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# Enabling Fluid Analysis for Queueing Petri Nets via Model Transformation

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**Abstract**

Due to the growing size of modern IT systems, their performance analysis becomes an even more challenging task. Existing simulators are unable to analyze the behavior of large systems in a reasonable time, whereas analytical methods suffer from the state space explosion problem. Fluid analysis techniques can be used to approximate the solution of high-order Markov chain models enabling time efficient analysis of large performance models. In this paper, we describe a model-to-model transformation from queueing Petri nets (QPN) into layered queueing networks (LQN). Obtained LQN models can benefit from three existing solvers: LINE, LQNS, LQSIM. LINE internally utilize fluid limits approximation to speed up the solving process for large models. We present the incentives for developing the automated model-to-model transformation and present a systematic approach that we followed in its design. We demonstrate the transformations using representative examples. Finally, we evaluate and compare the performance predictions of existing analytical, simulation and fluid analysis solvers. We analyze solvers' limitations, solving time, and memory consumption.

*Keywords:* Queueing Petri Nets, Layered Queueing Networks, Model transformation, fluid analysis

## 1 Introduction

The complexity of today's IT systems is increasing due to the emergence of new computing paradigms, such as cloud computing, big data analytics, or cyber-physical systems. The computing resources, such as CPUs, cannot be scaled-up vertically effectively anymore. Instead, horizontal scaling of resources (replication) provides the required power and addresses the growing needs of the users. As the complexity of the systems usually grows with their size, the performance analysis becomes even more challenging.

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In order to enable the performance analysis of such systems, efficient and accurate solution techniques for performance models are necessary. Simulation techniques generally require long simulation runs to achieve the required accuracy. On the other hand, exact analytical models suffer from the state space explosion problem [34], severely limiting the size of models that can be analyzed in practice. Fluid analysis is an approximate solution technique for continuous-time Markov chains that works especially well for models with a large state space while reducing the computational effort significantly [32]. Thus, fluid analysis techniques promise a trade-off solution for the two extremes.

According to [4], fluid analysis techniques have been developed to avoid the state space explosion by approximating the state space with a set of time-varying real variables and describes their evolution by a set of differential equations. In contrast to the well-known approach of analyzing via continuous time Markov chains, Hillston [14] proposed an underlying mathematical representation based on a set of coupled ordinary differential equations. This allows efficient performance analysis of the systems with large numbers of replicated components and users. We provide a brief overview of fluid analysis in Section 2.1 and 3.1.

### *1.1 Motivation*

Queuing Petri Nets (QPN) [1] are a powerful and expressive performance modeling formalism which are a combination of classic Queueing Networks (QNs) [3] and Colored Generalized Stochastic Petri Nets (CGSPN) [8]. It has been shown, that even relatively small architecture-level models representing a data center infrastructure and the software (e.g., as shown in [22]) may result in hundreds of places, thousands of transitions and millions of tokens when transformed into QPNs. Unfortunately, existing analytical solution techniques cannot be applied to QPN models of this complexity. Only time-inefficient discrete-event simulation can be used in these cases.

In this work, we leverage layered queueing networks (LQNs) formalism and its solvers. LQNs can be solved using LQNS which is the standard solver for LQNs [11], LQSIM which is a discrete-event simulation, or LINE [25] that leverages fluid-limit approximation to accelerate the solving. We provide more background on LQN and QPN formalisms in Section 2.3.

We use the power of model-to-model transformations to transform existing QPN models into LQN models which can be later solved using LQNS, LQSIM, and LINE. We transform QPN models systematically enabling the users without QPN or LQN expertise to profit from the LQN representation and the features of LQN solvers that are unavailable to the QPN solvers (e.g., SimQPN [18]). Without the automated transformation, the ability to manually transform QPNs into LQNs would be limited to experts in both fields. Moreover, the manual transformation of big models would be time inefficient and error prone.

Finally, the third incentive is the variety of currently existing QPN models. There exist high-level models for which automated transformations to QPN have been developed. The examples are: Palladio Component Model (PCM) [2],