Modeling the Performance of Ultra-Large-Scale Systems Using Layered Simulations

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***Abstract*—The backbone of cloud computing platforms like Amazon S3 and Salesforce is formed by Ultra-Large-Scale (ULS) systems, i.e., complex, globally distributed infrastructure consisting of heterogeneous sets of software and hardware nodes. To ensure that a ULS system can scale to handle increasing service demand, it is important to understand the system's performance behaviour, for example to pro-actively plan for hardware upgrades. A good performance model should address concerns from all stakeholders at the level appropriate to their knowledge, interest, and experience. However, this is not straightforward, since stakeholders of ULS systems have a wide range of backgrounds and concerns: software developers are more interested in the performance of individual software components in the system, whereas managers are concerned about the performance of the entire system in different configurations. In this paper, we adapt the "4+1 View" model for software architecture to performance analysis models by building simulation models with multiple layers of abstraction. As a proof-of-concept, we conducted case studies on an open source RSS (Really Simple Syndication) Cloud system that actively delivers notifications of newly published content to subscribers, and on a hypothetical, industry-inspired performance monitor for ULS systems. We show that our layered simulation models are effective in identifying performance bottlenecks and optimal system configurations, balancing across performance objectives.**

***Index Terms*—ULS, layered performance simulation, 4+1 view**

I. Introduction

Today's cloud computing platforms, such as Amazon S3/EC2 or Salesforce, are driven by Ultra-Large-Scale (ULS) systems, i.e., complex infrastructure that is distributed across the world and consist of thousands of heterogeneous software and hardware nodes [10]. Millions of people use, and typically depend on, such ULS systems, whereas thousands of developers are needed to maintain and develop them. Since software failure is a fact, not a risk in ULS systems, ensuring the performance of ULS systems is a top priority for cloud computing vendors. However, because of the complexity of ULS systems, it is typically impossible to have a dedicated system running in a lab environment for performance testing. As a result, organizations perform performance modeling to help them determine if their systems can scale with the growth in demand for cloud capacity.

Performance modeling is a structured and repeatable process of modeling the performance-related aspects of the design of a software system [18]. By solving or simulating the performance models, performance engineers can obtain estimates of, for example, response time and resource utilization at various arrival rates. Performance modeling can provide valuable information for system architects to catch bad designs early, and for developers to make informed decisions about potential performance hotspots [9], [18].

A good performance model should enable different stakeholders, each having different backgrounds and interests, to understand the performance of a software system without getting overwhelmed with unnecessary information [20]. Furthermore, visualization of the model is also important to improve the understandability of the program design. However, the current two major classes of performance models, i.e., analytical and discrete-event simulation models, do not support these two requirements.

Analytical performance models such as Layered Queueing Networks (LQN) use mathematical equations and statistical concepts to model the performance of software systems. The inputs of an analytical model are the average arrival rate of requests and a set of average values that represent the (hardware and software) resource usage of each request [9]. Outputs are the performance behaviour and resource utilization. The construction and usage of analytical models demand a substantial level of expertise [21]. Some techniques can automatically construct models based on representative runtime traces of a software system [6], but those are typically not available in ULS systems.

In contrast to analytical models, discrete-event simulation models capture the behaviour of a software system as a chronological sequence of events [12]. Performance statistics, such as the response time for each request, can be obtained by executing the simulation model against a simulation clock, which allows simulation of an 8-hour work day in a couple of minutes. Simulation models are usually created to test specific performance aspects for specific stakeholders, e.g., the performance impact of the Java garbage collection. Although dedicated libraries (e.g., [11]) exist to implement and visualize simulation models, the size and complexity of ULS systems prohibit the development of one global simulation model supporting all stakeholders.

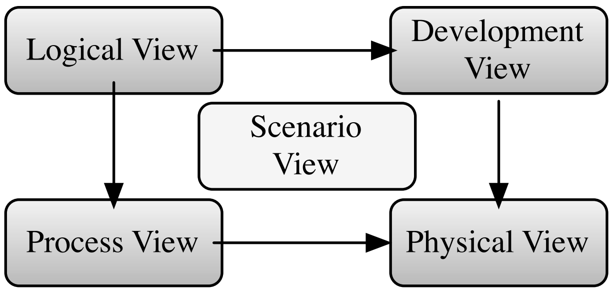


Fig. 1. The “4+1 View” model.

TABLE I
PERFORMANCE CHARACTERISTICS OF STAKEHOLDERS.

Stakeholder	Performance Concerns
End user	Overall system performance for various configurations
Developer	Organization and performance of system modules
System Engineer	Hardware resource utilization of the system
System Integrator	Performance of high-level components

In order to construct, in a systematic way, ULS simulation models that can address the performance concerns of multiple stakeholders of a cloud-based systems, we propose to incorporate the principles of the “4+1 View” Model for software architecture into layer-based simulation models. Similar to the “4+1 View” Model, our simulation model consists of multiple layers of different granularity, each targeting different performance concerns for different stakeholders. For example, system architects can use the model with rough estimates of resource requirements to evaluate different design options at the beginning of the development. Later on, performance analysts can use our layered simulation model with concrete resource consumption measurements to recommend optimal system configurations for different deployment scenarios.

Our main contributions are as follows:

- Our layered simulation models provide a clear separation of different aspects of a software system to aid stakeholders in understanding the performance of a system.
- We conducted two case studies to demonstrate the process of constructing layered simulation models, and to show that the models are useful in both discovering performance bottlenecks and selecting the optimal system configuration for ULS systems.

The paper is organized as follows. Section II reviews the “4+1 View” Model for software architecture from which our layered model is derived. Section III presents our layered models, whereas Section IV discusses their construction. Section V presents two case studies to demonstrate how to use layered simulation models to select optimal system configurations. Section VI discusses our approach and findings. Section VII presents related work and Section VIII concludes the paper.

II. “4+1 View” Model for Software Architecture

ULS systems forming the backbone of cloud computing infrastructure are often too complex to be represented by a single architectural diagram [3], [4]. Currently, a variety of formalisms is available to model different aspects of a software system. For example, developers use UML class diagrams to document system functionality, while system integrators use UML activity diagrams to represent the system runtime behaviour. Each notation describes the parts of the system that are of particular interest to a stakeholder.

TABLE II
MAPPING OF OUR SIMULATION MODELS TO THE “4+1 VIEW” MODEL.

Stakeholder	Layer in Our Model	“4+1 View” Model
Architects, Managers End users Sales Representatives	World View Layer	Logical View
Developers System Integrators	Component Layer	Development View Process View
System Engineers	Physical Layer	Physical View
All Stakeholders	Scenario	Scenario

In order to maintain a complete description of a software system, Kruchten proposed the “4+1 View” model [7]. This model contains five concurrent views (Figure 1), each representing the viewpoint of a particular stakeholder:

- The logical view focuses on the functional requirements of a software system, and primarily targets the concerns of end users.
- The process view addresses the concerns of system integrators, who specialize in bringing together different components of a software system. This view concerns the run-time behaviour of the system, e.g., concurrency, performance, and scalability.
- The development view considers the organization of software modules and mainly targets the concerns of developers and software managers.
- The physical view illustrates the software system from a system engineer’s perspective. This view describes how the software system is deployed and takes into account non-functional requirements such as reliability, availability and scalability.
- The “plus-one” view consists of a set of test cases and scenarios to show how the elements identified by the other four views work together. The plus-one view validates the software design.

Similar to software architecture, different stakeholders of a software system also have different performance concerns (Table I). For example, system engineers typically focus on optimal usage of the available hardware resources, whereas end users are interested in the general responsiveness of the system. A good simulation model should address each stakeholder’s concerns separately, without overloading stakeholders with unnecessary details. Inspired by the “4+1 View” model, this paper proposes a software simulation model that decomposes the performance of a software system into a three-layer hierarchy, with an additional layer to describe the different usage scenarios.

III. Layered Simulation Model

This section presents the concept of layered simulation models, whereas the next section discusses the construction

TABLE III
COMPONENTS AND CONNECTIONS IN FIGURE 2.

Layer	Component	Connected to
World view layer	Users, blogs	RSS server
	RSS server	Users, blogs
Component layer	In/out queues	Application logic
	Application logic	In/out queues, Hardware
	Hardware	Application logic
Physical layer	Hardware allocator	CPU, RAM, Disk
	CPU, RAM, Disk	Hardware allocator

of such models. As shown in Table II, each layer in a layered simulation model addresses the concerns of a group of stakeholders. The layers roughly correspond to the five views in the “4+1 View” model. The process and development views in the “4+1 View” are combined into a single layer (component layer) that captures the integration and performance of individual components in a software system.

System integrators can examine the dynamic aspects of the system by monitoring the communication between the simulated components of the system, even across different layers. The layers in our simulation model are linked to each other and can be constructed incrementally from high to low level of abstraction as details about the software become available. A partially complete model, e.g., a model that only contains high-level components such as databases and servers, can be used to guide the software design at the early stages of development. The following sections discuss in detail the purpose of each layer.

A. World View Layer

The world view layer represents the high-level system components and their relations as a network of nodes and edges. This layer is the top and most abstract layer in our model. It addresses high-level, often business-oriented, concerns such as evaluating whether the current infrastructure of the software system can support the projected growth in the customer base.

Initially, each high-level component in the world view layer represents a place-holder for the logic that will be added by lower layers. Performance analysts can assign rough resource estimates to these place-holders for initial analysis. Later on, in a complete model, the world view layer can still be used to measure the performance impact of adding new nodes to a distributed system or to test different deployment scenarios, since it hides the details of the underlying layers while transparently leveraging the detailed performance logic of those layers (if available).

Figure 2 shows an example layered simulation model constructed for an RSS Cloud system. RSS [14] is a format for delivering frequently-updated content to subscribers. In an RSS Cloud system, an RSS server actively pushes notifications of new content to the users. Table III summarizes the different components in each layer and the connections between them.

Figure 2a shows the world view layer of the RSS Cloud system. The simulation model consists of three high-level components, i.e., the websites that publish personal journals (blogs), the users that subscribe to the blogs, and the RSS server through which each blog is connected to its users. The bidirectional arrows in Figure 2a depict the two-way communication between components.

B. Component Layer

The component layer decomposes each high-level component defined in the world view layer into logical entities. Similar to the world view layer, the components and the communication between them are represented as a network of nodes and edges (Figure 2b).

For example, the RSS server in Figure 2a can be broken down into a number of components: the software component that represents the software logic, and the input and output queues that act as communication channels from the server to other high-level components defined in the world view layer. Performance analysts can define different processing requirements to each layer component, for instance the time required to process different types of service request, and the capacity of various logical resources, such as the thread pool and queues.

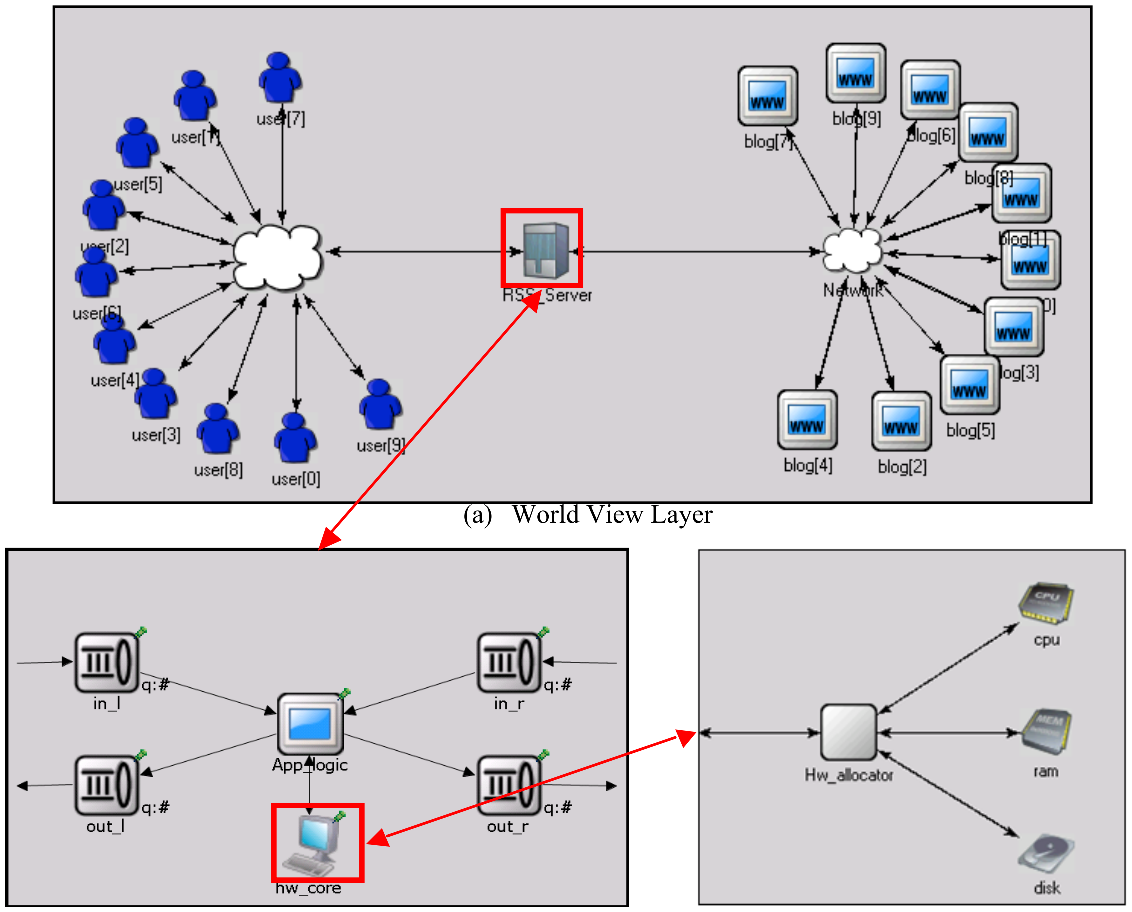
Developers can leverage the component layer to understand the communication patterns in a software system, to grasp the performance ramifications of handling different mixes of service request types, or to study the performance of different threading models. During the execution of a simulation model, performance analysts can temporarily stop the simulation program and examine internal information such as queue size or network bandwidth consumption.

C. Physical Layer

The physical layer connects the logical components in the component layer to the underlying hardware resources. The physical layer mainly targets the concerns of system engineers. Figure 2c shows three hardware resources in the RSS server: CPU, Memory, and Disk. Performance analysts can specify the hardware resource requirements for each type of service request. For example, a request to submit a new blog post may consume 50 kilobyte of Memory while the request is being processed. Using the Physical Layer, system engineers can study the behaviour of resource utilization at different request rates. Furthermore, system engineers can use this view to determine the performance bottleneck of the system at higher request rates.

D. Scenario Layer

The scenario layer uses a set of test case scenarios to show how the elements defined in the three other layers work together. Scenarios from the end user’s point of view include the different deployment scenarios and the composition of different types of service requests passed to the software system. For the example in Figure 2, one scenario could specify that there are four blogs connected to the RSS server, 50% of which are located in North America with an average bandwidth of 2 Megabit/second, and the rest are located in Europe with an average bandwidth of 1 Megabit/second. The scenarios define how the software components are deployed,



(a) World View Layer

(b) Component Layer

(c) Physical Layer

Fig. 2. Example Layered Simulation Model for an RSS Cloud Server.

and what workload is used in the simulation to estimate the system performance.

IV. Model Construction

The construction of a layered simulation model is an iterative process. The three layers in our proposed model can be constructed in a top-down fashion during different stages of the software development life cycle. For example, performance analysts would start with the world view layer to model the general deployment scenario of the software system. The world view layer can initially be constructed according to the system specification or to similar products in the market. Estimates of resource requirements are given to each high-level component. The partial simulation model is run with the request arrival rates that are either observed from similar systems or derived from existing benchmarking standards. Such a partial simulation model is similar to the Software Execution Model [18], [17], which is typically used in the early stages of software development, when only limited processing requirements are available. Similar to that kind of model, the accuracy of our partial simulation model should reflect the resource utilization and response time within 10% and 30% accuracy, respectively.

As more details become available, performance analysts can improve the simulation model by extending each high-level component with the component and physical layers, and by giving better resource estimates for different request types. Such an incremental model building approach requires programming libraries that support modular development of simulation models. With such programming libraries, one can initially use place-holders to represent high-level components. As more details become available, each place-holder can be expanded to model the logical and hardware resources.

All layers of the model are interconnected. As a request flows through the model, the request is passed between the layers transparently. For example in Figure 2, a request is first generated by a blog and passed to the internal components that make up the RSS server. The left- and right-most arrows in Figure 2b represent the incoming and outgoing ports of the RSS server for communication with other high-level components, such as the blogs and users.

V. Case Studies

We conducted two separate case studies using our layered simulation models. In the first case study, we demonstrate (1) the construction of a layered simulation model for an RSS

Cloud system and (2) how performance data can be extracted from the model. In the second case study, we show how our layer-based simulation model can be used to detect problems in ULS systems by helping to evaluate different design options.

To build our layered simulation models, we use the OMNet++ framework [11]. OMNet++'s compound modules provide the run-time infrastructure to perform discrete event simulation and the means to implement the three hierarchical layers in our model. Each layer of a software system comprises a collection of entities. Each entity contains a set of state variables to reflect the properties of the entity at any point in time during the simulation. The collection of state variables from all entities represents the overall state of the system.

Case Study 1: Modeling an RSS Cloud

In this case study, we demonstrate the process of constructing a simulation model for the RSS cloud system in Figure 2. We use the performance information obtained from our simulation model to determine the performance bottlenecks. A performance bottleneck is a phenomenon where the performance of the entire system is limited by a single component. For example, if a server CPU would be the performance bottleneck, the notification request rate may overwhelm that server's CPU capacity, resulting in a continuous growth of the request buffer usage. As a result, the average response time and throughput in the system would suffer.

1) System Description: In order to model an RSS cloud, we need to better understand the RSS communication protocol. The RSS protocol is heavily used by blogging service providers such as Wordpress.com [23] to publish new web content. The traditional "pull" mechanism used by RSS readers periodically queries the RSS server for updates of a specific feed. The pull mechanism introduces latency between the publication of new content and the reception of this content by the RSS readers. To eliminate the latency introduced by pulling, the RSS cloud [15] – an extension to RSS – actively delivers notifications of newly published items to feed subscribers. This mechanism is known as "push".

Because the RSS cloud requires the hosting server to actively send notifications for each new item, the push mechanism puts a heavy resource requirement on the blogging service provider's infrastructure. For example, each time new content is published, the hosting server must initiate a separate connection to each subscriber to send a notification. For a service provider hosting hundreds of thousands of blogs with possibly millions of subscribers, the resource requirements of sending notifications would potentially exceed the available capacity. Furthermore, the large number of notifications may overwhelm online feed aggregator services such as Google Reader [5] that automatically download feed content for hundreds of thousands of users. The sections below document our experience of constructing a layered simulation model for the RSS cloud.

2) World View Layer of the RSS Cloud System: Figure 2a shows the world view layer for the simulation model of the RSS cloud. In this layer, the service provider, which supports the RSS cloud extension, connects the various blogs to the subscribing users. When new content is published, the service provider will send a fixed-size (e.g., 5 kilobyte) notification to all subscribers. To simplify our simulation, we vary the number of subscribers in a normally distributed fashion around a mean of 20 subscribers per feed.

To ensure reliability, subscribers acknowledge to the RSS server the reception of the content update notification. To monitor the delivery of the notification, the RSS server uses an internal timer. If an acknowledgment is not received before the timer expires, the RSS server assumes that the message is lost and will automatically resend the notification until the maximum number of resends for a subscriber is reached.

The network connections between all entities are characterized by two parameters: bandwidth and latency. We vary these two parameters to model a realistic environment where subscribers and blogs are globally distributed.

3) Component Layer of the RSS Cloud System: Figure 2b shows the component layer of the RSS server. The RSS server has four major logical components: two pairs of IN and OUT queues that buffer the communication between the subscribers and the blogs, the "app_logic" component, which abstracts away the system logic of the RSS server, and the "hw_core" component, which represents the physical hardware platform on which the RSS server resides.

Two types of resources are required to process a notification in the RSS Cloud system:

- **Logical resources** In our simulation model, there is one logical resource, i.e., the thread pool in the RSS server. The threads in this pool will process each notification request. If all threads in the pool are busy, the request will wait in the buffer of the input queue until a thread becomes available.
- **Hardware resources** Each notification request received from the blog will consume a specific number of units from each hardware resource. If all resources are used up, the request will wait in the buffer until the required resources become available.

The overall resident time of a notification request in the RSS server is the sum of the wait time in the RSS server's queue for acquiring the resources and the processing time required by the RSS server.

4) Physical Layer of the RSS Cloud System: Figure 2c shows the hardware platform of the RSS server. In our simulation, we assume that each notification request will compete for three physical resources: CPU, disk and memory. Each request will require a certain number of units from each resource while the request is being processed. For example, we can specify in the simulation that our RSS server has access to 1 gigabyte of memory, and that each notification will hold 50 kilobyte of memory when it is being processed. The resources are released when the request is serviced.

5) Model Validation: To ensure that the simulation model is specified correctly, we tested our model with a simplified use case where only one blog and one user are connected to the RSS server. In the test, all requests generated by

TABLE IV
PROCESSING REQUIREMENTS FOR AN RSS NOTIFICATION.

Resource	Requirement
CPU	2 unit
RAM	5 kB
Thread	1
Processing time	2 seconds

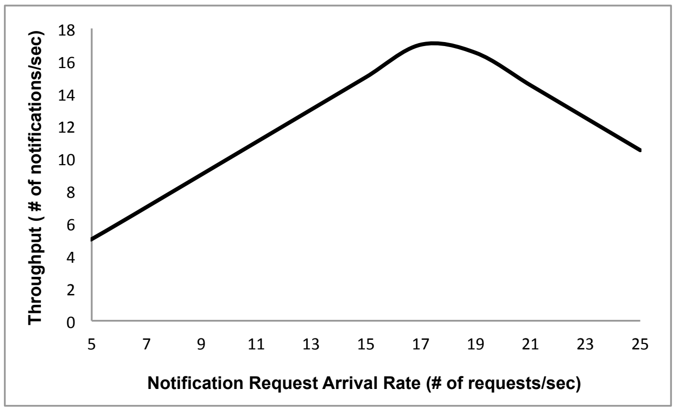


Fig. 3. Throughput of the RSS server at various request arrival rates (world layer).

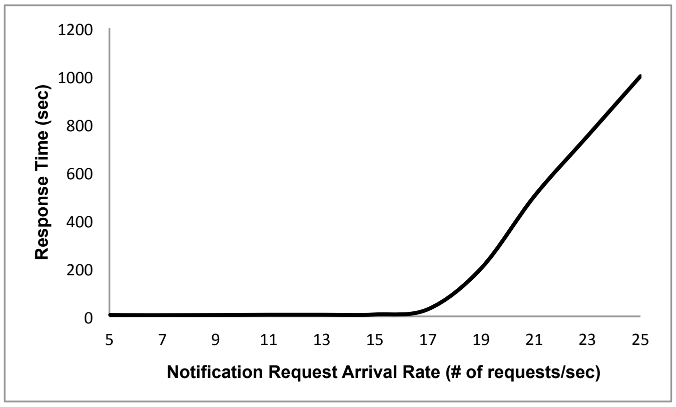


Fig. 4. Response time of the RSS server at various request arrival rates (world layer).

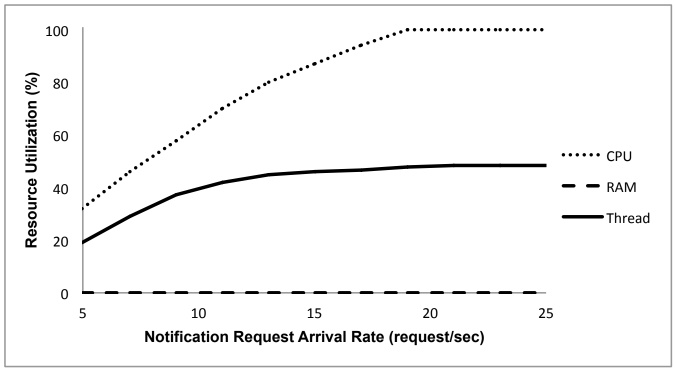


Fig. 5. Resource utilization of the RSS server at various request arrival rates (physical layer).

the blog component are serviced by the RSS server and subsequently received by the subscriber. Through visualization of the simulation and detailed traces, we are able to verify the timing of the requests as they propagate through the components in the different layers of our model.

6) Performance Bottleneck Identification: The core task of performance analysts is to determine if changes in the design of a software system would result in performance regressions, and whether or not such regressions would lead to performance bottlenecks. Here we show how layered simulation models are able to support performance analysts in these tasks.

We manually specify the resource requirements for processing an RSS notification request (Table IV), then examine the RSS server performance by varying the notification request arrival rate (but keeping it steady stream). Requests sent from the blogs to the RSS server are initially stored in the request buffer. Depending on whether or not the RSS server has enough resources (e.g., CPU, RAM, and a free thread) available, a thread will pick up the request from the buffer and allocate the required resources. Each request is processed for 2 simulated seconds during which all allocated resources are blocked by the thread. When the thread has processed the request, all previously allocated resources are released. The thread that has just been freed will pick up the next message in the request buffer.

To avoid random noise and fluctuations, we ran 10 simulations, each simulating one hour of operation with arrival rates ranging from 5 to 25 requests per second. During these simulations, we collected various statistics from different layers of the simulation model (Figures 3 to 5), such as throughput and response time of the world view layer, number of threads used in the component layer, and CPU and RAM utilization of the physical layer.

As evident from Figures 3 and 4, the system throughput and response time both degrade at 17 requests/second. In order to determine the bottleneck responsible for this, we examine statistics of resource utilizations (thread, CPU, and RAM) collected at the component and physical layers. Figure 5 shows that the CPU reaches 100% utilization at 17 requests/second while the thread and RAM utilizations are below 50%.

A request is only processed if all required resources can be allocated at once. If the CPU does not have enough capacity to serve a request, the request will wait in the buffer until the CPU becomes available, regardless of the availability of other resources. In other words, the CPU prevents other resources from being fully used and is therefore the performance bottleneck of the system. To ensure that the system can handle future growth of request arrival rate, system engineers should focus on CPU usage, for example by upgrading the CPUs or increasing the number of CPUs.

This case study has shown that a layered simulation model focusing on different stakeholders is able to identify performance bottlenecks in complex software systems.

Case Study 2: Evaluating Changes to System Design

As the demand for services increases, organizations examine different options to increase the performance of their systems

TABLE V
PERFORMANCE DATA COLLECTED PER LAYER.

Layers	Performance Data
World view layer	Response time, Transmission Cost
Component layer	Thread Utilization
Physical layer	CPU and RAM utilization

to cope with the high volumes of workload. In this case study, we use our simulation model to evaluate the performance benefits of migrating a centralized performance monitor for ULS systems to a distributed architecture. Since the performance of distributed systems is highly dependent on the configuration, the performance analyst should first determine which configuration of the distributed system provides the best performance.

1) System Description: Performance monitors are used to detect problems in the services provided by a ULS system. Such systems distribute computational units around the world to keep servers geographically close to the users. In the original design, one performance monitor would periodically collect performance data from each computational unit directly. While it is easy to administer, this centralized design has heavy resource requirements.

In a distributed design, each computational unit is connected to a local monitoring agent as shown in Figure 6. The local monitoring agents periodically collect, compress and upload the performance data to a central monitor for analysis. The central monitor may occasionally send back an updated set of monitoring policies to the local agents.

There are two major challenges involved with monitoring ULS systems:

- **Communication latency** ULS systems are decentralized around the world. Due to the large physical distances between the nodes and the central monitor, the performance data may not reflect the current state by the time the data is received by the central monitor.
- **Financial cost of data transmission** Depending on the frequency with which the performance data is sent, the cost of data transmission may be prohibitively high for ULS systems with many nodes deployed across the globe.

2) Simulation Model: Figure 6 shows the world view layer of the simulation model for the industry-inspired performance monitor used in our case study. The local monitoring agents and the central monitor are modeled using the same architecture as the RSS server (Figure 2).

Our simulation model has two tuneable parameters:

- **Data collection frequency** The rate at which local monitoring agents collect performance data from their respective computational units.
- **Data broadcast period** The amount of time an agent would wait between each successive upload of performance data. Data collected by the agents is first stored locally. When the send timer fires, all stored data is uploaded to the central monitor.

We conducted a series of simulated runs with 15 combinations of collection frequencies (0.1, 0.2, and 0.3 times per second) and broadcast periods (1, 3, 5, 7, and 9 seconds). Each of the 15 runs simulates an eight-hour workday. Each data collection consumes on average 30 Megabyte of memory and 10 CPU units, and lasts for 3 simulated seconds. Table V shows for each layer the performance data collected during a simulation run.

TABLE VI
CATEGORIZATION OF CPU UTILIZATION.

CPU Util.	Low	OK	High	Very High
Range (s)	< 30	30 – 60	60 – 75	> 75
Discretization	0.25	0.5	0.75	1

TABLE VII
CATEGORIZATION OF RAM UTILIZATION.

RAM Util.	Low	OK	High	Very High
Range (%)	< 25	25 – 50	50 – 60	> 60
Discretization	0.25	0.5	0.75	1

3) Evaluation of Configurations: In this section, we show that, by considering the performance data from all three layers, we are able to select a configuration that leads to a balance of three important aspects: cost, performance, and resource consumption. For this, we define a score to rank configurations according to multiple performance objectives.

Configuration Score We use the concept of configuration score to evaluate a given configuration of performance counters. This score needs to take into account that some counters are perceived by stakeholders in a fuzzy manner. For example, the difference between a CPU utilization of 20% and 25% is hard to observe and hence does not really matter. On the other hand, counters such as the response time and dollar cost are usually perceived by customers in a crisp way.

To account for the fuzziness of counter perception, we discretize the fuzzy counter values into discrete levels, where each level is ranked by a number between 0 and 1 according to stakeholder perception. Tables VI and VII show the categorization for CPU and RAM utilizations, respectively. For counters perceived in a crisp way (e.g., response time and cost), we use the original counter values.

The configuration score is calculated as the product of the discretized or crisp counter values of a configuration. As a simplified example, if a given configuration exhibits an average response time of 5.61 seconds, consumes on average 46% of the central monitor CPU, and has a cost of \$10, then the score of this configuration would be calculated as follows (taking into account the discretization levels of CPU Utilization in Table VI):

$$\begin{array}{rcl} Responsetime & = & 5.61\ seconds \\ Cost & = & \$10 \\ CPU\ Utilization & = & 46\% \rightarrow 0.5 \\ ----------- & & ----------- \\ \Rightarrow Score & = & 5.61 \times 10 \times 0.5 = 28.1 \end{array}$$

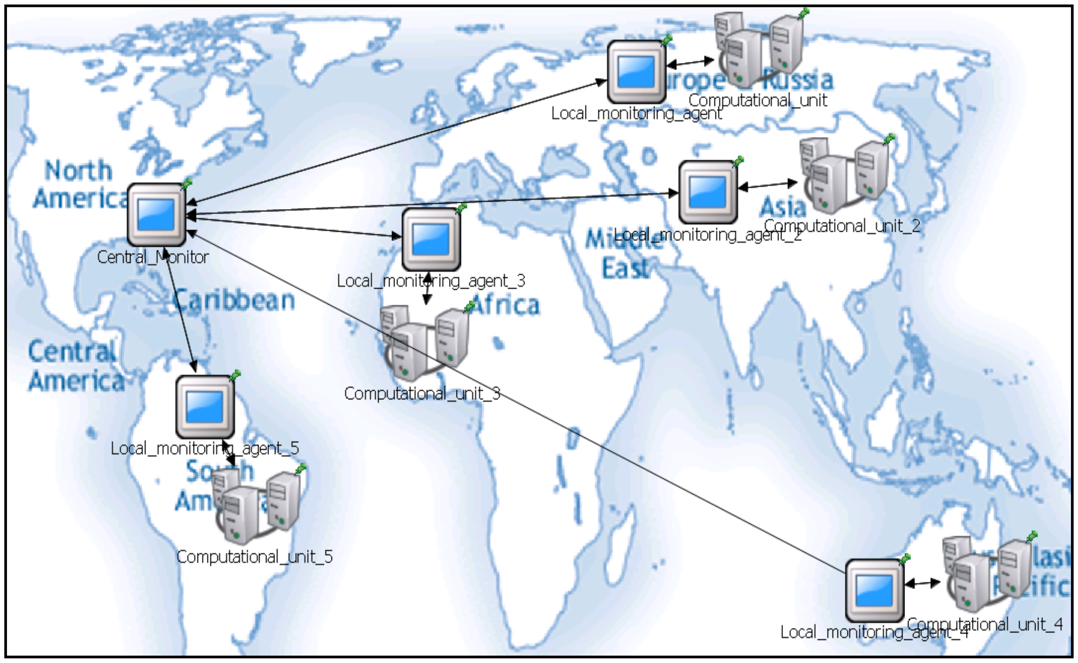


Fig. 6. World view layer of the performance monitor for ULS systems.

TABLE VIII
SIMULATION RESULTS FOR THE DISTRIBUTED DESIGN OF THE PERFORMANCE MONITOR.

Data Collection Frequency (Hz)	Layers	Data Broadcast Period (s)	Response time (s)	Cost per transmission ($)	Central Monitor Thread Util. (%)	Central Monitor CPU Util. (%)	Central Monitor RAM Util. (%)
0.1	World View	1	6.8	5.0	1.6	15.6	6.1
	Component	1	6.8	5.0	1.6	15.6	6.1
	Physical	1	6.8	5.0	1.6	15.6	6.1
0.2	World View	1	7.7	5.0	4.0	40.3	15.7
	Component	1	7.7	5.0	4.0	40.3	15.7
	Physical	**7**	**8.9**	**5.3**	**2.3**	**23.4**	**9.2**
0.3	World View	1	8.9	5.0	6.4	64.4	25.3
	Component	1	8.9	5.0	6.4	64.4	25.3
	Physical	**3**	**9.2**	**5.0**	**5.6**	**56.0**	**21.9**

Choosing the Optimal Configuration Since we aim to minimize resource consumption, response time and cost, the configuration that has the lowest score gives the best overall performance. Table VIII shows, for each data collection frequency, the three optimal configurations considering the performance data visible up to the designated layer in the second column. For example, we calculate the score of a configuration at the world view layer by multiplying the response time and the cost. If we are to calculate the score at the physical layer level, we would take the product of all five variables (response time, cost, thread, CPU and RAM utilizations). By doing this, we can determine whether early performance modeling by the world view layer stakeholders (Table II) is effective at picking the best configuration.

At the lowest data collection frequency (0.1 Hz), the optimal configuration can indeed be determined using the world view layer alone, since it picks the same configuration as the other two layers. This effect is explained by the fact that the system is only slightly loaded and the counters collected in the component and physical layers only exhibit small variations, e.g., RAM utilization ranges between 3% to 6%. As a result, all low level counters are discretized to the same range, diminishing the effect of these low level counters in the score calculation. Our discretization approach effectively hides the small variations of the performance counter that are insignificant in terms of stakeholder experience.

As the data collection frequency increases and more layers are being considered, our ranking algorithm outputs configurations that balance between cost, performance and resource consumption. For example, at the collection frequency of 0.3 Hz, the configuration selected by considering data collected up to the physical layers reduces the CPU utilization from 64.4% to 56% in a tradeoff of 0.3s increase of response time, while maintaining the same cost. In all our experiments, the world view layer performs at least as good as the component layer.

4) Evaluation of the Migration to a Distributed Architecture: Table IX shows the simulation result for the original design of the performance monitor at various data collection frequencies. Comparing to our distributed design (Table VIII), the original design, while providing better response time, consumes more hardware (e.g., CPU and RAM) and logical (e.g., thread) resources. At the collection frequency of 0.3 Hz,

TABLE IX
SIMULATION RESULTS FOR THE ORIGINAL DESIGN OF THE PERFORMANCE MONITOR.

Data Collection Frequency (Hz)	Response time (s)	Cost per transmission ($)	Central Monitor Thread Util. (%)	Central Monitor CPU Util. (%)	Central Monitor RAM Util. (%)
0.1	0.2	2.2	31.0	42.6	37.2
0.2	0.3	2.7	43.7	68.2	47.6
0.3	0.4	3.1	60.2	86.6	59.2

the CPU of the central monitor is close to running at its full capacity, which will likely result in system instability. Moreover, while the original design has lower cost per transmission, the performance data in the original design is transmitted more frequently due to the absence of a local batching mechanism provided by the local monitoring agent. As a result, the overall cost for monitoring all computational units would increase in the original design compared to the distributed design.

In this case study, we demonstrated the usefulness of our layered simulation model in evaluating the different design options for the performance monitor. Furthermore, we show that configurations selected by analyzing information from the top level can provide a good estimation of resource consumption. As more information from different layers is supplied, our ranking algorithm is able to select configurations that balance between cost, performance, and resource consumption.

VI. DISCUSSION

In this section, we discuss how our simulation models can be updated over time and what the major limitations of our approach are.

A. Updating the Simulation Model to Reflect System Changes

In discrete-event simulations, system components react based on received messages. Therefore, performance analysts can model the system's behaviour by specifying the state a component should be in when a specific message is received. For example, to simulate the time required to process an RSS notification request, performance analysts can specify that the RSS server would hold each request for 2 simulated seconds before forwarding the notification to subscribers. Performance analysts do not need to know the low-level programming details when constructing the model, which drastically reduces the modeling effort.

To update a model constructed for a previous release of a software system to a new version, the resource requirements of the configuration need to be updated. Furthermore, new system behaviour can be introduced into the model by adding new message types and their corresponding behaviour in the simulation code. Once the modified model reflects the new configuration and behaviour, new simulation runs can be performed.

B. Capturing Resource Requirements

Correct resource requirements are essential in deriving useful performance conclusions from a simulation model. To ensure that the simulation model accurately reflects the performance of the final system, resource requirements should be validated as information becomes available throughout development. Due to the lack of access to production data, we could only estimate a list of resources and processing requirements in our case studies.

VII. RELATED WORK

We discuss four areas of related work: approaches to construct multi-view models, approaches to apply performance modeling at each stage of development, and approaches to create analytical and simulation models.

Multi-View Models Kruchten et al. proposed the well-known "4+1 View" model to describe the different aspects of software architectures [7]. The "4+1 View" model focuses on supporting software architecture understanding for different stakeholders. Our simulation model, on the other hand, focuses on modeling system performance for different stakeholders.

Woodside proposed a Three-View Model for performance analysis of concurrent software [20]. The three views in Woodside's model are drawn from existing analytical techniques and are connected by a "core model" that applies the results of one analytical view to the input of another. Our approach is different from Woodside's Three-View Model, since our models are based on simulation models and do not require a "core model". Each layer in the simulation model is built on top of each other, tied together by test case scenarios.

Incremental Performance Models Performance modeling can be started at the early stage of software development. Smith et al. proposed a technique to create simple models such as a System Execution Model from usage scenarios with estimates of resource requirements in the beginning of software development [17], [19]. At a later stage, more accurate models such as LQN can be built as more information becomes available. Our model avoids the use of different techniques at different stages in the development, while detailed logic and resource requirements can be added to the simulation model as more information becomes available.

Another notable work in this area is the work on run-time performance control (e.g., [25]). Initially, there is no sufficient run-time information available about the software system. Hence, the models used to control the performance of the software system can only use statically available information. Once execution starts, more information becomes available, with which the initial models can be iteratively refined to converge to a more accurate model. Similar to this work, our layered models start out with incomplete information at the world view layer, before being refined based on more accurate lower-layer information.

Analytical models The Queuing Network Model (QN) has long been used to analyze the performance of software systems. Baskett et al. proposed algorithms to solve the open, closed, and mixed QN models [1]. Rolia proposed to model complex software systems with layers of servers [13]. Menascé proposed an approach to model both the software and hardware resources of a system in a combined model [8]. Woodside et al. proposed an automatic technique to create LQN models from traces of messages passing between software components [22], [6]. However, the quality of the generated layered model depends on the accuracy of the traces.

Performance data can be derived from analytical models by solving a set of equations. Because of the use of complex formulas, the knowledge encapsulated in an analytical model can be difficult to transfer to other stakeholders. Furthermore, in order to update analytical models, modelers must possess a certain level of expertise in mathematics. Models built using event-based simulation, on the other hand, can be described using source code, which may provide a lower entrance barrier.

Simulation models Smit et al. proposed a simulation framework to support capacity planning for Service-Oriented Architectures (SOA) [16]. Each service in an SOA-based system is modeled as an entity that can send and receive messages. Similar to Smit's work, our approach can readily be used to model the performance of SOA-based systems. Furthermore, our approach allows modelers to create highly accurate models through the use of layers.

Bause et al. extended Petri Nets with Queuing Networks [2]. Xu et al. used coloured Petri Nets to model the architecture of software systems [24]. The authors analyzed performance in time and space based on simulations of test cases. We also simulated test casesto analyze the performance of a software system, however our approach provides modelers with a structured way to construct models suitable for use by multiple stakeholders with varying objectives. Furthermore, by using multiple layers in the simulation model, we effectively create a single, synchronized performance knowledge base that all stakeholders can refer to.

VIII. Conclusion

A performance model should convey information about the behaviour of a ULS system relevant to the performance concerns of all stakeholders. Inspired by the "4+1 View" model for software architecture, we proposed an approach to construct simulation models with four layers of abstractions: the world view layer, component layer, physical layer, and usage scenario layer. These layers can be built gradually in a top-down manner as more information about the software project becomes available. Two case studies on complex software systems showed that our layered model can be used to identify performance bottlenecks and evaluate design changes.

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