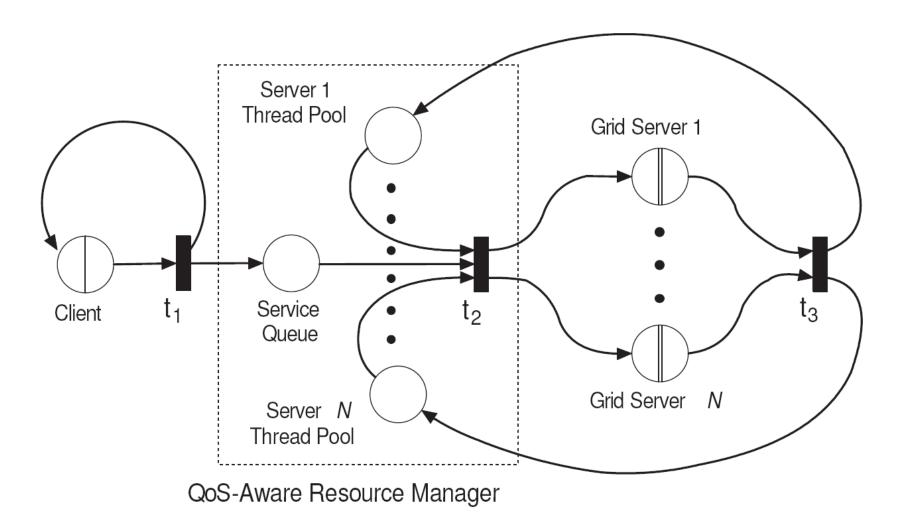
#### Further details in:

- R. Nou, S. Kounev, F. Julia and J. Torres. Autonomic QoS control in enterprise Grid environments using online simulation. In Elsevier Journal of Systems and Software, Vol. 82, No. 3, pp. 486-502, doi:10.1016/j.jss.2008.07.048, March 2009.
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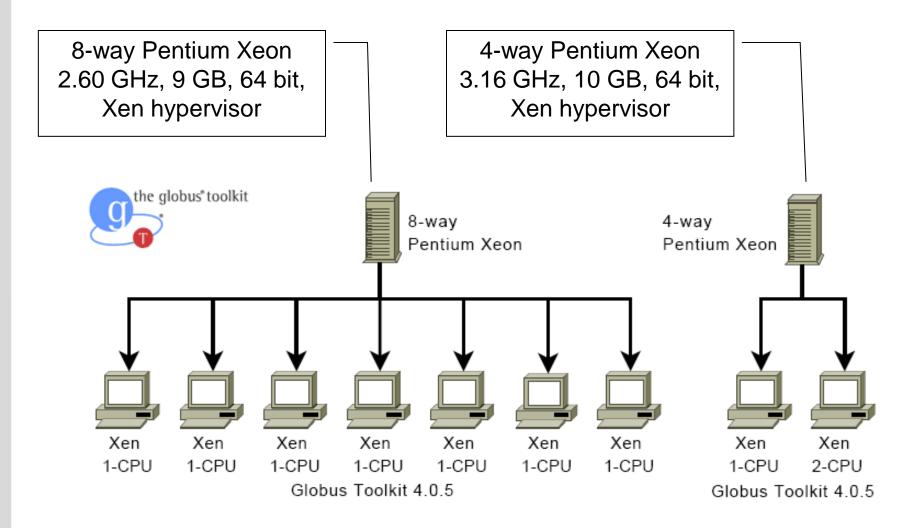




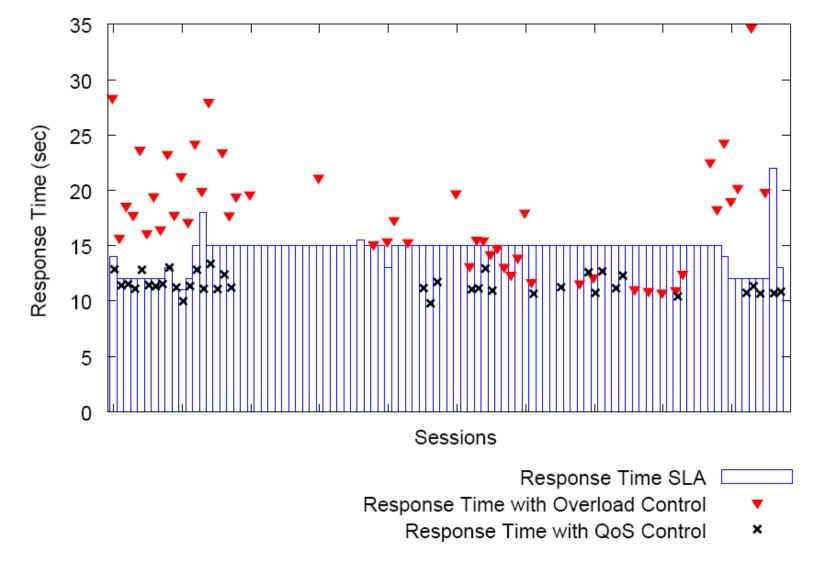












#### **Enterprise Data Fabrics**



- Lightweight modeling approach
- Automatic performance model extraction
- Automated capacity planning tool
- Promising results

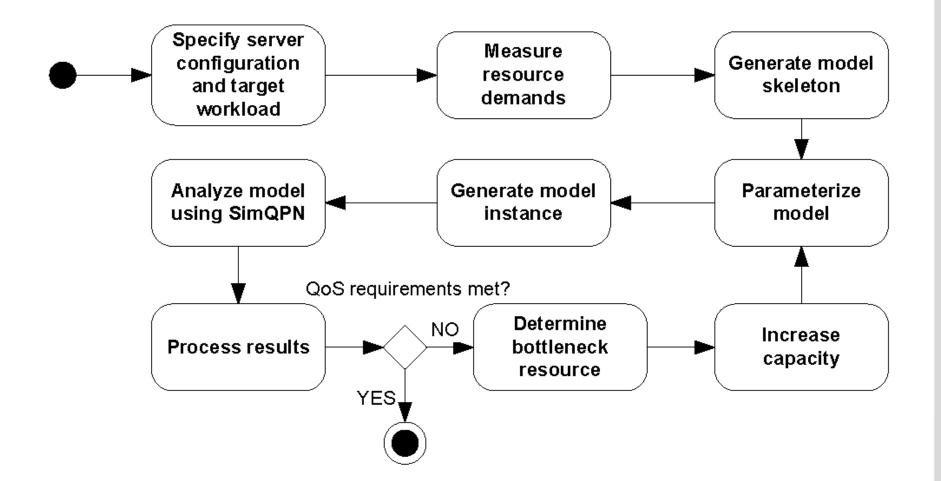


#### Further details in:

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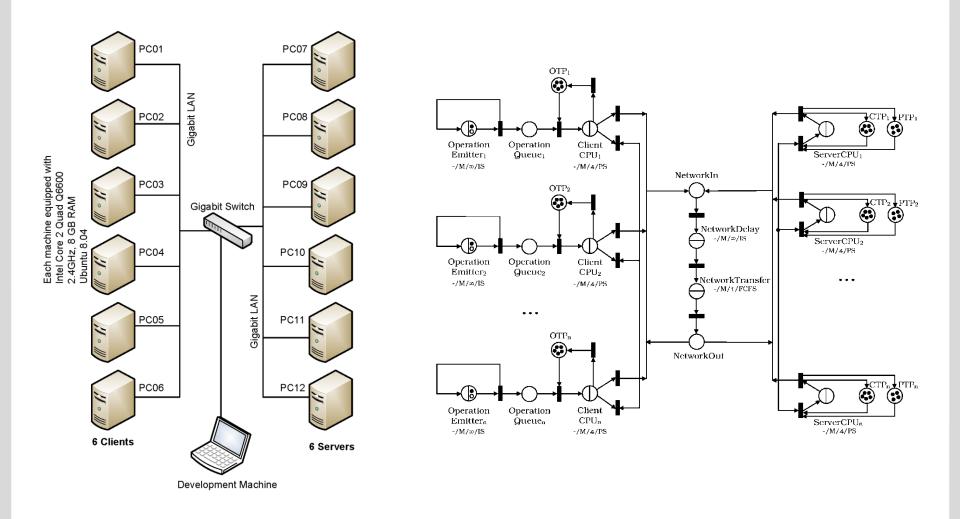
#### **Enterprise Data Fabrics**





#### **Enterprise Data Fabrics**





### **Message-oriented Event-driven Systems**



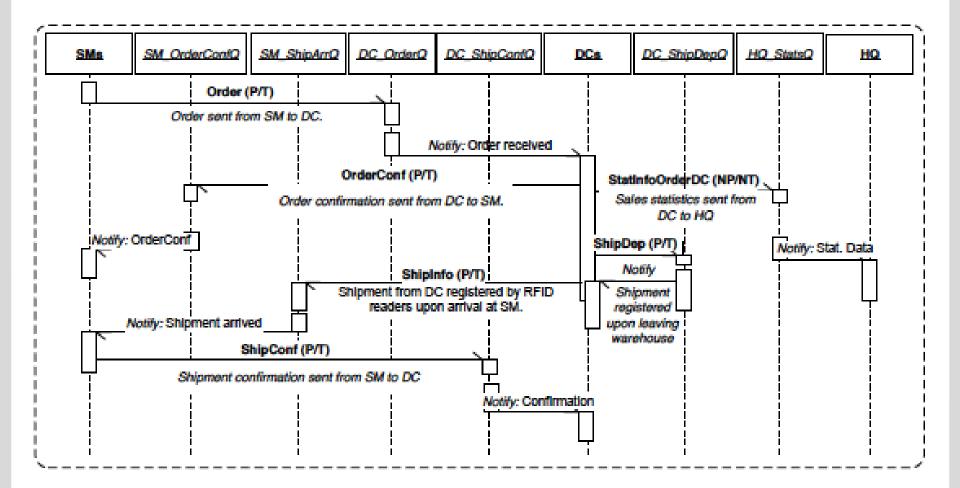
- Modeling methodology for event-based systems
- Modeling patterns
- Modeling case study based on SPECjms2007

#### Further details in:

- K. Sachs, S. Kounev and A. Buchmann. **Performance Modeling and Analysis of Messageoriented Event-driven Systems**. In Journal of Software and Systems Modeling (SoSyM), Springer Verlag, ISSN 1619-1366, DOI: 10.1007/s10270-012-0228-1, February 2012.
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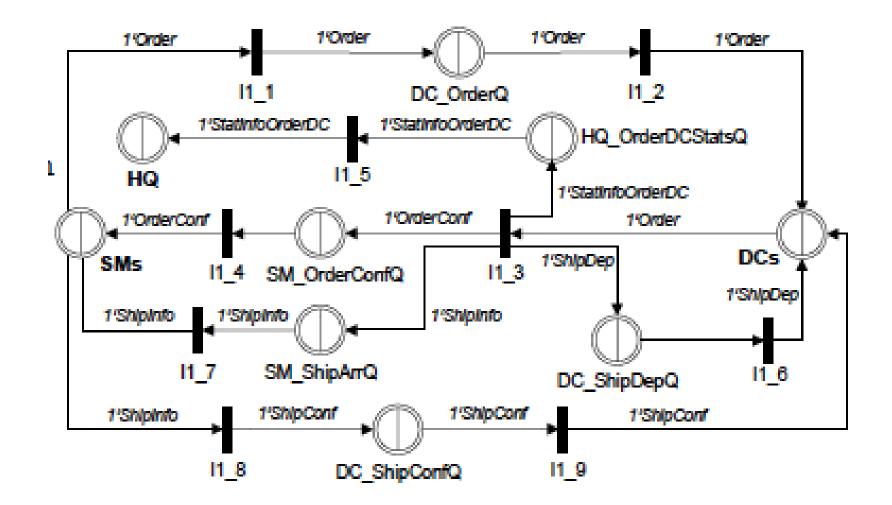
#### **Example Event-based Interaction**





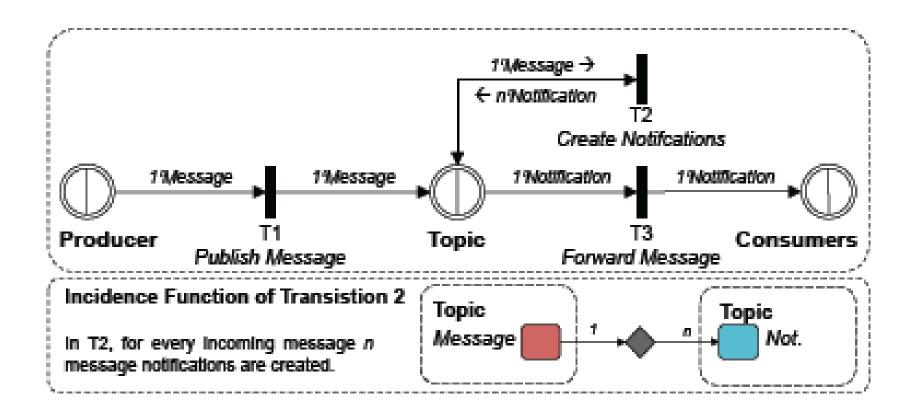
### **QPN Model of Example Interaction**





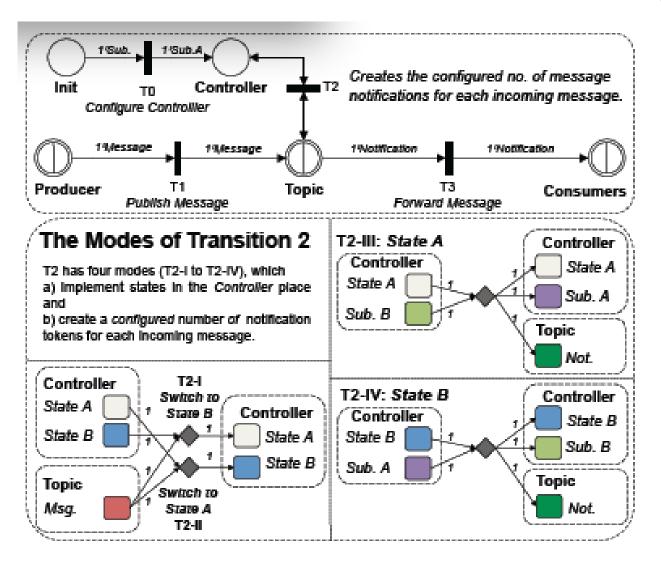
#### **Example Pattern**





## **Example Pattern (2)**





#### **QPNs as Intermediate Abstraction**



- Software performance models at the architecture level
- Palladio Component Model (PCM)
- PCM models mapped to QPN models
- Tracking of token identity across multiple places
- Efficient simulation using SimQPN

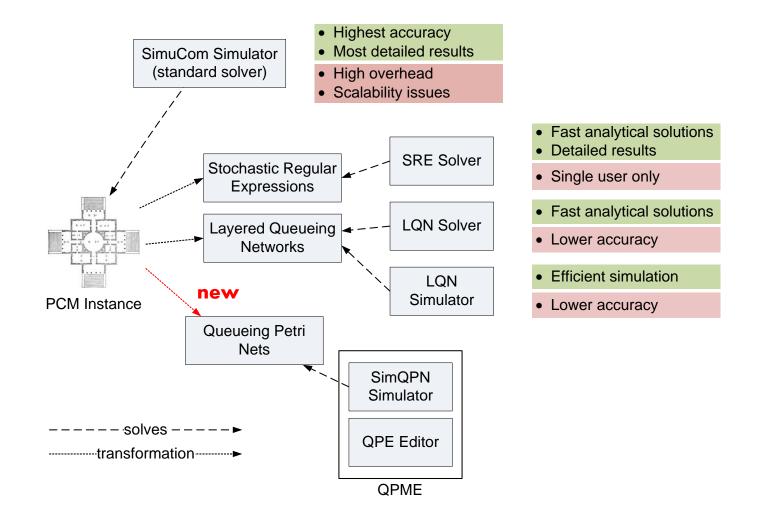


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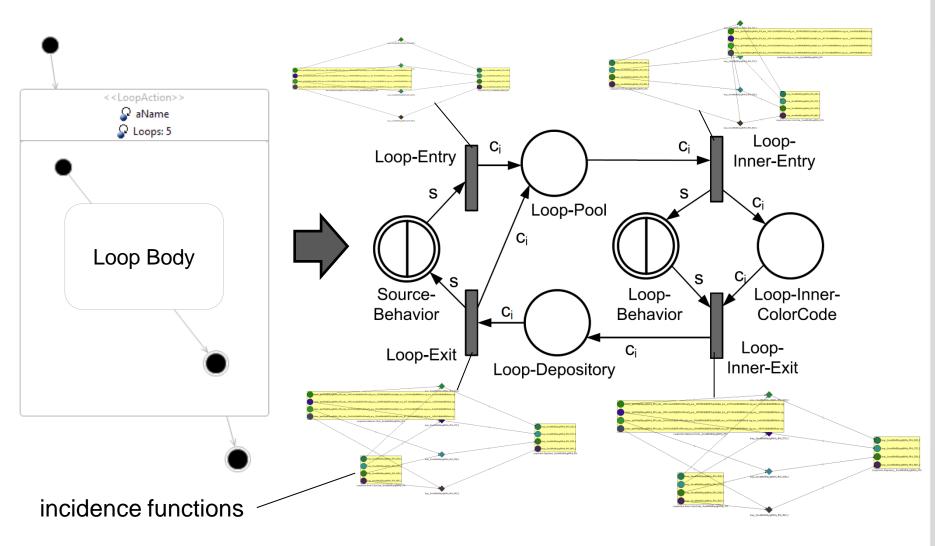
#### **Model-to-Model Transformations**





## **Example Mapping: Loop**

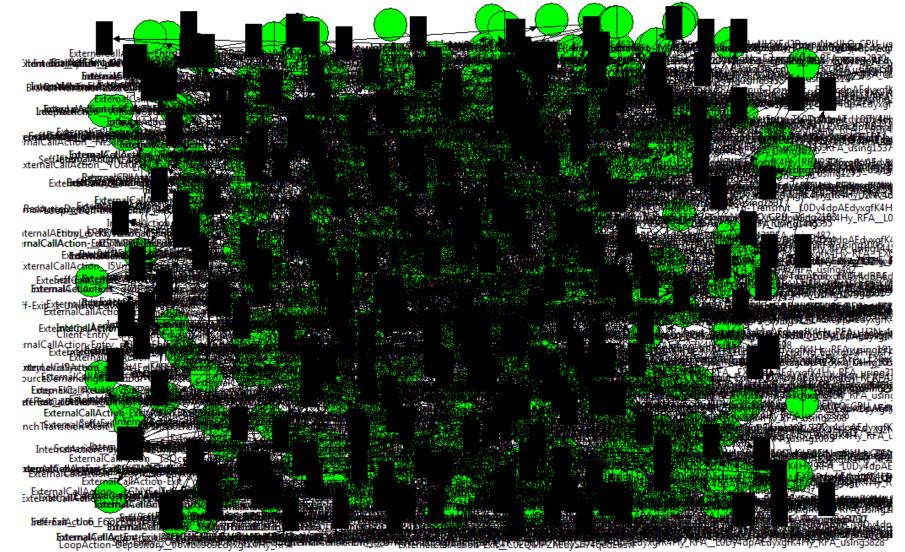




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#### **QPNs as Intermediate Abstraction**





## Accuracy vs. Overhead Trade-Off



- In-depth trade-off analysis of different solution techniques
- QPNs used with SimQPN as solution technique
- Optimal balance between accuracy and overhead





#### Further details in:

 S. Becker, S. Kounev, A. Koziolek, H. Koziolek, P. Meier. Quantitative Evaluation of Model-Driven Performance Analysis, Simulation, and Prototyping of Component-based Architectures. Under review.

### **Benefits of Queueing Petri Nets**



- Combine benefits of QNs and SPNs
- Integration of hardware and software aspects of behavior
- Flexible mapping of logical to physical queues/resources
- Efficient simulation techniques optimized for QPNs
- Good trade-off btw. expressiveness and analysis overhead
- Intuitive graphical representation
- Mature tool support

## **Tool Support**



- Queueing Petri net Modeling Environment (QPME)
- Distributed under Eclipse Public License (EPL) v1.0
- QPN Editor (QPE) and Simulator (SimQPN)
- Runs on all platforms supported by Eclipse
- Website at http://qpme.sourceforge.net/



#### Further details in:

- S. Spinner, S. Kounev and P. Meier. Stochastic Modeling and Analysis using QPME:Queueing Petri Net Modeling Environment v2.0. In Proceedings of the 33rd International Conference on Application and Theory of Petri Nets and Concurrency (Petri Nets 2012), Hamburg, Germany, June 25-29, 2012.
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# **Tool Support (2)**



- HiQPN-Tool
- Supports analytical solution techniques
- Runs on Sun-OS 5.5.x / Solaris 2
- Website at: http://ls4-www.cs.tu-dortmund.de/QPN/

#### Further details in:

- F. Bause, P. Kemper. QPN-Tool for Qualitative and Quantitative Analysis of Queueing Petri Nets. In Proceedings of 7th Intl. Conf. on Modelling Techniques and Tools for Computer Performance Evaluation, Vienna (Austria), May 3-6. 1994, pp. 321-334. Springer LNCS 794, ISBN 3-540-58021-2.
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## **Further Reading**



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- Papers available for download at http://descartes.ipd.kit.edu/publications/
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#### **Thank You!**





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