

Predictive modelling of SAP ERP Applications: Challenges and Solutions

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ABSTRACT

Analytic performance models are being increasingly used to support system runtime optimization. This paper considers the modelling features needed to predict the response time behaviour of an industrial enterprise resource planning (ERP) application, SAP ERP. A number of studies have reported modelling success with the application of basic product-form Queueing Network Models (QNMs) to multi-tier systems. Such QNMs are often preferred in the context of optimization studies due to the low computational costs of their solution. However, we show that these simple models do not support many important features required to accurately characterize industrial applications such as ERP systems. Specifically, our results indicate that software threading levels, asynchronous database calls, priority scheduling, multiple phases of processing, and the parallelism offered by multi-core processors all have a significant impact on response time that cannot be neglected.

Starting from these observations, the paper shows that Layered Queueing Models (LQMs) are a robust alternative to basic QNMs, while still enjoying analytical solution algorithms that facilitate their integration in optimization studies. A case study for a sales and distribution workload demonstrates that many of the features supported by LQMs are critical for achieving good prediction accuracy. Results show that, remarkably, *all of the features* we considered that are not captured by basic product-form QNMs are needed to predict mean response times to within 15% of measured values for a wide range of load levels. If any key feature is absent, the mean response time estimates could differ by 36% to 117% compared to the measured values, thus making the case that such non-product-form modelling features are needed for complex real-world applications.

1. INTRODUCTION

Analytic performance models have traditionally been used to support sizing and capacity planning for computer systems and applications. As the enterprise computing environ-

ments evolve towards adaptive and on-demand Infrastructure as a Service (IaaS) paradigms, such models may also be used to support runtime optimization [2]. In particular, models can be exploited to tune the use of resources and guide the acquisition and release of resources. This paper considers the use of analytic models in support of runtime optimization for a complex enterprise application environment. In particular, we focus on the performance analysis of the SAP Enterprise Resource Planning (SAP ERP, formerly SAP R/3) application [26].

SAP ERP is an integrated backend application with tens of thousands of installations worldwide designed for tracking and managing business processes in midsize and large enterprises. From a technical perspective, this application is built on top of a software integration platform that provides primitives to control the concurrency offered by application server and database server, the layered use of servers, asynchronous messaging, and priority scheduling for certain types of processing.

Different predictive techniques can be used to support runtime optimization for enterprise systems. Machine learning, analytic, and simulation modelling approaches are the most common [13, 32, 15]. Machine learning techniques fit models to observed data but are not able to anticipate performance when either the system infrastructure or the application undergo significant changes that have not been previously observed. Product-form Queueing Network Models (QNMs) are analytic stochastic models with efficient solution techniques, e.g., Mean Value Analysis (MVA) [17], that can be exploited for runtime optimization and performance prediction. However, they can be difficult to apply because system behavior does not typically satisfy the assumptions needed to enable the efficient solutions for such models, e.g., assumptions on scheduling and service time distributions [3]. To overcome these limitations, analytic models often include heuristics that must be validated, as is the case for the Layered Queueing Model (LQM) paradigm [24, 11] explored in this paper. In general, simulation models can do whatever analytic models can do, but require significantly more time to provide results with sufficiently tight confidence intervals. Even simulations that last several seconds can be too expensive to use in an optimization program that evaluates hundreds or thousands of models before returning the optimal solution. For this reason, an analytic model is preferable to a simulation model when it offers consistently accurate predictions.

This paper investigates the accuracy of various analytic modelling approaches for the SAP ERP platform. As a base-

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line, we explore the straightforward application of a QNM with product-form assumptions since several researchers have reported success with such models for other multi-tier systems [30]. We then investigate various non-product-form modelling features. Specifically, we consider the Method of Layers [24] LQM approach. This approach integrates modelling heuristics proposed to handle priority scheduling disciplines [6]. It also includes modelling features for studying the layered use of resources and different types of software request-reply relationships.

We quantify the improvements in accuracy the features offer with respect to the baseline results. To validate the LQM-based approach, we collect detailed measurements for a sales and distribution workload running on the ERP platform. We vary the number of users and the application server concurrency level to show our ability to predict the impact of such changes on mean response times.

Results from the case study suggest that modelling features of the type supported by LQMs are crucial for obtaining accurate mean response time estimates for the ERP system. Specifically, a LQM for the system that considers features such as the layered use of servers, threading levels, asynchronous messaging, a second asynchronous phase of processing for certain requests, and priority scheduling provides mean response time predictions that are within 15% of measured values for a wide range of load levels. If any key feature is absent, the mean response time estimates could differ by 36% to 117% compared to the measured values, thus making the case that such non-product-form modelling features are needed for complex real-world applications.

The remainder of the paper is organized as follows. Section 2 describes related work in analytic modelling and runtime optimization. The SAP ERP platform, its measurement infrastructure, and corresponding QNM and LQM models are explained in Section 3. Case study results are offered in Section 4. Section 5 offers summary and concluding remarks.

2. RELATED WORK

There are many types of analytic performance models for systems such as Markov chains [6], Stochastic Activity Networks (SAN) [25], Petri-Nets [21], QNMs [17, 6], and LQMs [24, 11]. Markov chain based approaches support detailed modeling of each individual system state. However, in general their solution efficiency does not scale for even modestly sized systems of the type we consider. Approximate mean value analysis (AMVA) [8, 10] is a technique that allows QNMs to be solved iteratively in a very efficient manner thereby permitting study of larger systems and the solution of models at runtime. However, the technique relies on product-form assumptions which restrict its applicability. In particular, behaviour commonly observed in complex enterprise systems such as contention for software resources, synchronous and asynchronous request-reply relationships between software entities, and priority based resource access all violate product-form assumptions [3].

Several extensions have been proposed to AMVA for improving the accuracy of the technique for systems where product-form assumptions are violated, see [6] for a survey. Since our focus is on runtime modelling, we only discuss and exploit non-product-form extensions that rely on the AMVA approach rather than approaches that are based on more computationally expensive techniques. For example,

Sevcik proposes the method of shadow servers that allows AMVA to be used for analyzing systems with priorities in access to resources [28]. Bryant et al. propose an alternative AMVA extension for the same problem [7]. Both these approaches report improved prediction accuracy while still leveraging the computational benefits of AMVA.

LQMs were developed starting in the 1980s to consider the performance impact of contention for software resources, e.g. server threads, and the interactions between software entities at various system layers, e.g., messaging between an application server and a database server. The approach decomposes a LQM into a hierarchy of QNMs. Each model in the hierarchy is solved using AMVA and the solution process is repeated until the individual estimates of the models are all consistent with each other. In this paper we use the Method of Layers (MOL) toolset to build and solve LQMs [14]. The toolset exploits the efficient Linearizer [8] AMVA technique to facilitate fast solutions. Additional details on LQMs and the MOL are provided in Section 2.1.

Others have proposed simpler but less general techniques for modelling software interactions. Menasce [19] proposes a 2-layer model for studying software contention. Similarly, Menasce and Bennani [20] describe a technique for predicting the mean response time of a single-layer multithreaded server system. Due to their simplicity these techniques do not have the modelling feature set required to study the ERP system we consider.

A number of researchers have had success applying QNMs to model the performance of non-production, benchmark multi-tier systems. For the sake of brevity we only discuss a representative subset of these papers. Urgaonkar et al. were able to validate a basic product-form QNM for the Rubis and Rubbos [1] open-source benchmark multi-tier applications [30]. They also considered various non-product-form extensions to the model to better account for several important features of their applications under study, e.g., an imbalance of load across multiple application servers. Chen et al. represent the TPC-W [5] and Rubis benchmark multi-tier applications as multi-station queues where the multiplicity refers to the number of server processes in each tier [9]. They use an approximation [27] that transforms a multi-station QNM to an equivalent single-station product-form QNM which can be solved using MVA. Lu et al. used simple product-form models in conjunction with a feedback controller to perform runtime optimization of a single-tiered Apache Web server system [18]. More recently, Woodside et al. applied a LQM to dynamically control the performance of a benchmark Web application at runtime [32].

To the best of our knowledge, this work is the first to validate a LQM for the SAP ERP platform. As described in Section 3, the ERP application is complex and is not as well-understood as the benchmark applications discussed previously. This makes performance prediction significantly more challenging and raises new questions about the types of modelling features that are needed to effectively model such systems.

2.1 Layered Queueing Models

LQMs were developed [31, 24] to study multi-process software systems that share hardware resources such as processors, disks and network elements. They are generalized QNMs that take into account both demands at hardware resources and at software resources. Instead of having typ-

ical QNM parameters, e.g., demands at devices per workload class, such parameters are characterized for each software component. These parameters are augmented with each software component's, e.g., a software server's, visit information to other software components, visit information to hardware devices, threading levels, and scheduling disciplines. We employ the Method of Layers (MOL) solution technique to predict the performance measures of systems represented using LQMs [24].

The MOL divides a LQM into two complementary QNMs, one for software servers and one for devices, and combines the results to provide performance estimates for the system under study. A *software contention model* describes the relationships in the software process architecture and is used to predict software contention delays. The software contention model is mapped onto a sequence of two-level submodels that estimate the software contention between clients, servers, and additional layers of servers. Clients are at the highest level of the software contention model, a topological sort determines the layer of each additional server. The average response times at one level of the model are estimated by viewing the servers at the next lower level as servers in a closed QNM. Clients or servers that request service at the higher level are considered as customer classes, and servers that provide service at the lower level are represented as queueing stations. Each server appears as a queueing station in exactly one submodel. The utilization of a server as a queueing station helps to determine the server's think time, i.e., idle time, when regarded as a customer class in other submodels. The submodels are solved iteratively, with each iteration refining estimates for demands and utilizations at the servers. The iteration terminates when the estimates change by less than a tolerance.

Another QNM, called the *device contention model*, is used by the MOL to determine queueing delays at devices. In this model, each client and server in the system is represented as a customer class, and each device as a queueing centre. Customer class think times include time spent not being utilized and time spent at other software servers. As in the method of complementary delays [16], the two models are solved alternately, with the solution of one determining some of the input parameters of the other. The results of the two models are combined to provide performance estimates for the system. The MOL alternates between the software and device contention models until the impact of software contention is balanced with reduced contention for devices. For a more comprehensive description of the algorithm readers are referred to the paper by Rolia and Sevcik [24].

The QNMs in both submodels are solved using AMVA [8] augmented with non-product-form extensions from the literature and with additional software system specific residence time expressions developed for LQMs. The response time for process communication via the remote procedure call primitive has been estimated as the residence time at a first-come first-served (FCFS) server [23]; multi-threaded servers have been considered in [24, 12] and are also used to predict the performance of multi-processor CPUs; other techniques have been developed to reflect the impact on performance of multiple phases of processing, i.e., where a caller is released but the server continues with additional phases of processing before it can accept another caller [31], and asynchronous remote procedure calls [29, 22]. These features capture the queueing delays incurred by a client or server requesting ser-

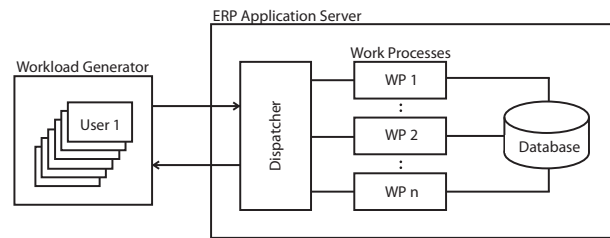


Figure 1: High-Level Overview of SAP ERP Architecture

vice at another station if that server is busy doing work on behalf of another customer.

3. SYSTEM AND MODEL DESCRIPTIONS

This section describes the architectural features of SAP ERP that are relevant for our performance modeling activity. Section 3.1 gives an overview of the ERP architecture characteristics, followed in Section 3.2 by a description of the sales and distribution workload we evaluate. Section 3.3 describes the measurements used in our models and finally Section 3.4 describes the queueing models for the system.

3.1 SAP ERP Architecture

This section offers a high-level overview of the architecture of the SAP ERP system, the interested reader can find additional information in [26]. The application server is composed of a dispatcher and pools of separate operating system processes, called *work processes*, which serve requests forwarded by the dispatcher. The dispatcher assigns each request to an idle work process. Service within a work process is non-preemptive. Work processes may access the database in a synchronous manner during which the work process remains unavailable to serve other requests due to a lack of preemptive capabilities.

Requests are served by three pools of work processes. The most important pool serves *dialog step* requests, which are responsible for processing and updating information and data that are displayed on the client-side through the graphical user interface; this information is exchanged between client and ERP application by means of a proprietary communication protocol. Each dialog step request alternates cycles of CPU-intensive activities and synchronous calls to the database for data retrieval. Additionally, dialog work processes generate asynchronous calls to the database that start being served only after completion of the dialog step which requests them. These asynchronous calls are of type *update* and *update2* and are handled by separate pools of work processes. Update2 requests are processed at a lower priority by the platform.

Other pools of work processes exist as well, but they were not performance bottlenecks in our study. Similarly, the coordination of the whole system is performed by various components of the underlying software integration platform, such as a message server, database gateway, and shared tables in memory. We do not explicitly model these components in our LQM of SAP ERP as they are not usually the primary reasons of performance degradation in the application.

3.2 Workload

In the experiments reported in the paper, we use a workload composed by a fixed mix of sales and distribution requests. This mix includes transactions which describe order creations, order listing, and delivery decisions¹. The sequence of transactions submitted to the ERP system is identical for all clients and repeated cyclically 20 times, which corresponds to an experiment duration of about 40 minutes excluding initial and final transients. The startup and warm down transients were approximately 15 minutes each.

Requests are sent to the system by a closed-loop workload generator with emulated users that are clients for the system. Each emulated user alternates between a new dialog step request and an exponential think time with mean $Z = 10s$. A request must complete before the next think time begins. The generator is provisioned on a virtual machine with one virtual CPU (vCPU). The ERP installation we have used is configured with an application server and a database server running on the same virtual machine provisioned with 2 vCPUs. The application server has 4 update and 1 update2 work processes. The database server could support up to 28 concurrent connections. We consider scenarios with either 6 or 3 dialog work processes and up to 175 clients. The two virtual machines run on a host with 4-cores, each running at 2.2GHz. The host has 32GB of RAM, and 230GB of storage space. The remaining core was not assigned to any other workload.

3.3 Measurements

The SAP ERP platform includes a comprehensive monitoring system, accessible via the STAD transaction, which reports on resource consumption of individual transactions. Additionally, OS level metrics such as process utilizations are collected through the SAPosco1 monitoring tool; client-side measurement of response times is provided by the load generator. Table 1 gives the metrics collected and their value for different number of clients $N \in \{10, 50, 75, 100, 150, 175\}$. Although CPU service demands are directly reported by the STAD monitoring tool for dialog, update, and update2 requests, we have no direct information on the service times of DB calls. We obtain these values by first multiplying the average DB process CPU utilization by the experiment duration and then dividing the result by the sum of the number of processed dialog steps, update, and update2 transactions. The resulting average CPU demand D_{db} is shown in Table 1 and it has been used as the service demand that all transactions place on the database server. Disk and network demands were not considered for this study since they were negligible in comparison to the CPU demands.

Tables 1 and 2 give the measurements obtained from the system under test. We note that the demand values in tables change a great deal as the number of users increases. The demands do not differ much for the two different threading levels. In each case we see the measured CPU utilization rising from 0.08 to either 0.85 or 0.84, respectively. This suggests that there is not a significant difference in how much CPU is used whether we operate with 6 or 3 dialog work processes. The measured response times are similar for the

¹Due to the non-disclosure agreements that are in place, we cannot provide in the paper more information on the characteristics of the individual transactions used in the experiment. However, we stress that these are representative of typical SAP ERP workload profiles.

two scenarios at low client population levels. However, the measured dialog response times behave differently for higher loads. For the 6 work process cases, mean response times rise to 209.62 msec and 293.11 msec for 150 and 175 clients, respectively. For the 3 work process cases, the response times rise to 320.32 and 473.23 msec, respectively.

Table 3 gives estimates of the demand values for the 6 work process case using a cubic spline function fitted with the demands from population 10, 100, and 175 as inputs. An asterisk is next to the population levels that have estimated values. The table shows that predicting demands for a range of customer populations from a small number of measurements is feasible. The demand estimates, were all within 3.3% of measured values for both the 6 and 3 dialog work process cases².

Finally, the STAD transaction also reports on dialog step, update, and update2 response times. We found that the reported dialog step response times were within 12% of those reported by the workload generation tool. We report response time results as measured by the workload generation tool.

Table 4 demonstrates the impact of asynchronous messaging and priorities on the runtime behaviour of the system. The table gives elapsed processing time, CPU time, and an expansion factor defined as the processing time divided by CPU time for update, update2, and dialog steps as the client population increases from 10 to 150. The CPU utilization increased from approximately 8% to 76% for this population range. The update2 requests have the greatest expansion factor, e.g., 5.59 for 150 clients, which means that they take the longest elapsed time to have a unit of CPU demand satisfied. This is likely because update2 requests can only operate at a lower priority than other requests. However, update requests are not known to operate at a low priority but they still have large expansion factors compared to dialog steps. This is because both update and update2 are scheduled asynchronously *after* the dialog step that causes them to start has completed and returned a result to the client. In the next subsection we discuss the modelling of these features in the LQM.

3.4 Queuing Models

This subsection presents a baseline product-form QNM and an LQM for the SAP ERP system under study.

3.4.1 Queuing Network Model

We begin by considering a near-product-form QNM for SAP ERP performance as a baseline model. The QNM is illustrated in Figure 2. The model is composed of a delay station that models the think times between the submission of requests. The delay station is placed in tandem with a two-server queue that represents the two vCPUs used in the experiments. Service times are assumed exponential at both stations. The system processes jobs belonging to 3 workload classes: dialog class, update class, and update2 class. The model is not strictly product-form because the classes have different mean service demands and the CPU is scheduled as first come first served.³ The population of the dialog class is

²The estimates for the three process case are omitted to save space.

³Such a choice was imposed on us by the tool we used to evaluate this model. However, we note that this is unlikely to qualitatively impact the conclusions of this study.

Table 1: Measurements for ERP System with 6 Dialog Work Processes

Metric	Source	10	50	75	100	150	175
dialog step mean response time [ms]	load generator	142.12	151.77	157.15	165.36	209.62	293.11
server CPU utilization	OS monitor SAPoscol	0.08	0.36	0.49	0.60	0.76	0.84
DB process CPU utilization	OS monitor SAPoscol	0.01	0.04	0.05	0.06	0.08	0.08
dialog step CPU service demand [ms]	STAD monitor	119.08	108.72	99.98	91.04	78.07	74.08
update CPU service demand [ms]	STAD monitor	44.11	39.21	35.80	32.62	29.61	28.76
update2 CPU service demand [ms]	STAD monitor	30.06	25.52	22.71	20.51	18.56	18.34
estimated DB CPU service demand [ms]	-	7.48	5.62	5.00	4.40	3.81	3.45
processed dialog transactions	STAD monitor	2522	12433	18610	24812	35933	42537
processed update transactions	STAD monitor	669	3299	4943	6588	9544	11251
processed update2 transactions	STAD monitor	169	822	1235	1646	2378	2806
experiment duration [s]	load generator	2516	2400	2400	2400	2400	2401

Table 2: Measurements for ERP System with 3 Dialog Work Processes

Metric	Source	10	50	75	100	150	175
dialog step mean response time [ms]	load generator	142.08	154.55	164.23	190.56	320.32	473.23
server CPU utilization	OS monitor SAPoscol	0.08	0.36	0.49	0.60	0.76	0.84
DB process CPU utilization	OS monitor SAPoscol	0.01	0.03	0.04	0.05	0.06	0.07
dialog step CPU service demand [ms]	STAD monitor	119.82	109.72	100.94	92.57	79.43	74.90
update CPU service demand [ms]	STAD monitor	47.92	41.94	37.82	35.21	31.02	29.74
update2 CPU service demand [ms]	STAD monitor	32.98	26.81	23.11	21.11	19.18	18.34
estimated DB CPU service demand [ms]	-	6.05	4.71	4.30	3.64	3.17	2.81
processed dialog transactions	STAD monitor	2719	12214	18193	24696	36054	42549
processed update transactions	STAD monitor	721	3248	4840	6566	9513	11268
processed update2 transactions	STAD monitor	181	811	1211	1639	2371	2816
experiment duration [s]	load generator	2637	2401	2401	2401	2401	2401

in the range. $N_{dia} \in \{10, 50, 75, 100, 150, 175\}$; the population of the update and update2 classes in the model are estimated as $N_{upd} = \frac{c_{upd}}{c_{dia}} N_{dia}$ and $N_{upd2} = \frac{c_{upd2}}{c_{dia}} N_{dia}$ where c_{upd} is the number of processed update transactions and c_{dia} is the number of processed dialog transactions as shown in Table 1. Such a choice of the populations ensures that the observed dialog, update, and update2 throughputs closely match measured values. Service demands at the vCPUs are obtained by summing the CPU and DB service demands in Table 1 for each class. Think times are chosen to be $Z_{dia} = Z_{upd} = Z_{upd2} = 10$ sec.

While such a model is straightforward, it does not consider software constraints such as the size of the dialog, update, and update2 work process pools and their impact on performance. Furthermore, it does not consider the layering of requests, priorities or asynchronous messaging behaviour and their queueing effects on performance. The purpose of LQMs is to provide a straightforward way of reflecting these features in models.

3.4.2 Layered Queueing Model

Figure 3 illustrates the LQM for the SAP ERP platform. Table 1 gives the service demand parameters for the layered queueing model for the system under study for the 6 dialog work process scenario. The parameters are summarized per dialog step request.

The model reflects the workload generator’s emulated users that submit requests to the application server of Figure 1. Emulated users are represented as clients that generate synchronous dialog requests to a pool of dialog work processes. The dialog processes have two phases of service. The first phase (P1) corresponds to executing business logic. It al-

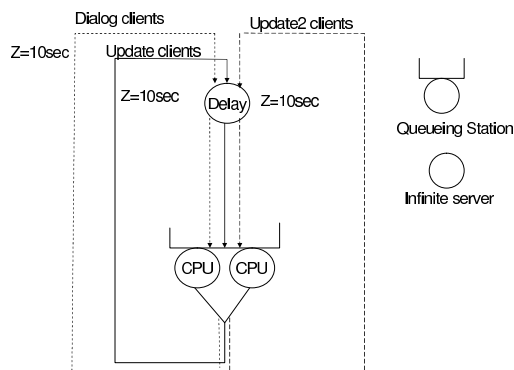


Figure 2: QNM for an ERP Application Server

ternates between using the vCPU and making synchronous calls to the database service, afterwards the client is released. The second phase (P2) causes asynchronous requests to the update and update2 pools of work processes. This is because in the ERP platform update requests are processed after the dialog step completes. A client’s dialog request does not typically incur any contention for the vCPU due to its own asynchronous update requests. All three types of work processes make synchronous visits to the database service. Client think times are illustrated as a visit to a delay centre named Think. The update2 processes access the vCPU at a lower priority than all other processes. The process pool

Table 3: Estimated Demands for ERP System with 6 Dialog Work Processes using Cubic Splines with Data for 10, 100, and 175 clients

Metric	10	*50	*75	100	*150	175
dialog step CPU service demand [ms]	119.08	105.87	98.11	91.04	79.30	74.08
update CPU service demand [ms]	44.11	39.21	35.80	32.62	29.61	28.76
update2 CPU service demand [ms]	30.06	25.14	22.51	20.51	18.68	18.34
estimated DB CPU service demand [ms]	7.48	5.92	5.08	4.40	3.66	3.45

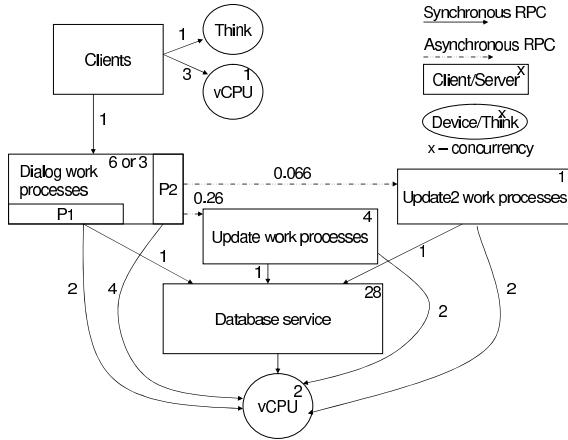


Figure 3: LQM for an ERP Application Server

sizes used in the model correspond to the ERP application’s configuration settings as discussed in Section 3.2. Note that the dispatcher for work processes is not represented explicitly as a software server in this model because it did not seem to have a significant impact on performance in our study.

In Figure 3, the numbers on the arrows flowing into an entity describe the number of visits to that entity by other entities in the model. The visit counts follow directly from the nature of interactions between clients, dialog work processes, update work processes, update2 work processes, the database service, the vCPUs and the Think delay centre. In particular, the relative number of visits to update and update2 processes are based on the counts of processed transactions as shown in the Tables 1 and 2. We also note that the second phase of processing has *near-zero* demands on the vCPU. Small non-zero demands are required by the MOL tool as an artifact of its assumption of a central server model for each phase of processing.

The impacts of the pools of work processes and the dual cores associated with the ERP VM are reflected in the LQM using multi-server queueing centres [24]. Asynchronous messaging is captured in the LQM using the residence time expressions described in previous work [29]. Priority scheduling is implemented according the method by Bryant et al. [7]. Two phases of processing are implemented in LQMs according to the residence time expressions devised previously [31] but adapted for use within the closed queueing model approach of the MOL tool.

4. MODELLING RESULTS

This section presents the results for the QNM and LQM models.

Table 4: Impact of Asynchronous Messaging and Priorities on Expansion Factor

Client Pop	Processing Time	CPU Time	Expansion Factor
Update transactions			
10	64.393	44.05	1.46
50	69.476	39.206	1.77
75	73.741	35.802	2.06
100	78.113	32.617	2.39
150	99.263	29.64	3.35
Update2 transactions			
10	58.337	30.059	1.94
50	63.72	25.523	2.50
75	67.358	22.713	2.97
100	75.264	20.51	3.67
150	103.58	18.532	5.59
Dialog transactions			
10	111.76	119.1	0.94
50	113.38	108.72	1.04
75	113.16	99.983	1.13
100	112.33	91.042	1.23
150	115.07	78.068	1.47

4.1 QNM Results

We begin with the results of the QNM for SAP ERP. The predictions for CPU utilization and dialog step response times are computed using a QNM simulator [4]. The results are given in Table 5 together with the values of N_{dia} , N_{upd} , and N_{upd2} used in the model. Note that response times are not monotonically increasing with the total population because the measured service demands change under increasing population values. The results in the table indicate that the QNM is effective at predicting CPU utilization, with a maximum error of 10% for $N_{dia} = 175$. However, when we look at the more challenging problem of matching the mean dialog response time we see that a basic QNM grossly underestimates the actual response times. In particular, for $N_{dia} = 175$ the predicted response time (165.00 msec) is significantly less than the measured value for the SAP ERP system (293.11 msec). Errors of similar magnitude are incurred for all but low load populations. Our interpretation is that the inaccuracies are the result of ignoring the effects of worker process pool sizes and other software system properties such as priorities and asynchronous messaging behavior.

Summarizing, the results of this subsection indicate that a basic application of QNMs cannot be used reliably for estimating fundamental performance metrics of the SAP ERP system such as end-to-end response times. Utilization can be predicted well, but this is in general much easier to match than response times in presence of large think times such as in the present case study. In the next section we show how a LQM can greatly enhance the predictive capabilities when applied to complex software systems such as the SAP ERP system.

Table 5: QNM Mean Dialog Response Times and Utilization for 6 Dialog Work Processes Case

Pop	Measured CPU U	Measured DialogResp	QNM (MVA)				
			Dialog Pop.	Update Pop.	Update2 Pop.	CPU Util DialogResp	
10	0.08	142.12	10	3	1	0.07	127.03
50	0.36	151.77	50	13	3	0.32	125.20
75	0.49	157.15	75	20	5	0.44	126.65
100	0.60	165.36	100	27	7	0.53	128.30
150	0.76	209.62	150	40	10	0.68	144.61
175	0.85	293.11	175	46	12	0.75	165.00

Table 6: LQM mean dialog response times for 6 dialog workprocess case with all features and excluded features

Pop	Measured CPU U	Measured DialogResp	All Features DialogResp	UpdateLowPri DialogResp	No Priority DialogResp	No Async DialogResp	No Threading DialogResp	No P2 DialogResp
10	0.08	142.12	139.67	139.15	139.69	140.04	138.56	139.67
50	0.36	151.77	149.14	145.79	150.98	151.33	146.73	149.23
75	0.49	157.15	158.42	152.20	164.12	162.09	158.48	158.42
100	0.60	165.36	170.63	160.25	183.73	176.27	177.27	171.24
150	0.76	209.62	241.19	205.70	292.89	259.82	286.02	243.40
175	0.85	293.11	329.66	252.45	375.87	378.74	345.78	326.88

4.2 LQM results

We now consider the following sets of results for the LQM model introduced in Section 3.4.2. Tables 6 and 7 give the results for the six and three dialog work process cases, respectively, for the following scenarios: where all modelling features are included (All features) as per Section 3.4.2; the update processes also run at a low priority as well as the update2 processes (UpdateLowPri); all processes run at the same priority (No Pri); where asynchronous calls are made to be synchronous calls (No Async); where threading levels are set to high values so there is no queuing for software processes (No Thread); and where the second phase of processing is included in the first phase (No P2). We note that only one modelling feature is changed at a time. Each case includes all the features or differs from the (All features) case by only one feature. Tables 8 and 9 give the results for the cases where all features are included but demands are estimated through cubic splines as shown in Table 3.

Tables 6 and Table 7 give measured and predicted mean dialog step response times for the 6 and 3 dialog work process case with between 10 and 175 customers, respectively. As mentioned previously, the response time behaviour of the system for the 3 work process case and the 6 work process case differ significantly for higher numbers of clients. For 150 and 175 clients, the 3 work process results are approximately 100 and 180 msec higher than for the 6 dialog process case, respectively.

From Table 6 and Table 7 we see that the mean response times predicted by the LQM for the (All features) case match the measured values closely. The greatest error for the 6 work process case is 15% at 150 clients. The greatest error for the 3 work process case is 24%, for the 175 client case. For the 150 client case, the LQM predicted a mean response time that is approximately 90 msec greater for the 3 dialog process case than the 6 dialog process case. Similarly, for the 175 client case, the LQM estimated mean response time for the 3 dialog process case is greater than that of the 6 dialog process case by approximately 260 msec. In effect, the LQM prediction is very close for 150 clients, but it over-estimates the degradation for 175 clients. We note that the model is very accurate for CPU utilizations of 76% and less

for both the 6 and 3 dialog process cases which is already a high utilization for a production enterprise application environment. The LQM also predicts the smaller increases in response times for client populations of 50, 75, and 100 that result when decreasing the number of dialog processes from 6 to 3.

We now consider disabling one feature at a time from the LQM. The following results are from Tables 6 and Table 7. First, we consider modelling the update processes at a low priority (UpdateLowPri) in addition to the update2 processes. This hides more of the update work from the clients and as a result response times drop. This seems advantageous for the 6 work process case but becomes too optimistic for the 3 work process case. Next, we consider disabling the use of priorities (No Priority). The results become pessimistic for the 6 dialog process case and very pessimistic for the 3 dialog process case. In the subsequent scenario we make all calls synchronous (No Async). The results become slightly pessimistic for the 6 dialog process case, but very pessimistic for the 3 dialog process case. To further consider the impact of dialog process pool size (No Thread) we increase the pool sizes in the model to match the number of clients. As expected we end up with predictions that are very similar for the 6 and 3 dialog process cases, differences are due to slightly different measured demands for the these two scenarios. Clearly, without the threading feature for modelling pool size we are not able to distinguish the impact of pool size. Finally, we consider the model without the second phase of processing (No P2). In this scenario the calls to update processes are made in the first phase, which from the analytic model's perspective permits a dialog request to compete for CPU resources with its own update requests. Note that update2 requests run at a low priority. In this scenario we see the mean response times for both the 6 and 3 dialog work process cases increase slightly, but enough to show that support for a second phase of processing is advantageous especially at high load.

To summarize, for measured CPU utilizations of 76% or less the LQM offered mean dialog step response time predictions very close to measured values. The greatest error for the 6 and 3 work process cases for this utilization limit was 15% for the 6 work process case at 150 clients. When

Table 7: LQM mean dialog response time results for 3 dialog work process case with all features and excluded features

Pop	Measured CPU U	Measured DialogResp	All Features DialogResp	UpdateLowPri DialogResp	No Priority DialogResp	No Async DialogResp	No Thread Dialog Resp	No P2 DialogResp
10	0.08	142.08	135.62	135.09	135.66	136.34	133.99	135.63
50	0.36	154.55	154.96	151.02	158.21	159.85	149.74	154.93
75	0.49	164.23	167.94	161.25	180.36	179.16	164.17	169.09
100	0.60	190.56	180.59	168.23	209.79	201.45	179.87	182.35
150	0.76	320.32	322.84	252.27	696.12	494.59	288.25	349.02
175	0.84	473.23	586.71	375.88	1068.62	824.17	339.32	631.40

Table 8: LQM mean dialog response times for 6 dialog work process case with all features and estimated demands

Pop	Measured CPU U	Measured DialogResp	All Features DialogResp
10	0.08	142.12	139.67
50	0.36	151.77	149.10
75	0.49	157.15	158.16
100	0.60	165.36	170.63
150	0.76	209.62	239.86
175	0.85	293.11	316.44

disabling features one at a time the greatest errors across the 6 and 3 work process cases were: (UpdateLowPri, 24%), (No Priority, 117%), (No Async, 29%), (No Thread, 36%), and (No P2, 16%). This shows the advantages of using the non-product-form features.

Table 8 and 9 provide results for LQMs with all modelling features included but with demands estimated using cubic splines, as in Table 3. The response time predictions match the measured response times closely showing that demand measurements from a small set of client population levels can be used to estimate the demands at other client population levels effectively.

5. SUMMARY AND CONCLUSIONS

The results of our study show that non-product-form features such as priority scheduling, asynchronous messaging, and the layered use of servers with finite numbers of work processes are all important for modelling the production enterprise application platform under study. The use of a second phase of processing for dialog requests also improved response time predictions. The LQM offered mean dialog step response time predictions within 15% of measured values for a wide range of load levels. When disabling key features one at a time the greatest errors across the 6 and 3 work process cases were: (No Priority, 117%), (No Async, 54%), (No Thread, 36%). Thus if priorities, asynchronous processing

Table 9: LQM mean dialog response time results for 3 dialog workprocess case with all features and estimated demands

Pop	Measured CPU U	Measured DialogResp	All Features DialogResp
10	0.08	142.08	135.62
50	0.36	154.55	154.43
75	0.49	164.23	167.35
100	0.60	190.56	180.59
150	0.76	320.32	324.31
175	0.84	473.23	586.71

or threading support for pool sizes are not included in the model response time estimates can differ from measured values by 36% to 117%. This shows the advantages of using the non-product form features.

We observed that measured demand values changed significantly from one population to another, yet given the demands for a low, medium, and high population level, a cubic spline did a very good job at estimating the demands of intermediate populations. Measured demand values for different threading levels did not change much. Use of the estimated demands did not significantly affect the predictive accuracy of the model.

Analytic models are favoured for runtime optimization because they provide fast solutions for even large systems compared to other techniques. The MOL tool offered solutions for each of the models considered in this paper in a fraction of a second on a laptop. This suggests that the approach could be used to support runtime optimization methods.

Our one concern about applying these methods at runtime follows from our experience in validating the models. We found it necessary to collect data for forty minutes to properly characterize steady state conditions and a mean dialog response time via measurement. Measurements of mean dialog response time from shorter time periods may differ more significantly from the predictions which correspond to the steady state. At runtime, we expect that such models are best used to determine the likely impact of changes to a system on application behaviour rather than to predict mean response times over short time scales that may be significantly affected by transient behaviour.

Our future work includes more validation exercises for the ERP application and other platforms. We plan to consider a greater variety of more controlled workloads and to integrate the approach into a runtime management system for the platform in infrastructure as a service environments.

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