Cross-layer Adaptation and Monitoring of Service-Based Applications *

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Abstract. The heterogeneity and dynamicity of services, their underlying infrastructures and environments make the problems of adaptation and monitoring an emerging issue for service based applications (SBA). While a wide range of research works aims to address these problems, most of them focus on a particular element of the SBA architecture. Indeed, those approaches are very fragmented and isolated; they do not consider the effect of changes and adaptations on the whole stack of the functional layers of SBA. In this paper we study the problem of cross-layer SBA monitoring and adaptation and define the requirements for the novel, integrated approaches that provide coherent and holistic solutions for monitoring and adapting the whole application. We illustrate the problem using a series of case studies and provide a set of requirements that the novel cross-layer approaches should address. Based on the taxonomy of those requirements, we also define the mechanisms and techniques that are necessary for addressing the requirements and that constitute an integrated cross-layer framework. Finally, we describe a uniform conceptual model underlying such a framework, and present a set of potential and existing principles and methodologies that enable cross-layer monitoring and adaptation.

1 Introduction

Service-Based Applications run in dynamic business environments and address evolving requirements. These applications should hence become drastically more flexible, as they should be able to adequately identify and react to various changes in the business requirements and application context. These challenges make monitoring and adaptation the key elements of modern SBA functionality.

The problem of monitoring and adaptation of various types of software system has gained a lot of interest both in the research community and in industry. In recent years, these aspects have attracted more and more interest in the area of SBA and in Service-Oriented Computing (SOC). However, the results and directions are still insufficient. A fundamental problem with the state-of-the-art results on monitoring and adaptation is their fragmentation and isolation. Usually, the existing adaptation and monitoring solutions target a particular functional layer, i.e., business process layer, service composition layer, or infrastructure layer. While these solutions are quite effective when

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considered in isolation, they may be incompatible or even harmful when the whole SBA is considered. Indeed, the realization of different SBA layers may be highly interleaved: different artifacts at one layer may refer to the same artifacts in another layer, while such relations are ignored by the isolated monitoring and adaptation solutions. As a consequence, wrong problems may be detected, incorrect decisions may be made, and the modifications at one layer may damage the functionality of another layer. Similarly, as various disciplines are involved (e.g., BPM, Grid, component-based software), they provide distinct solutions using different terminology, different levels of abstraction, and different models, which are hard if at all possible to integrate and align.

This paper aims to study the problem of cross-layer SBA monitoring and adaptation. Starting from a series of illustrative scenarios, we identify and classify the requirements that the novel cross-layer approaches should address. In particular, we identify the four key problems that may arise due to the isolated monitoring and adaptation, namely lack of alignment of monitored events, lack of adaptation effectiveness, lack of compatibility, and integrity of the adaptation activities. Based on the taxonomy of those requirements, we also *define the mechanisms and techniques* that are *necessary for addressing the requirements* and that constitute an integrated cross-layer framework.

The paper is structured as follows. Section 2 describes the model of the SBA, while Section 2.2 describes various monitoring and adaptation approaches applied to those applications. Section 3 illustrates the problem of the cross-layer adaptation and monitoring with a set of case studies. Finally, Section 4 discusses the possible mechanisms, principles, and solutions for the target cross-layer adaptation and monitoring framework.

2 Adaptable and Monitorable Service-Based Applications

An SBA is an application that cannot be implemented by a singular service, but requires the aggregation of multiple singular or composite services in a network to guarantee the application goals [1]. Services are independent entities that can achieve a specific task or a group of tasks and be re-utilized for different applications in different contexts. They can be provided by either the SBA owner itself or mostly by a third party.

2.1 Functional Layers of Service-Based Applications

An SBA can be illustrated by its three functional layers, business process management (BPM), service composition and coordination (SCC) and service infrastructure (SI). BPM is the highest level functional layer where the application activities, constraints and requirements are described without design details. At BPM, the entire business process is considered as a workflow and the business activities as the constituents of this workflow. SCC is the layer between BPM and SI layers where the basic workflow constructed at BPM is refined by the composition of suitable services that are capable of realizing the business activities and altogether accomplishing to build the whole SBA. SCC is the responsible layer to organize and manage the control and data flows among services in the composition. Finally, as the lowest layer we have SI, which provides the underlying run-time environment for the composed SBA. As well as the service realization, the collection of all available services is kept at this layer through a service registry, from which the identified services for the composition are discovered. In addition to the functional layers, we will introduce the key elements of each layer that we have identified as critical for the cross-layer monitoring and adaptation.

BPM Layer Workflow, key performance indicator (KPI) and agile service network (ASN) are the key elements relevant for the BPM layer.

Workflow is the abstract model of the complete business process defining logical decision points, sequential or parallel work routes and exceptional cases of the application. Business process may reveal the entire SBA or in some cases part of the SBA where SBA is actually a combination of business processes in a large-scale, cross-organizational domain. While business activities constitute the workflow by performing well-defined tasks, business rules together with business policies might have an implicit or explicit effect on the specification of business processes and activities.

KPI is a metric that shows quantitatively if the business performance meets the predefined business goals of the SBA. KPIs are formed by assigning target values to the business metrics that are relevant for the application. Value assignment is made based on business goals. Business metrics can be financial such as revenues, customer-related such as customer satisfaction index, process-related such as order fulfillment cycle time or "learning and growth" related such as innovation rate [2].

ASN is a model used to illustrate the cross-organizational interactions among companies, which collaborate to construct geographically distributed complex SBAs. ASN depicts the highest and most abstract business level where partners (constitutive companies) are nodes and their offerings and revenues are edges on the model. While ASN pictures overall relations of service providers without any details, the refinement of this model for a specific SBA signifies forming the business processes of the application.

SCC Layer Service composition and process performance metric (PPM), as well as the properties of constituent services are the key elements relevant for SCC layer.

Service composition is a combination of a set of services to realize a workflow. The designer needs to know the descriptions, interfaces and supported protocols of the available services to acquire the necessary input for composition. Consequently, the characteristics of the available services play a key role to decide how to compose the workflow although the designer is not interested in how these services are realized.

PPM is a metric that measures the performance of a process in terms of cost, quality or duration. Here, the process may refer to the whole composition (the whole workflow) or part of it (a subflow). PPM can be calculated for one instance or as an aggregate value. While instance PPMs are calculated based on process probes, which describe the information to be collected at process run-time, aggregate PPMs are calculated based on instance PPMs such as taking average of all instances.

Service metrics are basically QoS metrics which talk about several aspects of a service such as response time, cost, availability, reliability or scalability. QoS metrics expose non-functional properties of a service building a base for the overall performance metrics of the SBA.

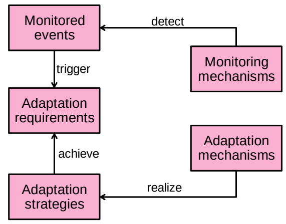

Fig. 1. Conceptual A&M framework

SI Layer Service registry, discovery and selection, and service realization are the key elements relevant for SI layer.

Service registry, discovery and selection constitute the infrastructural facilities to find and select the services required by the composition. Service registry is the information system where service descriptions are kept as a searchable repository. Service discovery and selection are the basic functionalities of a service broker that is contacted by the SCC layer for the selection of most suitable services for SBA realization. Here, service discovery implies information retrieval from the service registry by the service broker. Next step for the broker is the service selection based on the acquired information about available services.

Service realization corresponds to the run-time environment on top of where services are implemented and executed. Every entity which contributes to the underlying fabrics of a service can be categorized as a part of the run-time environment. To exemplify one can speak of grids, clusters, data servers, software, protocols and network infrastructure.

2.2 Monitoring and Adaptation

A general framework for SBA monitoring and adaptation defined in [3] is represented in Figure 1. In this framework with *Monitoring Mechanism* we mean **any** mechanism that can be used to check whether the actual situation corresponds to the expected one. Thus, the meaning is very broad; it goes beyond traditional run-time monitoring and may include run-time verification and testing, post-mortem analysis, data mining, etc. With these mechanisms one may detect *Monitored Events*, i.e., the events that deliver the relevant information about the application execution, evolution, and context. In turn, monitored events trigger *Adaptation Requirements*, which represent the necessity to change the underlying SBA in order to remove the difference between the actual (or predicted) situation and the expected one. In order to satisfy those requirements it is necessary to define *Adaptation Strategies*, which in turn are realized with the appropriate *Adaptation Mechanisms* – the techniques and facilities provided by the underlying SBA or by the operation and management platform in different functional SBA layers.

A wide range of the adaptation and monitoring problems as well as the existing approaches identified and realized at different functional SBA layers can be mapped onto this framework. Such adaptation and monitoring mechanisms should then be used

Table 1. Monitoring at different functional SBA layers

Layer		Subject	Events	Mechanisms
BPM	Business Process monitoring	business process model; transaction protocol; data and control flow	violation of correctness properties of instance executions; correspondence to the model; violation of transactional property	BAM/BI; process log analysis, process mining
	KPI monitoring	KPI	KPI violations	BAM/BI, special approaches
SCC	Monitoring functional properties	service composition; data and control flow	violation of functional properties of a composition; violation of functional properties of a constituent services	special purpose monitoring engines based on temporal logics; rule languages; calculi
	Monitoring non-functional properties	PPMs, utility functions, QoS metrics	violations of expected values/thresholds, SLA violations	special purpose monitoring engines, service monitors
SI	Grid monitoring	grid infrastructure (sites, virtual organizations); grid applications	wide range of infrastructural and application events	grid monitoring platforms and architectures
	Monitoring of component-based systems	components (state, bindings, messages, internal data), component platform (performance, dependability, state of resources)	component- and middleware-related events	middleware monitoring mechanisms, internal component monitoring mechanisms

by the holistic integrated cross-layer adaptation and monitoring framework as building blocks. Note, however, that currently not for all of the presented elements appropriate mechanisms and techniques have already been defined. New approaches still have to be provided by the research in order to enable cross-layer monitoring and adaptation in a holistic, integrated manner.

We will describe monitoring and adaptation at different layers according to the key elements of the monitoring taxonomy presented in [3]: i.e., subject of monitoring, monitored events, monitoring mechanisms, and adaptation requirements, adaptation strategies/actions, adaptation mechanisms respectively.

Monitoring in Different SBA Layers At the BPM layer the monitoring approaches focus on monitoring business activities (BAM, [4, 5]) and KPIs [6, 7]. At the SCC layer the monitoring engines and frameworks provide means to observe the execution of composed services (specified, e.g., in BPEL), including functional and non-functional properties and metrics [8–10] of the compositions, or the constituent services [11, 12]. Monitoring at infrastructure layer may be realized on top of Grid monitoring solutions or based on the middleware for component-based systems [13, 14].

While the existing approaches may cover a wide spectrum of the problems and application domains, they are usually considered in isolation from each other; exploit different models of monitored events, and different platforms. As we will see in the following sections, this may lead to inconsistencies in functioning of the SBA.

Adaptation in Different SBA Layers At the BPM layer, possible adaptation strategies cover business process, KPI and ASN adaptation [15, 16]. Mostly ad-hoc modifications are applied as an adaptation mechanism. At the SCC layer, the adaptation approaches focus on either the composition [17, 18] or the services [19, 20]. Automated composition, model-driven transformation and dynamic service binding are common adaptation mechanisms for this layer. Finally, adaptation at the SI layer may be service-discovery

Table 2. Adaptation at different functional SBA layers

Layer		Requirements	Strategies/actions	Mechanisms
BPM	Business process adaptation	optimize process; recover from unforeseen execution; customize process	modify business process control flow (add, delete, replace process tasks and process fragments), modify business process data flow (change data dependencies, values); process re-design	ad-hoc modifications (performed by business analysts); evolution
	KPI adaptation	adjust to changed business goals, business context, ASN elements	add or remove KPI, change KPI values	ad-hoc modification; negotiation; evolution
	ASN adaptation	optimize costs; transactionality; accommodate to ASN changes	change transaction protocol; change service; renegotiate for an offering	ad-hoc modification, negotiation, evolution
SCC	Composition-related adaptation	adjust to changed process model or KPI, optimize process, recovery	re-composition; control/data flow changes; PPM changes	automated composition; model-driven transformations; fragmentation
	Service-related adaptation	service changes; optimization; SLA violation	replace a service; re-execute a service; renegotiate QoS	dynamic binding; negotiation
SI	Service discovery-related adaptation	optimization, adjust to business requirements	change registry; update registry (new services, new descriptions); change discovery mechanism; change selection mechanism	platform-specific; reputation management
	Service realization-related adaptation	optimization, adjust to infrastructural failures	modify/re-configure service platform (software, OS, virtual machines, physical platforms); modify/re-configure service resources (allocate/release resources, load balancing); adapt resource management (change resource broker, re-configure/re-execute grid application)	ad-hoc changes; self-* techniques

[21, 22] or service-realization-related [23, 24]. To achieve different kinds of SI adaptation, various self-* techniques can be used.

Although the state-of-the-art approaches may address a significant adaptation need for an SBA, none of them are complete. They focus on a local solution for a specific adaptation requirement without taking into account its dependencies or effects on different SBA layers. As we will illustrate in the next section, such ad-hoc approaches are not promising in terms of addressing a proper solution to construct an adaptable SBA.

3 Requirements for Cross-layer SBA Adaptation and Monitoring

In this section we will illustrate a range of problems occurring due to the adaptation and monitoring mechanisms at different functional SBA layers in isolation from each other. We will illustrate each of those problems using the scenarios from the automotive domain case study. For each of the problem we will demonstrate the model of the SBA used, the scenario leading to the problem, and the requirements that the cross-layer adaptation and monitoring framework should meet in order to resolve that problem.

3.1 Lack of Alignment of Monitored Events

In many cases, if the monitoring is performed by specific mechanisms provided at different layers in isolation from each other, then the corresponding events are not aligned and the critical information is not adequately propagated across layers. This may lead

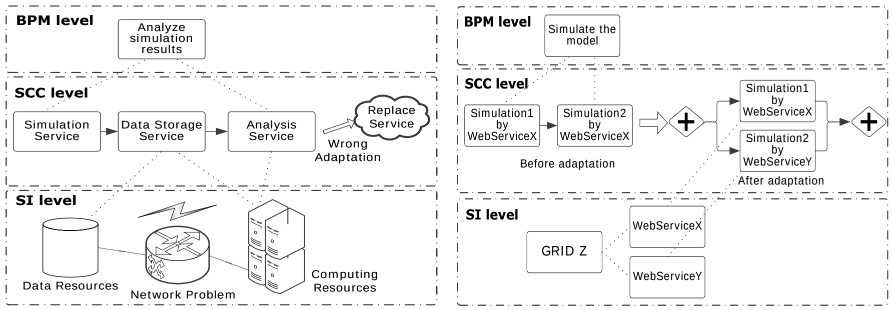

Fig. 2. Cross-layer requirements: lack of alignment and effectiveness

to the situations where the source of the monitored problem is identified incorrectly, or where the same problem results in separate events at different layers and then triggers different (possibly contradictory) adaptations, etc.

Model At BPM layer the relevant part of the SBA is represented by the "manufacturing" business process. The goal of the process is to design and simulate the new models and move to mass production after simulation verification. Activities are realized by the appropriate software services provided by the partners in ASN. Underlying infrastructure comprises computational resources equipped with the sophisticated resource management and load balancing mechanisms.

Scenario While the process is executed, the "analyze simulation results" activity takes abnormally much more time than it is expected; i.e., the composition PPM is violated, which is detected by the appropriate monitor at the SCC layer. As a result, in order to satisfy the adaptation requirement to compensate the PPM violation, the service is substituted with another service and the analysis task is performed again (Figure 2(a)).

Problem However, the expected effect is not achieved: the source of the problem is not the analysis service, but the network problem during the transfer of a large amount of data. That is, the real problem occurs at the SI layer, while detected at SCC, so it is incorrectly diagnosed. A correct solution here could be to monitor it also at SI and perform adaptation there (e.g., by allocating resources in proper way) or to perform appropriate process fragmentation at SCC to minimize data transfer. Note that monitoring the same problem at different layers is not enough: the events still have to be aligned. For instance, independent monitoring in the SCC and SI layers could trigger execution of the process fragmentation and resource re-allocation respectively. Without coordination, these adaptations may be in conflict with each other and have unpredictable result.

While the presented scenario shows the problem when the monitored information is not propagated bottom-up, similar problem may occur if the events are not delivered to lower levels of the SBA stack. Consider, for instance, a situation, where at BPM a policy for quality control is changed, which results in increasing duration of the "verify simulation results" task. When observed at the SCC layer, this event triggers the appropriate adaptations at this layer, while the change should be processed at the BPM layer (e.g., by changing the corresponding KPIs, which would also require changes in the PPMs at the SCC layer).

Requirements In order to avoid the problems represented in the above scenario, the following requirements should be addressed: (i) to provide necessary monitoring mechanisms at all the layers, where the problem of interest may be observed (ii) to provide means to propagate the monitored information across the layers in order to properly diagnose the actual source of the problem (iii) to align and correlate the monitored events across functional layer in order to avoid spontaneous and uncoordinated adaptation activities at different layers.

3.2 Lack of Adaptation Effectiveness

Another possible problem is that the adaptation activities may fail to achieve the expected effect, since they do not take into account the properties of other layers.

Model At the BPM layer the relevant part of the SBA is represented by the "manufacturing" business process. At SCC each of the business activities is realized by one or more services provided by ASN partners. E.g. "simulate the model" business activity can be realized by a service that accepts the simulation requests and runs them on top of a high performance computing grid. SI layer provides the run-time environment for such services, i.e., the grid computing resources where simulation tests are run, and the storage resources where the test data and results are kept.

Scenario At BPM layer, it has been monitored that KPI value for average duration of simulations is not met because the simulation runs take too much time. The adaptation requirement is to compensate KPI violation by reducing the total simulation time. To achieve that, it is decided to parallelize simulation tests at service level by agreeing with a new simulation service provider and enabling concurrent run of these two different simulation services (Figure 2(b)).

Problem The new service might be using the same grid resources to run the simulation tests as the original one. In this case there will not be an improvement in total performance of the process.

Requirements In order to overcome the problem of this sort, it is crucial to take into account features and properties of the whole SBA stack when the adaptation requirements are defined and the adaptation strategy is identified. In the example this would mean to relate the requirement to parallelize the activity in SCC layer with the allocation of service resources in SI layer, thus the proper service (with independent resources) would be selected.

3.3 Lack of Compatibility

The problem of cross-layer compatibility of adaptation activities refers to the situation, where the adaptation performed at one functional SBA layer is not compatible with the requirements and constraints posed by other layers.

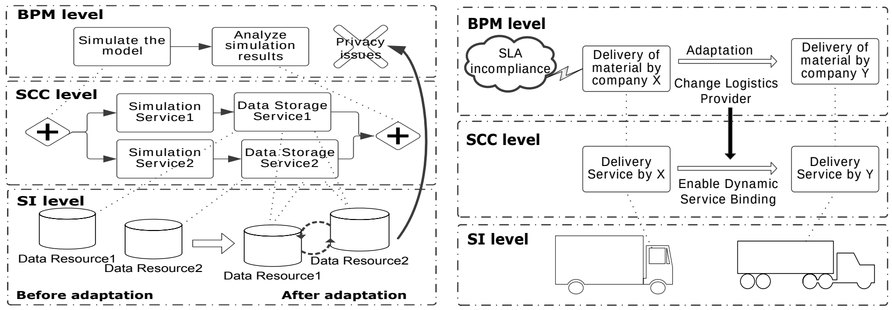

Fig. 3. Cross-layer requirements: lack of compatibility and integrity

Model As in previous scenario, the BPM layer is represented by the "manufacturing" business process, the SCC layer is realized as a composition of the appropriate services, while at the SI layer a grid infrastructure underlies the simulation services.

Scenario At SI level, it has been monitored that required QoS value of the simulation service is not met due to the unavailability of some of the storage resources (they have reached full capacity utilization being unable to store new simulation data). The adaptation requirement posed at the SI layer in this case is to compensate the QoS degrade (SLA noncompliance). It is achieved by the following adaptation strategy: perform load balancing of the storage resources (transfer excessive data to additional resources)(Figure 3(a)).

Problem The applied adaptation strategy may, however, violate privacy issues stated at the BPM layer. In particular, a special business rule may require that simulation data for each automobile model must be kept at a separate server with the access by the authorized entities only. This implies that at the BPM layer such distribution of data is not permitted. Therefore, the adaptation performed at the SI layer violates the requirements of BPM layer.

Requirements In order to take into account the issue of the cross-layer adaptation compatibility, it is necessary to consider how the identified adaptation activities influence the SBA as a whole. In particular, it is crucial to be able (i) to define certain "boundaries" for each of the layers and (ii) to check that the adaptation activities of other layers do not cross those boundaries. In the above scenario, for instance, it would be necessary to be able to analyze how the resource re-allocation may affect the privacy issue. Indeed, this implies that both these elements are appropriately modeled and specified, and the corresponding analysis is done before the adaptation is executed.

3.4 Lack of Integrity

The problem of cross-layer adaptation integrity deals with a situation, where it is not enough to perform the adaptation at a particular layer only, but several actions at different layers should be performed.

Model At the BPM layer, we are interested in "plan and purchase material from suppliers" business process. The process is correlated with manufacturing process; the goal is to acquire the required components before moving to the manufacturing phase. The "decide on supplier" business activity is provided by a service that keeps up-to-date information about available suppliers and their offerings, and discovers, and selects the most appropriate supplier based on the purchase specification of the material. The "delivery of material" business activity has to be performed by a delivery service, probably involving some other services. The SI layer is realized by the appropriate service execution platform, e.g., composition engines, service bus, database, etc.

Scenario At the BPM layer, it has been monitored that the logistics provider company, which is responsible for the delivery of material, does not comply with the SLA contract. The adaptation requirement is to compensate the SLA violation, and can be achieved by switching to a new logistics provider available in the ASN. This, in particular, requires the negotiation and agreement with a partner with matching service offerings (Figure 3(b)).

Problem During the adaptation action, several process instances might have already been started for some material and components. Change of the logistics provider will indeed affect these instances as the corresponding activity ("delivery of material") has to be performed by the new one. Indeed, it is also necessary to adapt at the SCC layer by changing the composition instance accordingly: it is needed to bind to the new services corresponding to the new provider, align with the new interface and data formats if they are different for the new provider, perform some compensation actions for the old provider if the delivery procedure has already been triggered, etc. This may also require adaptations at the SI layer as the new service may have particular constraints on the the low-level protocols or security policies.

Requirements To address this problem, novel mechanisms are necessary to identify, aggregate, and enact wide range of adaptation actions available at different functional layers. Indeed, these actions should be performed in a coordinated manner; some centralized mechanism should be able to control and manage isolated layer-specific tools. In our example, such a centralized tool should analyze which layers are "affected", identify all adaptation actions to be performed at different layers, and schedule a coordinated procedure that executes those actions in a holistic way.

4 Towards Cross-layer Adaptation and Monitoring

In this section we will show how the presented requirements for cross-layer adaptation and monitoring are positioned in the general A&M framework and what kind of mechanisms and principles are necessary to achieve them. We will also show how these mechanisms and principles may be realized by the existing and novel approaches, thus defining a tentative roadmap for the research activities on cross-layer adaptation and monitoring. We remark that our goal here is not to come out with a concrete solution for this problem, but rather to agree on a common vision of the problem and to identify the most prominent directions to be investigated.

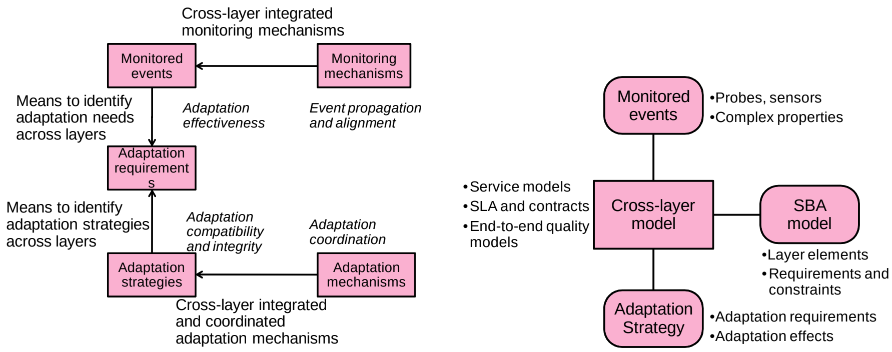

Fig. 4. Cross-layer adaptation and monitoring framework

4.1 Required Mechanisms for Cross-layer Adaptation and Monitoring

Figure 4(a) represents the placement of the requirements for the cross-layer adaptation and monitoring in the general adaptation and monitoring framework. It also shows the mechanisms and approaches necessary to achieve those requirements.

Cross-layer integrated monitoring mechanisms To guarantee the requirements of alignment and propagation of monitored events across functional layers, novel mechanisms and approaches have to be provided. These mechanisms will be built on top of the monitoring capabilities provided by the isolated functional layers; they will provide a holistic, integrated infrastructure for the SBA monitoring. In particular, they should

- provide ways to express properties of interest in terms of events and properties specific to a particular layer and a particular monitoring mechanism in an integrated and uniform manner;
- relate events and mechanisms of different layers to each other to enable their correlation, aggregation and alignment;
- provide an infrastructure for subscribing, detecting, and propagating the relevant events across monitoring engines defined at different functional layers.

Cross-layer integrated and coordinated adaptation mechanisms As for adaptation, cross-layer mechanisms should guarantee that the adaptation activities being triggered at different layers are properly managed and coordinated. In order to avoid spontaneous, concurrent and even conflicting adaptations performed at different layers in isolation, there is a need to provide centralized mechanisms that are able to

- aggregate and coordinate different adaptations when they appear to be related or triggered by the same events;
- control (e.g., activate or deactivate) adaptation mechanisms at different layers;
- validate different adaptation activities to check if they are in conflict, interleaved, or have interdependencies.

Means to identify adaptation needs across layers Another set of important cross-layer mechanisms deals with the capability of properly identifying the necessary adaptation requirements, when the changes concern not a single layer, but the whole application. That is, these mechanisms would address the problem of adaptation effectiveness by providing ways to

- properly identify the source of the problem and the corresponding requirements to be managed by adaptation;
- map these requirements onto the relevant functional layers, i.e., identify the specific needs at each affected layer;
- identify the adaptation strategies at different layers that, enacted together, would achieve the expected goal.

In the scenario described in subsection 3.2 such mechanisms would first detect that the problem occurs due to the computational bottleneck at the level of the simulation service and therefore the activity should be parallelized, and then require that this is achieved both at SCC and at SI layer by replacing a service and ensuring that the service realizations are independent.

Means to identify adaptation strategies across layers Finally, there is a need that the mechanisms address the problems of the adaptation compatibility and integrity. From the perspective of the general adaptation and monitoring framework, these mechanisms should support the identification and selection of the adaptation strategies. In particular, novel approaches should

- validate the adaptation strategies against the whole model of the application to avoid actions that have undesired side-effects with respect to other layers or can even damage the expected functioning of those layers (compatibility problem);
- foresee whether the adaptation strategies are sufficient to achieve the corresponding requirements or some other actions are needed;
- should further search for the additional or more appropriate adaptation strategies when the selected strategies are insufficient or may in turn trigger some other adaptations (integrity problem).

As one can see, such mechanisms aim to support quality assurance for adaptation as they deal with the analysis of adaptation activities against the model of the system, against the adaptation requirements, and against other adaptations.

4.2 Required Principles for Cross-layer Adaptation and Monitoring

To provide a basis for the cross-layer SBA monitoring and adaptation and to enable various mechanisms described in subsection 4.1, it is necessary to explicitly relate different conceptual elements to each other and across different layers. This vision is reflected by the conceptual model represented in Figure 4(b). Without loss of generality, the model shows that various specific elements of the application, of the adaptation mechanisms and capabilities, and of the monitoring mechanisms and capabilities should be related to a centralized, high-level model which defines some cross-cutting aspects of the SBA.

More precisely, the following relations should be defined by the elements of a cross-layer framework:

- *Cross-layer representation of monitored events*. Cross-cutting aspects of the SBA functioning should be used to capture and represent relevant monitored events, monitoring mechanisms and information sources (probes, sensors, engines, etc.) at a particular layer; to abstract from the low-level realization and specification details; to characterize the input of monitoring engines in terms of those cross-cutting aspects thus making the cross-layer relations among events transparent.
- *Cross-layer representation of adaptation strategies*. To enable the analysis of adaptation integrity, effectiveness, and compatibility, the adaptation strategies and mechanisms of different layers should also be characterized in terms of the relevant cross-layer models. In particular, this representation should be able to describe key aspects of the adaptation strategies (the requirements to be achieved, the effects of the strategy enactment) abstracting away the specific information about how the adaptation strategy is represented and realized in the approach.
- *Cross-layer representation of the SBA model*. In order to understand the relation and the impact of the adaptation activities on the elements of the SBA architecture, the latter should also be characterized in terms of some cross-cutting models. In this way, the specific requirements and constraints, posed by the SBA engineers on the modules and constructs of different layers will be related to the monitored events (i.e., to the changes in the SBA or its context) and to the adaptations (i.e., to the effects they have on the SBA).

To define and describe such cross-layer model, various languages, notations, and concepts may be exploited. The specific realizations of the cross-layer frameworks may target specific needs and application domains; as a result, they will provide concrete languages and solutions for the problem. Possible candidates both for the cross-cutting concepts and for the approaches towards their definition and modeling may be

- *Service models*. Various models of services make up a substantial part of the SBA model at all the functional SBA layers. At the BPM layer services comprise the ASN and characterize the participants of the domain, their economic properties, relations, and requirements [2]. At the SCC layer the services are aggregated into service compositions, for which the descriptions of both their functional (interfaces, data formats, protocols, etc.) and non-functional (QoS) characteristics are exploited. At the SI layer the services are represented both by the registry-specific descriptions used to discover and select the services and by their realizations, i.e., infrastructures and their configurations. As such, the service models may also be used to define the cross-layer monitoring properties and adaptation strategies.
- *SLA and contracts*. Service-level agreements transcript the common understanding about services, priorities, responsibilities, and guarantees with the main purpose to agree on the level of service between the service provider and the customer [25]. It may specify a wide range of the service characteristics, such as the levels of availability, serviceability, performance, or operations, at different functional layers of SBA. Different cross-layer monitoring properties (e.g., regarding service QoS or functionality) and adaptation strategies (e.g., re-negotiation or substitution) may be expressed in terms of SLA violations or SLA parameters.
- *End-to-end quality model*. The end-to-end SBA quality model allows for describing different quality attributes of service-based applications. In this way, it provides

a uniform terminology to characterize cross-cutting quality aspects of SBAs and therefore to relate different functional layers. In [26] it was demonstrated that such a model may serve as a basis for expressing monitoring and adaptation aspects of the SBA.
- *Horizontal relations*. While the above concepts and models refer to the vertical relations among different layers, it is also important to reflect and exploit horizontal relations between different elements across the same functional layer. This would allow for relating different cross-cutting aspects to each other and thus enable more accurate and detailed analysis. At BPM layer, such relations may be defined between the functional models of the SBA (e.g., workflow models and transactional protocols), the service models (ASNs), and non-functional models (e.g., KPIs). Similarly, at the SCC layer, such relations may be between the functional composition models (e.g., orchestrations), the non-functional models (e.g., process performance metrics) and the models of the constituent services (e.g., service interfaces, QoS, etc.). Finally, at the SI layer the relations exist between the discovery mechanisms and service models, and service deployment and infrastructure configurations (e.g., containers, resources, etc.).
- *Quality assurance for adaptation*. As it is in the reference scenarios, in order to deal with the adaptation problem across functional layers, it is necessary to come up with the means to analyze the impact and effects of adaptations on the application as a whole before its execution, that is, to perform certain validation and verification activities regarding SBA adaptations. Applied to SBA adaptation in general, this problem was already analyzed and discussed in [27]. Cross-layer adaptation poses additional requirements as it is necessary to integrate adaptation strategies and mechanisms that use different specifications, formalisms, and models.

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