Adaptive, Model-based Cloud Computing Security Management

By

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Abstract

The cloud computing model introduces a new paradigm shift in computing platforms with highly scalable, distributed, and shared computing resources. However, despite the potential cost savings and revenues reaped by adopting the cloud model, it still has a set of open issues that impacts its wide adoption. Security is at the top of these issues. In addition to the traditional technology-related problems, the cloud model introduces a set of new and critical security problems including loss-of-control, lack-of-trust, data isolation, and tenants' security controls' integration. These security problems are not mitigated yet by the existing cloud platforms. Cloud security solutions should take into consideration that it is hard to get cloud tenants and service providers to manually customize their shared cloud services' security. Moreover, the set of a cloud service tenants usually emerges at real-time. Each service tenant usually has a set of security requirements which changes over time to reflect new risks and business objectives.

In this research, we have successfully invented a new cloud computing security management platform addressing these security problems. The invented security platform depends on capturing cloud platform, services and security specification details using a set of novel system and security mega-models. Cloud stakeholders use these models to specify their assets-security requirements. Then, our platform automates the integration of these requirements within target services at runtime.

Identifying security requirements that need to be satisfied requires deep experience with system and security to pinpoint possible threats, vulnerabilities, and attacks. This is even worse when adopting the cloud model where services are publicly accessible to malicious users who could exploit services' vulnerabilities and flaws to breach tenants' security. Our platform delivers a novel, extensible, and online signature-based security analysis service that automates services' security analysis. The outcomes of the analysis service are feed into our security-patching component.

Furthermore, given that tenants do not have direct control on their outsource shared cloud-services, our platform provides a new security monitoring service that automatically realizes tenants' security metrics, used in assessing services' security status, into security probes and automatically deploys, collects, and analyzes probes' generated measurements.

We evaluated each component of our platform using a set of benchmark applications. Then, we conducted three case studies using our platform in mitigating three key cloud security problems. The evaluation results are very supportive and demonstrate that our platform successfully automated the security management of the shared, multi-tenant cloud services.

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma, except where due reference is made in the text of the thesis. To the best of my knowledge, this thesis contains no material previously published or written by another person except where due reference is made in the text of the thesis.

Mohamed Almorsy

List of Publications

During my PhD project, I have managed to publish a bunch of peer-reviewed conference and journal papers as well as a book chapter that support our analysis, findings and contributions.

[1] **Mohamed Almorsy**, John Grundy, and Amani Ibrahim, "Adaptable, model-driven security engineering for SaaS cloud-based applications", International Journal of Automated Software Engineering, Volume 29, September 2013.

[2] **Mohamed Almorsy**, John Grundy, and Amani Ibrahim, "Adaptive Security Management in SaaS Applications", Security, Privacy and Trust in Cloud Systems, Springer.

[3] **Mohamed Almorsy**, John Grundy, and Amani Ibrahim, "Automated Software Architecture Security Risk Analysis Using Formalized Signatures", 2013 IEEE/ACM International Conference on Software Engineering (ICSE 2013), San Franciso, May 2013, IEEE CS Press.

[4] **Mohamed Almorsy**, John C. Grundy, Amani S. Ibrahim, "MDSE@R: Model-Driven Security Engineering at Runtime", 4th International Symposium on Cyberspace Safety and Security (CSS 2012), Dec 12-13 2012, Melbourne, Australia.

[5] **Mohamed Almorsy**, John C. Grundy, Amani S. Ibrahim, "VAM-aaS: Online Cloud Services Security Vulnerability Analysis and Mitigation-as-a-Service", The 13th International Conference on Web Information System Engineering (WISE 2012), Nov 28-30 2012, Paphos, Cyprus, Springer.

[6] **Mohamed Almorsy**, John C. Grundy, Amani S. Ibrahim, "Supporting Automated Vulnerability Analysis using Formalized Vulnerability Signatures", 27th IEEE/ACM International Conference on Automated Software Engineering (ASE 2012), Sept 3-7 2012, Essen, Germany, ACM Press.

[7] **Mohamed Almorsy**, John C. Grundy, Amani S. Ibrahim, "Supporting Automated Software Re-Engineering Using "Re-Aspects", 27th IEEE/ACM International Conference on Automated Software Engineering (ASE 2012), Sept 3-7 2012, Essen, Germany, ACM Press.

[8] **Mohamed Almorsy**, John Grundy and **Amani S. Ibrahim**, "TOSSMA: A Tenant-Oriented SaaS Security Management Architecture", 5th IEEE Conference on Cloud Computing (CLOUD 2012), IEEE CS Press, Waikiki, Hawai, USA, June 24-29 2012.

[9] **Mohamed Almorsy**, John Grundy and **Amani S. Ibrahim**, "SMURF: Supporting Multi-tenancy Using Re-Aspects Framework", 17th IEEE International Conference on

Engineering of Complex Computer Systems (ICECCS 2012), Paris, France, July 2012, IEEE CS Press.

[10] **Mohamed Almorsy**, John Grundy and Amani S. Ibrahim, "Collaboration-Based Cloud Computing Security Management Framework", In Proceedings of 2011 IEEE International Conference on Cloud Computing (CLOUD 2011), Washington DC, USA on 4 – 9 July, 2011, IEEE.

[11] **Mohamed Almorsy**, John Grundy Ingo and Mueller, "An analysis of the cloud computing security problem", In Proceedings of the 2010 Asia Pacific Cloud Workshop 2010 (co-located with APSEC2010), Sydney, Nov 30 2010.

The following publications, which I am a co-author, have been published during my candidature as a part of my collaboration with colleagues in our research group.

[1] Amani S. Ibrahim, John C. Grundy, James Hamlyn-Harris, **Mohamed Almorsy**, "DIGGER: Identifying Operating System Dynamic Kernel Objects for Run-time Security Analysis", International Journal on Internet and Distributed Computing Systems (IJIDCS).

[2] Amani S. Ibrahim, John C. Grundy, James Hamlyn-Harris, **Mohamed Almorsy**, "Identifying OS Kernel Runtime Objects for Run-time Security Analysis", 6th International Conference on Network and System Security (NSS 2012), Nov 21-23 2012, Wu Yi Shan, Fujian, China, Springer.

[3] Amani S. Ibrahim, John C. Grundy, James Hamlyn-Harris, **Mohamed Almorsy**, "Operating System Kernel Data Disambiguation to Support Security Analysis", 6th International Conference on Network and System Security (NSS 2012), Nov 21-23 2012, Wu Yi Shan, Fujian, China, Springer.

[4] Amani S. Ibrahim, John C. Grundy, James Hamlyn-Harris, **Mohamed Almorsy**, "Supporting Operating System Kernel Data Disambiguation using Points-to Analysis", 27th IEEE/ACM International Conference on Automated Software Engineering (ASE 2012), Sept 3-7 2012, Essen, Germany, ACM Press.

[5] Amani S. Ibrahim**,** James Hamlyn-Harris, John Grundy and **Mohamed Almorsy**, "Supporting Virtualizaion-Aware Security Solutions using a Systematic Approach to Overcome the Semantic Gap", 5th IEEE Conference on Cloud Computing (CLOUD 2012), IEEE CS Press, Waikiki, Hawai, USA, June 24-29 2012.

[6] Amani S. Ibrahim, James Hamlyn-Harris, John Grundy and **Mohamed Almorsy**, "CloudSec: A Security Monitoring Appliance for Virtual Machines in the IaaS Cloud Model", 5th International Conference on Network and System Security (NSS 2011), Milan, Italy on 6 – 8 September, 2011.

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Part 1

Problem Analysis

Chapter 1
Introduction

The cloud computing model [2] introduces a new generation of computing platforms with more emphasis on increasing business benefits and reducing IT infrastructure cost. This model is leading IT industry towards new service models that can utilize resource virtualization, service outsourcing, and the pay-per-use payment model [3]. The cloud model introduces a win-win solution for both cloud providers and service providers, and service consumers. Service consumers can scale their resources up and down at runtime utilizing the cloud elasticity feature which enables consumers to allocate and de-allocate resources on the fly. On the other hand, service providers can optimize cost and resource utilization through the cloud multi-tenancy feature which enables providers to co-locate different service consumers (tenants) to share the same service instance.

Securing such dynamic, virtualized, and multi-tenant platforms and services is a big challenge [4]. Our analysis of the cloud computing model shows a set of key factors that complicate the cloud computing security problem and need to be addressed by cloud security solutions. These factors include: *First*, the cloud model has different stakeholders (cloud platform provider, cloud service provider, and cloud consumer) involved in securing the cloud platform, the cloud hosted services, and tenants' data. Each stakeholder owns a piece of information required in developing the service security model. Moreover, each stakeholder may have their own security requirements that should be supported by the same service instance, in case of multi-tenancy. *Second*, outsourcing assets to be hosted on the cloud without tenants' involvement in securing these assets raises the loss-of-control problem (tenants do not have control on the security enforced on their cloud hosted assets) and lack-of-trust problem (tenants do not trust that the claimed security level by service providers is actually applied). *Third*, the key cloud characteristics - multi-tenancy and elasticity - have negative impact on the cloud security. Multi-tenancy increases tenants concerns about the security isolation between different tenants' assets that are co-located on the same cloud service instance. Elasticity increases tenants concerns about the elasticity of the operated security to cover newly allocated resources. *Fourth*, the cloud model itself has a complex layered architecture (servers and infrastructure, hypervisor, virtual machines, platforms, services, and applications) with long dependency stack. Each layer has a set of security issues, inherited from the underlying technology used by the cloud model, as well as a set of deployed security controls. This in turn complicates the

management task of such huge number of cloud services and heterogeneous security solutions. *Fifth*, the cloud model introduces different service delivery models. Each service model has different possible deployment models and security controls to be used which complicates the development of standard security models for each service delivery model.

Delivering a secure cloud platform requires addressing these factors with a consistent and comprehensive model. From our analysis of the cloud model, we figured out that the current cloud security model considers security as a crosscutting concern while each cloud layer and service has to enforce and manage their security individually. The cloud model lacks a strong security management platform that can address the large amount of the cloud-hosted services, security controls deployed, stakeholders involved with the cloud platform, constantly changing security requirements of different tenants, multi-tenancy and elasticity problems, loss of control and the lack of trust problems raised by cloud tenants.

The main responsibility of any security management framework as defined by ISO27000 [5] and NIST-FISMA [1] standards is to help in capturing and defining assets' security specifications, enforcing specified security, and monitoring and improving security to meet target security objectives. Although, this mission is obvious, we did not find relevant efforts that help in fulfilling these tasks consistently. Moreover, we have figured out major gaps and limitations in these existing efforts when projected on the cloud computing model and its related security challenges. Below we summarize some of these limitations. A detailed discussion of the existing, relevant efforts is introduced in the related work chapter 3.

– *Security Management Process:* Existing security management standards that represent the basis for adoption by any security management system, such as ISO27000 [5], NIST-FISMA [1], do not fit well with the cloud model. This is because they assume that the owner of the assets to be secured has full control over the security management process of these assets. Thus, outsourcing IT assets and sharing of cloud resources between different tenants are hard to address by these standards. Furthermore, the existing security management frameworks, such as POSTIF: Policy-based security management [6], Ontology-based management [7], hybrid approach of both [16], and model-based security management [8], focus mainly on automating the configuration of heterogeneous security controls. This is in contrast to addressing the early phases of the security management process, such as how to capture security requirements and how to extract and report feedback on system security status. Moreover, the integration of the deployed security controls within target IT systems (cloud services in our case) is not addressed and currently done manually. This is not feasible in the cloud model where we have potentially hundreds of stakeholders with different security requirements.

- *Security Specification Phase:* The specific security requirements to be enforced by a security management system arise from the stakeholder security objectives that must be satisfied by the target IT systems. Refining security objectives into security requirements and policies is done using risk assessment approaches. Existing risk assessment and management frameworks, such as OCTAVE [9], CORAS [10], Saripalli [11], Xuan [12] Shirlei et al [13], focus on the manual process of identifying security risks, threats and proposing mitigation solutions. Although some tools do exist, they focus on the documentation and modeling of the identified risks rather than automation of the identification process. Automation is a key requirement in cloud computing security because of the cloud complexities discussed above. The security risk assessment process involves vulnerability analysis, threat analysis, and attack analysis. Existing vulnerability analysis efforts that help in identifying security flaws and bugs focus on specific vulnerability types e.g. SQL Injection or Cross Site Scripting (XSS) attacks. However, the cloud model is publicly accessible to end-users who may be malicious users. Moreover, even one of the cloud service tenants may be a malicious attacker who has high privileged permissions to exploit more complex vulnerabilities. Thus, there is a need for an online and comprehensive security analysis approach.
- *Security Enforcement Phase:* Enforcing the identified security requirements is done through the security engineering process. Existing security engineering efforts usually focus on design time security engineering [14-16] where security requirements are captured during the system development, by service providers, and are not expected to change at runtime. On the other hand, adaptive application security has been investigated in some research [17] [18, 19]. These approaches mainly focus on low level details, including in-memory objects update, or deliver adaptive security solutions/architectures only for specific security objectives, such as delivering adaptive access control mechanisms [20]. Some security engineering approaches for Service-Oriented Architecture (SOA) applications exist. Such efforts depend on the nature of SOA-based applications which is not the prominent architecture of cloud applications (mainly web applications). Multi-tenant security efforts [21] help in specifying and realizing security requirements on cloud web-based applications composed of web services. Each application instance, customized for a specific tenant, is deployed on a separate Virtual Machine (VM). They assume that web applications are composed of web services only. Security is maintained through using separate VMs for each tenant. Approaches to extend applications' capabilities to support multi-tenancy do exist as well [22-26]. These efforts mostly focus on extending existing application security capabilities and on handling the isolation security problem. Enabling multi-tenant security engineering "tenant-oriented security", to the best of our knowledge, has not been addressed.

– *Security Monitoring Phase:* Confirming that the operated security is effective and efficient is a very important phase in the security management process. This becomes crucial and complicated under the cloud computing model, given that service consumers (tenants) do not have control on their cloud-assets. Existing efforts in the security monitoring area [27-31] either support security monitoring using controls log-based measurements (lagging security metrics) which is not efficient for proactive security, or support manually specified and collected security measurements which cannot be used with cloud outsourced assets. We could not find an easy to use formalized language that could help in capturing customized (user-defined) dynamic, runtime security metrics. Most of the existing efforts are either too formal such as Event-Calculus [190], or domain-specific such as [203, 204, 205]. Automated security metrics' realization including monitoring (injecting necessary probes at relevant components) and analysis of the generated security measurements are not supported.

In this thesis, we introduce a novel, adaptive, model-based, and multi-tenant cloud computing security management framework addressing these new cloud computing security challenges and mitigating gaps found in the existing relevant security management efforts. Our solution is adaptive to cope with the dynamic nature of both the security problem (requirements change according to current security status and risk) and the cloud model (cloud services and their tenants change over time). It is model-based to work on abstract level away from the underlying platform or target service details. Our approach is based on extending the boundaries of the cloud consumers and providers' security management processes to include their cloud hosted services and cloud platforms respectively. This means that stakeholders can go through the security management process for their cloud hosted assets as if they have been hosted inside enterprise perimeters. Moreover, they can use the same security specifications, security enforcement, and monitoring and improvement approaches used internally and thus mitigate the loss-of-control and the lack-of-trust problems arise from adopting the cloud model. Our framework can be deployed on cloud platforms and used to manage the security of deployed services for corresponding service tenants. As none of the cloud stakeholders possess the information required to secure a given service, we base our approach on joint-collaboration between different cloud stakeholders in securing their cloud-hosted assets.

We evaluated each component of our cloud security management platform separately using a set of benchmark applications and a set of soundness and completeness metrics whenever applicable (introduce in chapter 4). Furthermore, we have conducted three case studies to evaluate different parts of the platform (two or more components) in addressing specific cloud security problems. The first case study targets automated, online patching of services' reported vulnerabilities (virtual patching) using the enforcement component and analysis component. The second case study targets facilitating addressing multi-tenant security isolation problem

when migrating legacy applications for the cloud computing – to support multi-tenancy. The third case study addresses a complete multi-tenant security management cycle using our security management platform. The evaluation results were very supportive and demonstrate that our platform successfully automated the security management process of the shared, multi-tenant cloud-hosted services.

1.1 Motivating Scenario

In this section, we introduce a simple motivating scenario, shown in Figure 1-1, which we wish to satisfy using our research. Although this scenario is a typical scenario that most probably exit in any cloud platform hosting Software-as-a-Service applications, it still cannot be satisfied neither by the existing security management nor security engineering efforts.

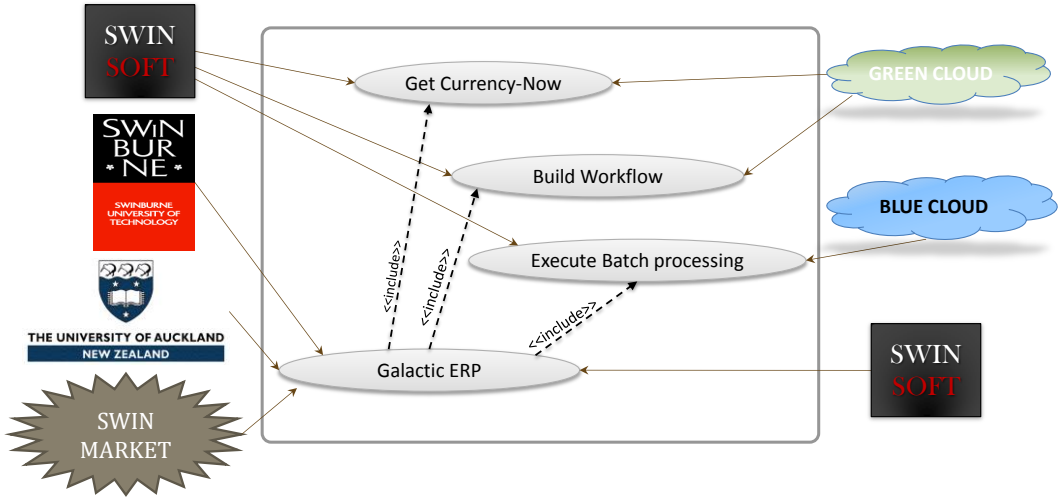


Figure 1-1. Motivating scenario use-case diagram

Consider *SwinSoft*, a virtual software house focusing on developing business applications, has developed their new enterprise resources planning (ERP) product. The code name of this product is Galactic. This product is developed as a web-based, multi-tenant, cloud application. SwinSoft has decided to host Galactic on a SaaS cloud platform delivered by *GreenCloud*. During the development of Galactic, *SwinSoft* has decided to use external third-party services to speed up their application development and reduce the time to market. These services include:

– *Build Workflow Service:* This is a customizable workflow engine that enables different tenants to model their business processes. This service is developed by *GreenCloud* and deployed on their cloud platform.
– *Get Currency-Now Service:* This is an online service that retrieves current and historical currency exchange rates. This service is also developed by *GreenCloud* and deployed on their cloud platform.

- *Batch-Monster Service:* This is an online ERP-posting service (performs batch posting of system transactions) based on the map-reduce model. This service is developed and deployed on another cloud platform called *BlueCloud*.

Swinburne University is planning to buy a new ERP solution in order to automate its internal processes and facilitate the communications with Swinburne students, staff, and community. After long investigation and cost analysis of the existing ERP solutions, Swinburne decided to go for Galactic ERP as a SaaS application, to save upfront investment required when deploying new ERP solutions while keeping infrastructure cost as optimal as possible by delivering it on use/load wise. At the same time, *Auckland University* becomes interested to adopt Galactic as their ERP system. However, both Swinburne and Auckland have their own business requirements as well as their own security requirements. Below we summarize some of the security requirements of both stakeholders.

- *Swinburne Security Requirements:* Each user should have their own privileges according to their roles in Swinburne. Such privileges should capture and consider the context of the users such as their locations, time, and nature of the devices used…etc. Based on these attributes, the security level and security mechanisms to be used should be applied; Users should not have different identities to deal with the different IT systems including internally deployed systems as well as Galactic ERP service; Users' information should be kept secured. Any communication between the users and the system or other underlying systems or services should be kept secured; and Swinburne data should be kept isolated from other customers and SwinSoft employees as well. These security requirements should not conflict with any other customer of Galactic ERP or even with security policies defined by SwinSoft or other providers involved in the service delivery.
- *Auckland Security Requirements:* Auckland assigns high risk impact to the Galactic service because of the criticality of data processed by this service. Thus, they have strong security constraints that are different from their local systems. They plan to use more complicated security solutions to protect their cloud assets. This includes the following requirements: To apply an attribute-based access control (ABAC) model [32] for access control that is based on user context; To apply two-factor authentication security system currently deployed in Auckland network; To apply transaction accountability and auditability on all user transactions; and Auckland data should be kept confidential at rest and at transmission.

SwinSoft has to satisfy Galactic tenants' security requirements in order to convince them to procure the application. SwinSoft software and security engineers have to manually customize and redeploy Galactic services after capturing these new security requirements. However, SwinSoft developers, as most of software engineers, do not have enough experience in the

security engineering area. So they face many problems developing tenants' security requirements inside their delivered applications and services.

SwinMarket, a new Galactic tenant, becomes also interested to use Galactic point-of-sale system to operate in their stores. Galactic should be integrated with the *SwinMarket* systems that automate their internal business process including General Ledger and Purchasing systems. This means that SwinSoft has to revisit Galactic application security requirements to incorporate SwinMarket security needs.

Few months later, Swinburne has decided to change their security requirements to match their new business needs. Moreover, Auckland has decided to change their security requirements in order to address new security threats found in Galactic and may result in breaching their assets confidentiality. This means that SwinSoft development team has to revisit those tenants' operated security with relevant change requests.

SwinSoft is now looking for a security management and engineering approach that could help them in capturing and enforcing different tenants' security requirements rather than the current methodologies that deliver one set of application security not linked to different service tenants' security requirements. Moreover, they are looking for an approach that helps in modifying security requirements of a given tenant independent of the other tenants. This approach should support registering new tenants who can apply their security requirements at runtime without a need for service customizations. It is highly recommended that the proposed approach is a configuration-based rather than customization-based to avoid delays in modifications, being overwhelmed with change requests, and improve service availability.

1.2 Research Roadmap

To deliver our cloud security management platform, we have adopted an iterative approach where each iteration is supported with a prototype as a proof-of-concept. Working iterative helped to keep adding components to the proposed platform, each new component addresses one of the research questions/gaps. The order of iterations reflect the logical dependencies between the research gaps we found in the area of cloud computing security management. Below we discuss details of our research project roadmap.

First, we investigated the existing efforts in the area of the cloud computing security to identify the existing research problems, research gaps, and setting the research scope. We published results of our detailed analysis of the cloud computing security problem in [4].

Second, we projected the existing security management standards including ISO27000 [5] and NIST-FISMA [1], and security management efforts on the cloud computing model using

the requirements and challenges we identified in the first milestone. A practical solution to the cloud computing security management problem must conform to the existing security standard. Thus the objective of this step was to assess the existing security standards when applied to the cloud computing model. We selected NIST-FISMA security management standard (as one of the two main security management standards). The standard does not target securing outsourced services, thus we had to adapt NIST-FISMA standard to fit with the cloud model. Our revised cloud-aligned NIST-FISMA standard is based on improving the collaboration of the cloud stakeholders in delivering the whole platform and service security model. We developed a simple prototype based on the modified model, and verified it using the motivating scenario discussed above (published in [33]). The rest of our platform is aligned with the revised NIST_FISMA standard.

Third, once we confirmed that our modified cloud security model works well with the cloud model, we started to work on every task of the security management process (specifying, enforcing, and monitoring security) to see how we can improve or automate and re-integrate with our developed framework. We started with the security enforcement step because it represents the core of the whole security process, whereas a failure to automate, implies rejecting the hypothesis (that we can deliver automated cloud security management) we are trying to prove in this project. Assuming that we succeeded in capturing the set of security objectives of each tenant, how can we enable services to support enforcing these multi-tenant security requirements? To do this we investigated the existing security engineering, adaptive application security, and multi-tenant SaaS engineering approaches. These efforts do not support multi-tenancy security engineering, fully adaptive security, or runtime integration of third-party security controls. We proposed a new approach for security engineering, MDSE@R. In MDSE@R, service providers should deliver a service description model that captures their services' details (called a Service Description Model – SDM) as part of their service delivery package. Customer security engineers develop their security specification model (SSM) that captures all security objectives, requirements, etc. MDSE@R then weaves both models together at runtime and reflects the resultant weaved system-security model onto the running system using dynamic-weaving Aspect-Oriented Programming - AOP. We validated MDSE@R with a set of open source applications from our benchmark set discussed above. The results show that MDSE@R successfully used in capturing different sets of security requirements and realization controls, and correctly integrating these security controls within target system entities. The results were published in CSS2012 [34]. As an extension of this approach we modified MDSE@R to fit with the multi-tenancy problem – i.e. to support enforcing different sets of security requirements at runtime. TOSSMA is a tenant-oriented SaaS security management architecture that supports capturing and enforcing different security requirements, for different

tenants, on the same service instance at runtime. TOSSMA was validated on the same set of open source applications. Results were published in CLOUD2012 [35].

Fourth, MDSE@R helps adding security at runtime for new and existing applications, but for existing applications with built-in security, the new injected security capabilities may result in conflicts with the already built-in security capabilities. Thus, we have to introduce a pre-processing step where the existing, built-in security capabilities are re-engineered. This may include modifying, replacing and disabling existing security. We investigated existing system and security maintenance, and retrofitting approaches. A limited work was introduced in this area. A reasonable justification of this is that once a model-driven engineering approach was used in developing the application, the maintenance task will mainly relay on updating existing models. Moreover, addressing security as an afterthought is always claimed to be a bad practice [36]. Existing efforts do not help enough in automating security reengineering tasks, as most of these efforts focus on using aspect-oriented programming (AOP) to deliver dynamic system updating through replacing existing methods with updated versions [37]. We propose a new approach that helps in reengineering system and security whatever was the information available including system models, source code or at the worst case system binaries are only available. Our approach is based on a new concept we introduced "Re-aspect" – Reengineering aspects – which extends the AOP with more flexible signature specification constructs (to capture signature of code entities to be modified) and more supported actions (delete, inject, modify, and replace). Re-aspect advice encapsulates code to inject (in case of replace or insert re-aspect) or code to be used in system modification (in case of modify re-aspect). We validated our approach on the same set of open source web applications. The results show that "Re-aspects" is sound enough in automating the software security retrofitting process. We documented our approach and results and published it in ASE2012 and ICECCS2012 [38, 39]

Fifth, a key source of security requirements is the security analysis task that pinpoints service security issues. Moreover, given a system either secured or not, how can we verify that it is not still vulnerable to known weaknesses or vulnerabilities. Existing techniques focus on specific types of weaknesses such as SQL Injection, OS Command Injection, XSS, etc. These techniques use static analysis, dynamic analysis, string based analysis, runtime analysis, or hybrid approaches. These efforts are not comprehensive enough to cover a wide - range of vulnerabilities. Conducting vulnerability analysis of the services before hosting on the cloud or getting tenants to use it is an important task that helps in reducing the risk of tenants' data breaching. Moreover, such efforts are not extensible enough to address new vulnerabilities that emerge at runtime. Having an online vulnerability analysis is a key requirement of the cloud computing security problem. To deliver a comprehensive and extensible approach, we

developed a formal weakness/vulnerability specification approach independent of the service implementation or details of the programming language used (currently, vulnerabilities are specified informally e.g. in CWE database). In our approach, vulnerability signatures are specified in Object Constraint Language (OCL). We have developed a source code vulnerability analysis extension that receives the source code of the service under test along with the vulnerabilities' signatures. It generates a list of found vulnerabilities in the source code along with the entities that match the specified vulnerabilities' signatures. We have evaluated our approach in capturing definitions of the top ten weaknesses published by the Open Web Application Security Project – OWASP [40], and in analyzing a set of benchmark applications using these signatures. The evaluation results show that our online security analysis tool has high precision and recall rates. This means that we can depend on it in analyzing SaaS applications against possible vulnerabilities and attacks. Our approach along with the evaluation results have been published in ASE2012 [41]. We then extended this approach to support not only source code analysis (vulnerability analysis) but also system architecture and design artifacts (threat and risk analysis). This extension along with the evaluation results have been published in ICSE2013 [42].

Sixth, given the set of security objectives, identified vulnerabilities, and enforced security controls, how to confirm that the system is now secure enough, meets the specified security objectives, and blocks the possible security attacks. Security monitoring is a very raw field where a very limited amount of research has been done so far. Existing efforts do not help in automated security monitoring. They mostly help in developing manual security metrics or manual collection of security measures. We have developed a general approach that captures security metrics in general signatures as OCL invariants. These metrics definitions are used to generate required security probes. These probes are integrated within the target services using AOP that intercept service execution and extract values of different attributes of the services to be evaluated. The collected measures are sent back to analysis service that analyze such measures and generates the corresponding metric values. The evaluation results show that our approach is successful in capturing different categories of security metrics, automating the generation and deployment of security probes, and analyzing the generated measurements. This approach along with the evaluation results are submitted to ASE2014.

1.3 Key Contributions

In this research, we have introduced a set of solutions to address relevant security problems that arise from the adoption of the cloud computing model. Below we summarize the key contributions we have achieved in the area of cloud computing security management.

A novel alignment of one of the existing security management standards (NIST-FISMA standard) to fit with the cloud computing model and its new application service hosting model (multi-tenancy model) [33]. Existing security management standards focus on enterprise security management where assets are fully owned and controlled by the customers. On the other hand, cloud consumers do not have control on their outsourced cloud assets, especially in the SaaS applications. Thus, existing security management standards do not fit well with the cloud computing model. Our proposed security management standards-to-cloud computing alignment is based on improving the joint-collaboration between different cloud stakeholders where each stakeholder participates with the piece of information they own about the cloud model or the hosted services. Our proposed alignment is introduced in Chapter 5.

A novel, integrated, and multi-tenant cloud computing security management model and platform. Our security management platform, to the best of our knowledge, represents the first proposal of a security management platform for the cloud computing model that address the loss-of-control and lack-of-trust problems taking into consideration the multi-tenancy dimension. Our security management model is based on NIST-FISMA standard as one of the two main security management standards. Our aim is to be comprehensive enough to cover most of the tasks done by security experts during the security management process. To the best of our knowledge, this is the first proposal of multi-tenant security management platform that operates as a cloud service shared among all cloud stakeholders including service tenants and service providers.

A novel, model-driven, tenant-oriented security engineering approach [34, 35]. We introduce a novel multi-tenant, model-driven security engineering at runtime approach (we call MDSE@R). Given cloud services are shared among different tenants who have their own security requirements, the service-oriented security engineering approaches (a service can reflect one set of security requirements that are captured during design time) are no longer suitable to satisfy tenants' needs. We introduce a tenant-oriented security engineering approach that enables different tenants to manage (define security, enforce security, and monitor security) their service instances' security at runtime without a need for service customization. MDSE@R introduces a comprehensive system description mega-model (SDM) that captures all system details (this model is developed by service providers using UML) and security specification mega-model - SSM (that captures each tenant's security details, developed by each service tenant using our SecDSVL). The SSM is based on a deep analysis of the main entities and tasks existing in security management standards. We developed SecDSVL, a security domain-specific visual language, to help security engineers and administrators in developing security specification models. MDSE@R also introduces a common security interface that helps in

integrating third-party security controls with the target IT assets at runtime. Security vendors need to develop one adaptor for their security services that complies with our common security interface. Thus, they do not need to develop different adaptors for different cloud services. Our proposed MDSE@R approach is introduced in Chapter 6.

An extensible online cloud services' security analysis service [41, 42]. We introduce a security analysis service that can analyse service architecture, design, source code, and binaries to identify the existing security design flaws and bugs. The key contributions of our novel security analysis service are: integrated security analysis throughout different service artifacts including architecture, design and code; the security analysis service is extensible, thus we can add different security analysis mechanisms without a need to modify the underlying platform; and security analysis is signature-based, thus any vulnerability, threat, or system design security metric could be easily specified and verified against the system without a need to develop new plugins. This helps to support online analysis for known and unknown vulnerabilities that arise at runtime as far as a signature of such vulnerabilities exist. Our proposed security analysis approach is introduced in Chapter 8.

An extensible and automated cloud applications' security monitoring service. The main contribution of our novel security monitoring service is that we did not develop a predefined set of security metrics. Service users can define their own security metrics to be used in diagnosing the security status of their IT assets. The security monitoring service uses these metrics signatures (definitions) to generate and deploy required security probes that are responsible for collecting required measurements from the target cloud services. Moreover, it uses these signatures in generating metric evaluation expressions to be used in analyzing collected security measurements and generating metric values. Our security monitoring approach is introduced in Chapter 9.

A novel approach to help migrating legacy applications to the cloud and disabling hardcoded security functionalities [38, 39]. In order to help in managing services security using MDSE@R we may need to disable the existing security APIs and functions in a legacy application. To do this we introduce a novel system and security reengineering approach using a new concept called reengineering aspects "Re-aspects". This new concept helps in capturing system modification details including the signature of system entities to modify, actions to apply, advice(s) or code to use in realizing this change. Our re-aspects engine uses these details to realize the captured change request details. This approach is supported with two signature specification approaches including code-snippets signatures and OCL-based signatures. We have used re-aspects to address two other problems: the patching/mitigation of reported vulnerabilities and in migrating legacy applications that are not designed with multi-tenancy in

mind to support cloud computing multi-tenancy. Our proposed security reengineering approach is introduced in Chapter 7.

An automated vulnerability virtual patching approach [43]. This approach is based on integrating MDSE@R and vulnerability analysis service. The reported vulnerabilities by the vulnerability analysis service are fed in MDSE@R to inject relevant security controls (as vulnerability mitigation actions) at critical (vulnerable) system entities. Our proposed virtual patching approach is introduced in Chapter 10 as a case study.

1.4 Thesis Structure

This thesis deals with cloud computing security management problem taking into consideration the loss-of-control, lack-of-trust, and multi-tenant security problems that arise from the adoption of the cloud computing model. In this thesis we introduce our solution to address these problems. Our solution is based on an adaptive, model-based cloud computing security management approach that enables tenants to extend their security capabilities to include cloud hosted assets. By this approach tenants can define their security requirements, their security controls, and security metrics and attributes they want to follow up. The thesis structure is depicted in Figure 1-2. The thesis is divided into three parts. Part (1) gives an overview of the cloud computing model, the key security problems and challenges arise from the adoption of the cloud model, and the key limitations of the existing research efforts. Part (2) gives details of our solution – the adaptive, model-based cloud computing security management approach. Part (3) gives details of the case studies we conducted to evaluate our approach and the key conclusions, limitations and future work.

In Chapter 2, we introduce a detailed analysis of the cloud computing security problem. We tried to identify different the key factors that really contribute to the cloud computing security problems and should be addressed by any cloud computing security solution. These factors include cloud characteristics (multi-tenancy and elasticity), cloud architecture, underlying technologies, and service delivery models used.

In Chapter 3, we give a comprehensive literature review of the main relevant research areas related to our research problem, including cloud computing, security management, security engineering, security engineering, security analysis, and security monitoring. We summarize the key efforts done in each area, key limitations of these efforts, and key gaps compared to the security problems and issues of the cloud computing model that we need to address in our research project.

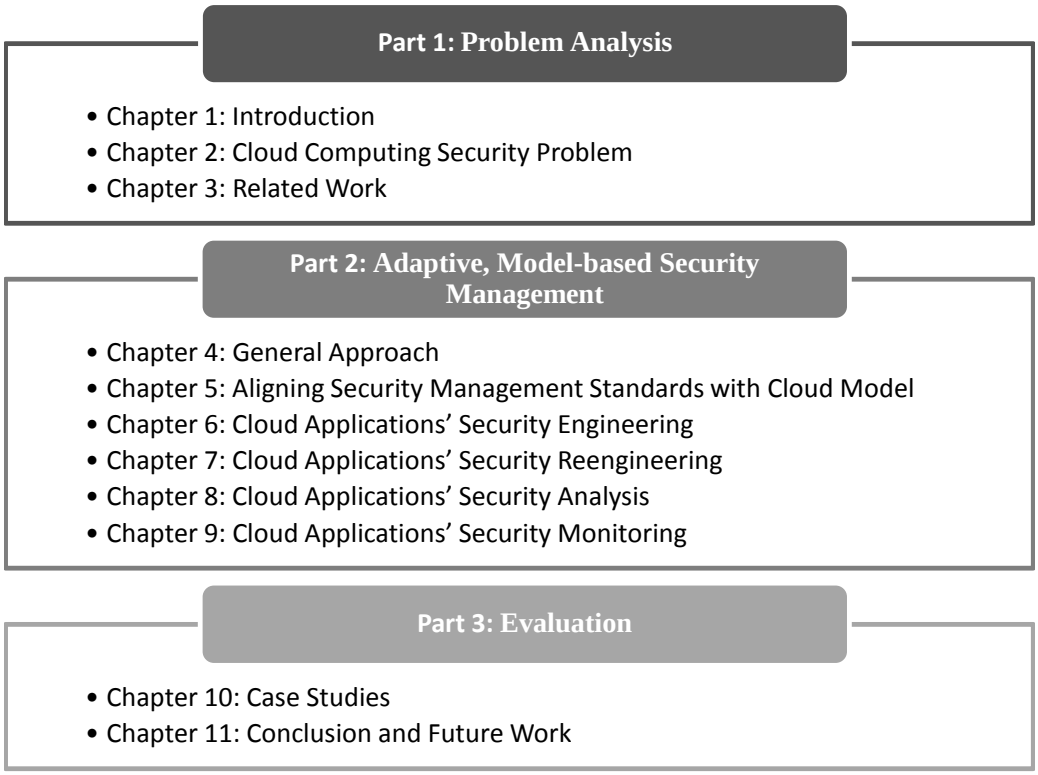


Figure 1-2. Thesis structure

In Chapter 4, we introduce the main idea of our security management platform which is the autonomic computing model (MAPE-K). We also describe the "big picture" of our platform, our solution high-level architecture, and the main components of the security management platform.

In Chapter 5, we describe how we aligned one of the main security management standards (NIST-FISMA standard) to fit with the cloud computing model and how we attested the proposed model with a prototype with a simplified version of our motivating example.

In Chapter 6, we describe our security enforcement approach developed as model-driven, multi-tenant security engineering at runtime approach (MDSE@R). The proposed approach enables each tenant to manage their assets security using security specification models that capture their security details using SecDSVL (security domain-0specific visual language). Then, MDSE@R realizes these security models using aspect-oriented programming. We introduce a detailed evaluation of our MDSE@R approach, including SecDSVL usability evaluation, usage, example, and a set of benchmark applications.

In Chapter 7, we present our security reengineering approach and our new change request realization concept "reengineering aspects" re-aspects. MDSE@R helps in injecting tenants' security requirements at runtime; however, it does not help with applications that have built-in security functions or APIs. We give details of the reengineering aspects concept, how re-aspects

help in impact analysis and change propagation as main steps of the software reengineering and maintenance. We describe a detailed evaluation of our security reengineering approach on a set of benchmark applications and a set of security related change requests.

In Chapter 8, we present our novel, online signature-based security analysis approach. This approach is based on capturing signatures of weaknesses, vulnerabilities, attacks' signatures, and security metrics using formalized signatures developed with Object Constraint Language (OCL). These signatures are automatically transformed into C# code that is used to analyse the applications/services source code to pinpoint matched entities. We introduce a detailed evaluation of our approach and developed prototype.

In Chapter 9, we introduce our novel security monitoring approach using formalized security metrics schema with metric signature specification approach based on OCL. We describe our underlying security monitoring platform that is responsible for transforming these security metrics into a set of security probes to be deployed into system entities, collecting measurements from the system status attributes, and in analyzing the collected measurements using the specified security metrics' signature after being transformed into C# code.

In Chapter 10, we present a set of case studies that we have conducted in order to evaluate our proposed cloud security engineering approach. We describe three case studies where each case study assesses the application of the platform or parts of the platform in a specific cloud security problem. The first case study addresses the problem of online virtual patching of the newly reported security vulnerabilities. The second case study addresses the problem of migrating legacy applications to fit with the cloud model (mainly the isolation of different tenants' data). The third case study shows the application of our platform in realizing a full security management cycle of a SaaS application with different tenants.

In Chapter 11, we summarize the key problems we addressed throughout our research project, summarize key contributions of the research project introduced in this thesis, the main limitations of our platform, and future tasks that we plan to address.

Chapter 2
Cloud Computing Security Problem

In this chapter we discuss the key factors, we figure out from our analysis, contributing to the complication of the security problem under the cloud computing umbrella i.e. we address the question why security is different and more challenging in cloud computing than for other kinds of computing domains? Such factors need to be addressed by cloud security solution that targets security issues in the cloud computing model. This chapter is organised as follows. In Section 1, we give a general introduction of the cloud computing model and why cloud computing security is ranked as one of the top concerns when adopting the cloud model. In Section 2, we discuss the implications of different factors on the security of the cloud model. In Section3, we discuss the key enablers that can help addressing these cloud computing security problems.

2.1 Introduction

The cloud computing model provides the next generation of internet-based, highly scalable distributed computing systems in which computational resources are offered 'as a service' [2]. The cloud model is based on the pay-as-you-go payment model where tenants – users of the cloud-hosted software applications – pay only for the amount of resources they use. Tenants can expand or shrink their resources on the fly according to current needs [44].

The cloud model has motivated industry and academia to host a wide spectrum of applications ranging from high computationally intensive scientific or business applications down to light-weight services. The cloud model also helps in addressing the "long tail market" for small and medium enterprises (SMEs) [67]. This is because it does not require large upfront investment in IT infrastructure, software licenses, and other computing infrastructure. Moreover, governments and other organizations have become more interested in the possibilities of using cloud computing to reduce IT costs and increase capabilities and reachability (availability and accessibility) of their delivered services. According to a recent Gartner survey [45] on cloud computing revenues, the cloud market was worth USD 68 Billion in 2010 and will reach USD 148 Billion by 2014. These revenues imply that cloud computing is a promising computational platform. Despite the potential benefits of improved reliability, quality, cost savings and increased revenues that can be gained from the cloud computing model, a major downside is that it increases malicious attackers' interest and ability to find applications and platforms vulnerabilities to exploit.

This is because of the increased availability and public accessibility of such applications on the internet. In addition, the cloud model is still not mature enough [46] - there are a lot of open issues that impact the model creditability and pervasiveness from the cloud consumers' perspective. For example, vendor lock-in, multi-tenancy and isolation, data placement and management, service portability, elasticity engines, SLA management, and cloud security are well-known open research problems [46-48].

From the cloud consumers' perspective, security is a major concern that hampers the adoption of the cloud computing model [49]. This is due to, among other reasons: *First*, enterprises outsource the security management of their cloud-hosted assets to a third party (cloud provider) that hosts their IT assets. This results in the well-known loss-of-control problem [50], where cloud consumers do not have security control over their outsourced assets. *Second*, different tenants' assets co-exist at the same location and using the same software service instance. Tenants are unaware of the soundness of operated service security and what security controls are actually used to secure tenants' data and ensuring no data privacy breach. *Third*, the lack of security guarantees in the Service Level Agreements (SLAs) between cloud consumers and cloud providers. Most existing SLAs focus on reliability, availability and performance quality of service attributes, rather than security [51]. *Fourth*, hosting this set of valuable assets on publicly accessible infrastructure increases the interest and ability of attackers to exploit vulnerabilities in the cloud platform or the hosted services to achieve malicious benefits, such as compromising one tenant's data to another tenant who may be a competitor.

From the cloud providers' perspective, security requires a lot of expenditure (e.g. security solutions' licenses) and resources (security is a resource intensive aspect). Moreover, security is a difficult problem to master due to its complexity (as we illustrate later in this chapter). The cloud provider does not know what software the tenants are running which may introduce security risks to the platform. On the other hand, ignoring or delaying security in the cloud computing roadmap will violate the expected revenues stated above. Thus, cloud providers have to understand consumers' concerns mentioned above and seek out new security solutions that resolve such concerns. In order to deliver a security engineering and management approach that helps addressing the security problems arise from the adoption of the cloud computing model, we have to gain a deep understanding of the cloud computing model to understand the key factors and root causes that should be addressed by any security engineering or management approach that address the cloud computing model. This is what we are discussing in the next sections.

2.2 Cloud Security Analysis

In this Section we summarize the existing challenges and issues involved in the cloud computing security problem. We have grouped these issues, as shown in Figure 2-1, into architecture-related issues, service delivery model-related issues, cloud characteristic-related issues, cloud deployment models-related issues, and cloud stakeholder-related issues. Our objective is to identify the weak points in the cloud model by highlighting their root causes. This helps us in formulating our research problem, key challenges and requirements that we should address in our approach.

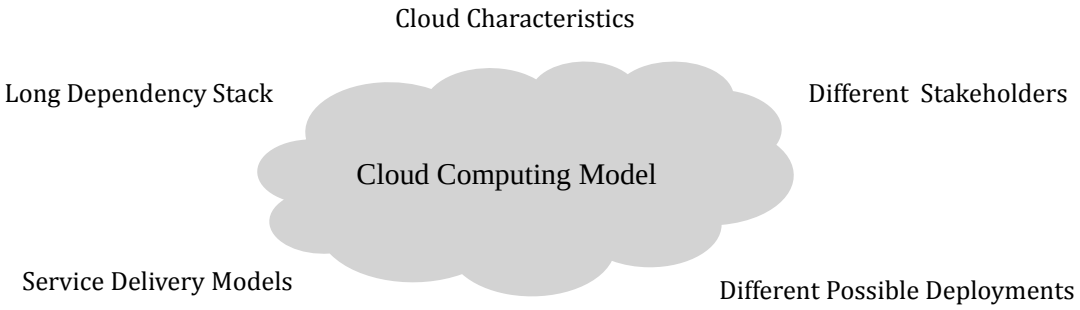


Figure 2-1. Key factors contributing to the cloud computing security

2.2.1 Deployment Models Security Implications

The cloud computing model has three different service delivery models and three possible deployment models [2] including: *Private Cloud:* a cloud platform that is dedicated for specific enterprise(s). This is usually deployed within enterprise network perimeter and enterprise IT department has full control on the cloud platform. The main objective of this model is to remove customers' concerns about the security of their cloud hosted assets on the expense of increasing IT infrastructure cost; *Public Cloud:* a cloud platform available to public users to register and use the available infrastructure and resources over the internet. Tenants use cloud resources using pay-as-you-go payment model; and *Hybrid Cloud:* a combination of private cloud platform that can extend to use resources on a public cloud platform.

Of these three models, public clouds are the most vulnerable deployment models because they are available for public users to host their services. Those users may be malicious users or services. In this case, we grant high privileges to malicious users who can exploit more advanced and complicated vulnerabilities to breach the security of not only one tenant data but other cloud tenants' as well. Thus, we need to have an online security analysis tool that can automatically check and pinpoint any vulnerabilities in the shared, multi-tenant cloud application. Moreover, we need to enable tenants in securing their assets as hard as they see.

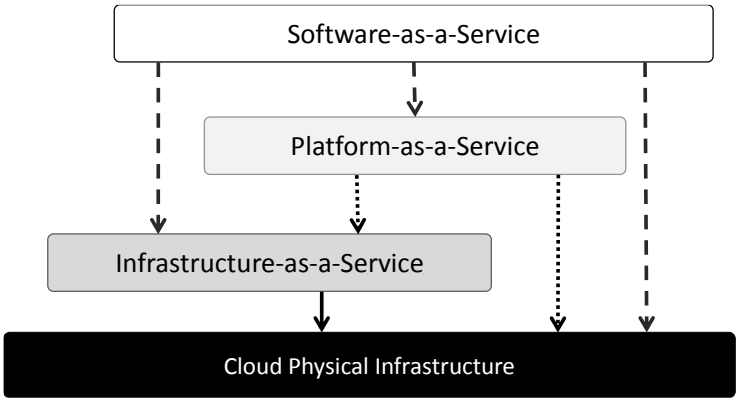


Figure 2-2. Cloud service delivery and deployment models

The cloud model introduces three basic service delivery models, as illustrated in Figure 2-2. These service delivery models deliver different types of services for different types of cloud tenants. Here, we summarize these models and their security implication: *Infrastructure-as-a-Service (IaaS):* in this service delivery model, cloud providers deliver computational resources, storage and network as internet-based services. This service model is based on virtualization technology – i.e. deploying a special software "hypervisor" [52] on top of the infrastructure, which enables creation of different virtual machines that share the same physical server. Amazon EC2 is the most familiar IaaS platform; *Platform-as-a-Service (PaaS):* In this service delivery model, cloud providers deliver platforms, tools and other business services that enable customers to develop, deploy, and manage their own applications, without installing any of these platforms or support tools on their local machines. The PaaS model may be hosted on top of IaaS model or on top of the cloud infrastructures directly. Google Apps and Microsoft Windows Azure are the most well-known PaaS providers; and *Software-as-a-Service (SaaS):* in this service delivery model, cloud providers deliver applications hosted on the cloud infrastructure as internet-based services for end users, without requiring installing the applications on the customers' network. This model may be hosted on top of PaaS, IaaS or directly hosted on cloud infrastructure. Salesforce.com CRM is an example of a well-known SaaS platform.

Each service delivery model has different possible implementations, as shown in Figure 2-2 and discussed above. This complicates the development of standard security model for each service delivery model. Moreover, these models may co-exist on one cloud platform leading to further complication of the security management process. These service delivery models are based on existing technologies such as web applications, service-oriented architecture, and virtualization technologies which already suffer from security problems. Of these different service delivery models, SaaS model is the weakest model where most of the attacks target to breach the model security. In this project, we focus mainly on the SaaS model. However, this

work could be applied easily on the PaaS model (mainly web services). We plan to wave the work we have done in this research with work done in our research group on IaaS model.

2.2.2 Cloud Architecture Security Implications

The cloud computing model depends on a deep stack of inter-dependent layers of objects (VMs, APIs, Services and Applications), as shown in Figure 2-3, where the functionality of a higher layer depends on lower platform layers. The IaaS model covers cloud physical infrastructure (storage, networks and servers), virtualization layer (hypervisors), and virtualized resources layer (VMs, virtual storage, virtual networks). The PaaS model covers the platform layers (such as application servers, web servers, IDEs, and other tools), and APIs and services layers. The PaaS model depends on the virtualization of resources as delivered by IaaS. The SaaS model covers applications and services offered as a service for end users. The SaaS layer depends on a layer of platforms to host the services and a layer of virtualization to optimize resources utilization when delivering services to multiple tenants.

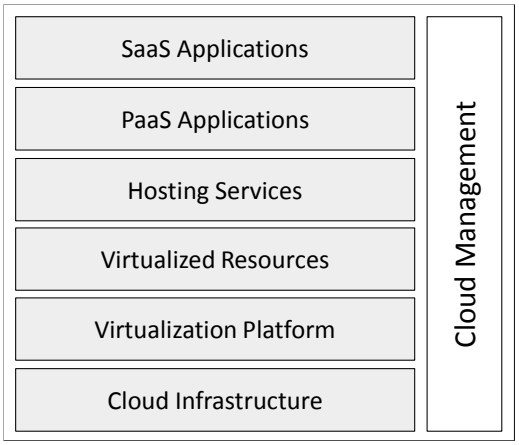


Figure 2-3. Cloud computing model layers

This deep dependency stack of cloud objects complicates the cloud security problem as the security of each object or cloud layer depends on the security of the lower objects/layers. Furthermore, any breach to any cloud objects will impact the security of the whole cloud platform. Each cloud layer/object has a set of security requirements and vulnerabilities so it requires a set of security controls to deliver secured services. This results in a huge number of security controls that need to be managed. Moreover, managing such heterogeneous security controls to meet security needs is a complex task, taking into account conflicts among the security requirements and among security controls at each layer. This may result in an inconsistent security model. Hence, a unified security control management module is required.

This module should coordinate and integrate among the various layers' security controls based on security needs.

2.2.3 Cloud Stakeholders Security Implications

The cloud computing model has different involved stakeholders, including: cloud provider (an entity that delivers infrastructures to the cloud consumers), service provider (an entity that uses the cloud infrastructure to deliver applications or services to end users), and service consumer (an entity that rents and uses services hosted on the cloud infrastructure). Each stakeholder has their own security management systems and processes; each one has their own expectations (requirements) and capabilities (delivered) from/to other stakeholders; and each one owns a piece of information that could help in building a complete security model. This leads to:

- A set of security requirements that need to be defined on a shared service/resource by different service tenants that may conflict with each other. Thus security configurations of each service need to be maintained and enforced at the tenant level instead of the currently used model – i.e. on the service level model. At runtime the system should support the possibility of security requirements updating based on current tenants' needs to mitigate new risks;
- Providers and consumers need to negotiate and agree on the specified security properties. However, no standard security specification notations are currently available that can be used by all of the cloud stakeholders to represent and reason about their offered or required security properties (currently only availability, reliability and performance attributes are supported); and
- Each stakeholder has their own security management processes used to define their assets, expected risks and their impacts, and how to mitigate such risks. Adopting the cloud model results in an inherent "loss of control" by both involved parties - cloud providers are now not aware of the contents and security requirements of services hosted on their infrastructures; and cloud consumers who are not able to control security on neither their assets security nor other services sharing the same resources. Security SLA management frameworks represent a part of the solution related to security properties specification, enforcement and monitoring. However, current SLAs still do not cover security attributes in their specifications [51]. Moreover, SLAs are high level contracts where the details of the security policies, security controls and how to change them at runtime are not clearly stated, enforced or monitored.

Furthermore, cloud providers are faced with a lot of changes on security requirements while having a huge number of security controls deployed that need to be reconfigured in accordance

with security requirements' changes. This further complicates the cloud providers' security administrators' tasks. Transparency of what security is enforced, what risks exist, and what breaches occur on the cloud platform and the hosted services must exist among cloud providers and consumers. This is what is called "trust but verify" - TBV [53], where cloud consumers should trust in their providers in the meanwhile cloud providers should deliver tools to help consumers in verifying and monitoring their enforced security.

2.2.4 Cloud Characteristics Security Implications

To achieve efficient utilization of resources, cloud providers need to increase their resource utilization while minimizing cost. At the same time consumers need to use resources as much as they require while being able to increase or decrease resource consumption based on actual demands. The cloud computing model meets such needs via a win-win solution delivered by two key cloud characteristics: multi-tenancy and elasticity. Both characteristics turn out to have serious implications on cloud model security as we discuss below.

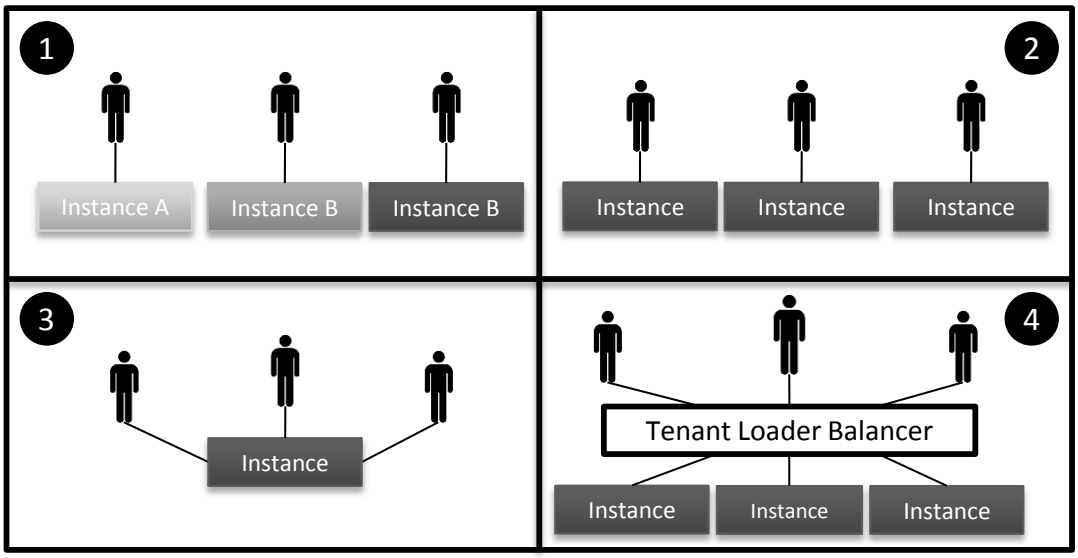


Figure 2-4. Cloud multi-tenancy models

2.2.4.1 Multi-tenancy Security Implications

Multi-tenancy implies sharing of computational resources, storage, services, and applications with other tenants. The concept of "multi-tenancy" actually has different realization approaches, as shown in Figure 2-4.

In approach 1, each tenant has their own dedicated instance with their own customizations (customization may include special development to meet customer needs). In approach 2, each tenant uses a dedicated instance, like approach 1, while all instances are the same but with

different configurations (configurations represent adjustments of application parameters or interfaces to meet specific tenant needs). In approach 3, all tenants share the same instance with runtime configuration (the application is divided into core application components and extra components that are loaded based on the current tenant requests – similar to SalesForce.com). In approach 4, tenants are directed to a load balancer that redirects tenants' requests to a suitable instance according to current work load. Approaches 3 and 4 are the most risky models from the security perspective as service tenants become coexisting on the same process, memory, and hardware. This sharing of resources may violate the confidentiality of tenants' IT assets which leads to the need for secure multi-tenancy. Secure multi-tenancy has two key requirements as discussed below.

- *Secure Isolation and Location Transparency:* Maintaining isolation between tenants' data (at rest, processing and during transmission) and location transparency where tenants have no knowledge or control over the specific location of their resources to avoid planned attacks that attempt to co-locate with the victim assets [54]. In some cloud platforms, tenants can specify high level policies on data location such as country or region level. In IaaS, isolation should consider VMs' storage, processing, memory, cache memories, and networks. In PaaS, isolation should achieve isolation among running services and APIs' calls. In SaaS, isolation should achieve isolate among transactions carried out on the same instance by different tenants and also tenants' data at rest and processing.
- *Security Engineering of Multi-Tenant Services*: Different tenants of the cloud services have their own business requirements as well as security requirements that they are keen to enforce on their cloud hosted assets and data. Although the current cloud computing model does support the capture of different business requirements (through the different multi-tenancy models discussed above), there is little or no support to capture or reflect different sets of security requirements for different tenants. This becomes more complicated when we know that different tenants with different requirements usually emerge at runtime. Moreover, tenant security requirements can change at runtime to reflect their business needs and current security risks that they consider.

2.2.4.2 Elasticity Security Implication

Elasticity implies being able to scale up or down resources assigned to services based on the current demands. Scaling up and down of a tenant allocated resources gives the opportunity for other tenants to use the victim tenant's previously assigned resources. This may lead to confidentiality issues. For example, if tenant A has scaled down so she releases resources, these resources are now assigned to tenant B who in turn might use it to deduce the previous contents of tenant A.

Moreover, elasticity usually depends on a service placement engine that maintains a list of the available resources from the provider's offered resources pool. This list is used to allocate resources to cloud services. Such placement engines should incorporate cloud consumers' security and legal requirements such as avoid placing competitors services on the same server, data location should be within the tenants' country boundaries. Placement engines may include a migration strategy where services are migrated from physical host to another in order to meet demands and efficient utilization of the resources. This migration strategy should take into account the same set of tenants' security constraints. Furthermore, security requirements defined by service consumers should be migrated with the service and initiates a process to enforce security requirements on the new environment, as defined by cloud consumers, and updates the current cloud security model.

2.2.5 Service Delivery Models Security Implications

We summarize the key security issues and vulnerabilities for each cloud service delivery model. Some of these issues fall under the responsibility of cloud providers, while others are the responsibility of cloud consumers.

2.2.5.1 IaaS Security Issues

Below we discuss the key security issues in each component of the IaaS service delivery model:

- *Hypervisor Security:* a hypervisor is the "virtualizer" that maps from physical resources to virtualized resources and vice versa. It is the main controller of any access to the physical server resources by VMs. Any compromise of the hypervisor violates the security of the VMs because all VMs operations become traced unencrypted. Hypervisor security is the responsibility of cloud platform provider.
- *VM Security:* This involves securing virtual machines' operating systems and workloads from common security threats that affect traditional physical servers, such as malware and viruses, using traditional or cloud-oriented security solutions. The VM's security is the responsibility of cloud consumers. Each cloud consumer can use their own security controls based on their needs, expected risk level, and their own security management process. However, the security of the cloud platform from a given VM is the responsibility of the platform provider. This requires a new model for security controls that can work from the virtualization layer (at the hypervisor level). This new model is called virtualization-aware security solutions [55, 56].
- *Securing VM-Images Repository:* unlike physical servers, VMs are still at risk even when they are offline. VM images can be compromised by injecting malicious codes in the VM

file or even stole the VM file itself. Securing the VM images repository is the responsibility of cloud providers. Another issue related to VM templates is that such templates may retain the original owner (creator) information that may be incorrectly accessed by a new consumer.

- *Virtual Network Security:* Sharing network infrastructure among different tenants within the same server (using a vSwitch - Virtual Switches represent networking entities connecting Virtual Machines in a virtual network at layer 2 [52]) or in the physical networks increases the possibility to exploit vulnerabilities in DNS servers, DHCP, IP protocol vulnerabilities, or even the vSwitch software. This may result in network-based VM attacks.
- *Securing VM Boundaries:* VMs have virtual boundaries compared with physical server ones. VMs that co-exist on the same physical server share the same CPU, Memory, I/O, network interface cards, and others (i.e. there is no physical isolation among VM resources). Securing VM boundaries is the responsibility of the cloud provider.

2.2.5.2 PaaS Security Issues

The key security issues in each component of the IaaS service delivery model are:

- *SOA Related Security Issues:* the PaaS model is based on the service-oriented Architecture (SOA) model. This leads to inheriting all the security issues that exist in the SOA domain. These issues include Denial-of-Service (DOS) attacks, Man-in-the-middle attacks, web services and XML-related attacks, replay attacks, dictionary attacks, injection attacks and input validation related attacks [57]. Applying security mechanisms such as mutual authentication, authorization and WS-Security standards [58] is important to secure the cloud services. This task is a shared responsibility among cloud providers, service providers and consumers.
- *API Security:* PaaS may offer APIs that deliver management functions such as business functions, security functions, application management, etc. Such APIs should be provided with security controls and standards implemented, such as OAuth [59] (open identity protocol that help in authorizing third-party applications when accessing web services using HTTP protocol), to enforce consistent authentication and authorization on calls to such APIs. Moreover, there is a need for the isolation of APIs in memory. This issue is the responsibility of service providers. Maintaining isolation between the different tenants' data accessed by the same service is another key security problem that should be considered by the service provider.

2.2.5.3 SaaS Security Issues

In the SaaS model enforcing and maintaining security is a shared responsibility among the cloud providers and service providers (software vendors). The SaaS model inherits the security issues discussed in the previous two models as it is built on top of one or both of them as well as data security (data locality, integrity, segregation, access, confidentiality, backups) and network security.

Web applications represent the dominant deployment model for SaaS applications. Web applications represent 63% of the total reported vulnerabilities over the last three years [60]. Thus, SaaS applications to be hosted on the cloud infrastructure should be continuously validated and scanned for vulnerabilities using web application scanners. Such scanners should be online and up to date with the recently discovered vulnerabilities and attack paths maintained in the Common Weaknesses Enumeration (CWE – a database of the well-known software weaknesses that documents a detailed description of the weaknesses, mitigation actions, prevention actions, etc.). Results (vulnerabilities found) should be recorded in the National Vulnerability Database (NVD – a database of the reported vulnerabilities in every well-known software system along with other vulnerability details such as criticality, exploitability, etc). Getting security experts to analyze every service on the cloud is a very challenging task. Thus vulnerability scanners should deliver high precision (small false positives) and recall (small false negative) rates and support automated analysis without any human intervention. This requires formalizing the existing vulnerability definition databases in terms of vulnerability signature, categorization, preconditions, consequences, mitigation action, and so forth.

Automating vulnerability mitigation is another key requirement in securing SaaS services. Vulnerability mitigation actions should be formalized to ease the automated realization of such actions using different sets of security controls "virtual patching" [43]. The web application firewall is a well-known example of vulnerability mitigation controls that should be in place to mitigate discovered vulnerabilities (examining HTTP requests and responses for applications specific vulnerabilities). As a reference to assess such vulnerability scanners and mitigation controls, we can use the top ten vulnerabilities reported by Open Web Application Security Project (OWSAP) [40] according to the number of reported vulnerabilities every year. Such vulnerabilities include injection attacks (SQL injection, OS command injection, XML injection), cross site scripting attacks (Input validation) weaknesses, improper authorization attacks, and so forth. We will explain these vulnerabilities in more detail in the security analysis chapter.

2.2.5.4 Cloud Management Security Issues

The Cloud Management Layer (CML) is the "microkernel" that can be extended to incorporate and coordinate different components. The CML components include SLA management, service monitoring, billing, elasticity, IaaS, PaaS, SaaS services registry, and security management of the cloud. This layer is very critical since any vulnerability or security breach of this layer will result in an adversary who has got access control, like an administrator, over the whole cloud platform. This layer offers a set of APIs and services to be used by client applications to integrate with the cloud platform. This means that the same security issues of the PaaS model apply to the CML layer as well.

2.2.5.5 Cloud Access Methods Security Issues

Cloud computing is based on exposing resources over the internet. These resources can be accessed through (1) web browsers (HTTP/HTTPS), in case of web applications - SaaS; (2) SOAP, REST and RPC Protocols, in case of web services and APIs – PaaS and CML APIs; (3) remote connections, VPN and FTP in case of VMs and storage services – IaaS. Security controls should target vulnerabilities related to these protocols to protect data transferred between the cloud platform and cloud consumers such as Man-In-The-Middle attack.

2.3 Cloud Computing Security Enablers

Via our review of current cloud security issues we have determined a set of key security enablers that should be improved by the cloud computing community to mitigate the issues discussed above. Some of these factors are considered parts of security controls' must have features and the rest are related to the security management platform itself which is built to be adaptive to incorporate possible security controls.

2.3.1 Identity Federation and Access Management

Identity is at the core of any security aware system. It allows users, services, servers, clouds, and any other entities to be recognized by systems and other parties. Identity consists of a set of claims and information associated with a specific entity [61]. This information is relevant based on the context. An identity management system should not disclose user personal information "privacy". Cloud platforms should deliver or support a robust and consistent identity management system. This system should cover all cloud objects (servers, VMs, services, applications, operations) and cloud users with corresponding identity context information. It should include: identity provisioning and de-provisioning, identity information privacy, identity linking, identity mapping, identity federation, identity attributes federation, single sign on,

authentication and authorization. Such system should adopt existing standards, such as SPML, SAML, OAuth, and XACML, to securely federate identities among interacting entities within different domains and cloud platforms.

2.3.2 Data Cryptography

Confidentiality is one of the key security requirements when adopting the cloud computing model to host enterprise assets. Encryption is the main solution to the confidentiality objective, for data, processes and communications. Different problems arise in the cryptography area from the adoption of the cloud model:

- *Format-Preserving Encryption* [62]*:* Due to the lack of trust problem between the cloud stakeholders (consumer does not trust the service provider or the cloud provider), cryptography security requirements are increasing where one might encrypt every single field in customers' data at transmission and at rest. Data stored on the cloud and processed by services and applications then have a different format. Thus, we need to use format-preserving encryption – e.g. encrypting integer data should result in integer as well to be able to store in the database.
- *Homo-Morphic Encryption [63]:* The lack-of-trust and possibility of malicious insiders (cloud platform administrators who have access to servers memory) add a new cryptography requirement to keep data encrypted even at processing time (in memory). This means that cloud services and applications should be able to process such encrypted data – i.e. data will not be decrypted at any time on the cloud platform.
- *Key Management [64]:* Encryption algorithms are either symmetric key-based or asymmetric are key-based. Both encryption approaches have a major problem related to encryption key management - i.e. how to securely generate, store, access and exchange secrete keys. Moreover, PaaS requires application keys for all APIs and service calls from other applications. The applications' keys must be maintained securely along with all other credentials required by the application to be able to access such APIs.

2.3.3 Secure Cloud Software Development Lifecycle

Integrating security engineering into the software development lifecycle [65, 66] - includes elicitation of the security requirements, threat modeling, augmentation of security requirements to the systems models and the generated code consequently. Engineering cloud-based applications should involve a revolution in the lifecycles and tools used to build secure systems [67]. The PaaS provides a set of reusable security enabling components to help developing secure cloud-based applications. Also security engineering of the cloud-based application

should change to meet new security requirements imposed on such systems. Applications should support adaptive security (avoiding hardcoded security) to be able to meet vast range of consumers' security requirements. Adaptive application security is based on externalizing and delegating the security enforcement and applications security management to the cloud security management, service provider and tenant security controls.

2.3.4 Security Performance Tradeoff

The cloud computing model is based on delivering services using SLAs. SLAs should cover objectives related to performance, reliability, and also security. SLAs also define penalties that will be applied in case of SLA violation. Delivering high security level, as one of the SLA objectives, means consuming much more resources that impact on the performance objective. The more adopted security tools and mechanism, the worst the impact on the performance of the underlying services. Cloud management should consider the trade-off between security and performance using utility functions for security and performance (least security unless stated otherwise). Moreover, we should focus on delivering adaptive security where security controls configurations are based on the current and expected threat level and considering other tradeoffs.

2.3.5 Security Management

The large number of cloud stakeholders, the deep dependency stack, and the large number of services deployed on the cloud platform, and the huge number of security controls to deliver security requirements, complicate the cloud computing security management task. A cloud security management platform should support capturing and consolidating security requirements and policies, specifications; security controls' configurations according to the policies specified; and monitoring and feedback from the cloud platform and services, and security controls to the security management and the cloud stakeholders.

When consumers use applications that depend on services from different clouds, they need to maintain their security requirements enforced on both clouds and in between. The same case occurs when multiple clouds integrate together to deliver a bigger pool of resources or integrated services, their security requirements need to be federated and enforced on different involved cloud platforms. Given that the cloud management layer has to manage performance, reliability, availability, elasticity - resource allocation, etc., a good design for this layer is to use the kernel design pattern where different components delivering different functionalities are easily integrated. This means that the security management module should function as a plug-in for the cloud management layer.

2.4 Chapter Summary

The cloud computing model is a very promising computing model for service providers, cloud providers, and cloud consumers. However, in order to best utilize the model we need to block the existing security holes. Based on the details explained above, we can summarize the cloud security problem as follows:

- Some of the security problems are inherited from the technologies used, such as virtualization, SOA, and web applications.
- Multi-tenancy and isolation are major dimensions in the cloud security problem that require a vertical solution from the SaaS layer down to physical infrastructure (to develop physical alike boundaries among tenants instead of the virtual boundaries currently applied).
- Security management is very critical to control and manage this number of requirements and controls.
- The cloud model should have a holistic security wrapper, such that any access to any object on the cloud platform should pass through security components first.

Based on this discussion, we recommend that cloud computing security solutions should:

- Focus on the problem abstraction, using model-based approaches to capture different security views and link such views in a holistic cloud security model.
- Be inherent in the cloud architecture where delivered mechanisms (such as elasticity engines) and APIs should provide flexible/extensible security interfaces.
- Support for multi-tenancy, where each user can see only their security configurations, elasticity, to scale up and down based on the current context.
- Support integration and coordination with other security controls at different layers to deliver integrated security.
- Be adaptable to meet continuous environment changes and stakeholder needs.

In this research project, our objective is to mitigate the loss-of-control and lack-of-trust problems that arise from the adoption of the cloud computing model by both providers and consumers. This is realized by getting cloud consumers involved in securing their cloud hosted assets. This includes: (i) defining security requirements; (ii) enforcing security using different sets of security controls either deployed on the cloud platform, in their network perimeter, or on another cloud platform; and (iii) monitoring and improving enforced security according to the current security status of the cloud hosted assets and new business and security needs.

Chapter 3

Related Work

In this chapter, we review, analyze, and summarize the key existing efforts in different research areas relevant to our research problem, cloud computing security management, and our proposed solution, adaptive, model-based security management model for the cloud computing model. This chapter is organized as follows. In Section 1, we give an overview of the research areas we cover in our state-of-the-art analysis. In Section 2, we review the related work in the area of security management standards and frameworks. In Section 3, we review the related work in the area of security analysis. In Section 4, we review the related work in the area of security engineering, multi-tenant and adaptive security. In Section 5, we review the related work in the area of security and software re-engineering. In Section 6, we review the related work in the area of security measurement and metrics. This also covers relevant efforts from the service-level agreement and software requirements monitoring areas. In Section 7, we summarize the key limitations, we identified in these areas that are either relevant to the research problem and target solution.

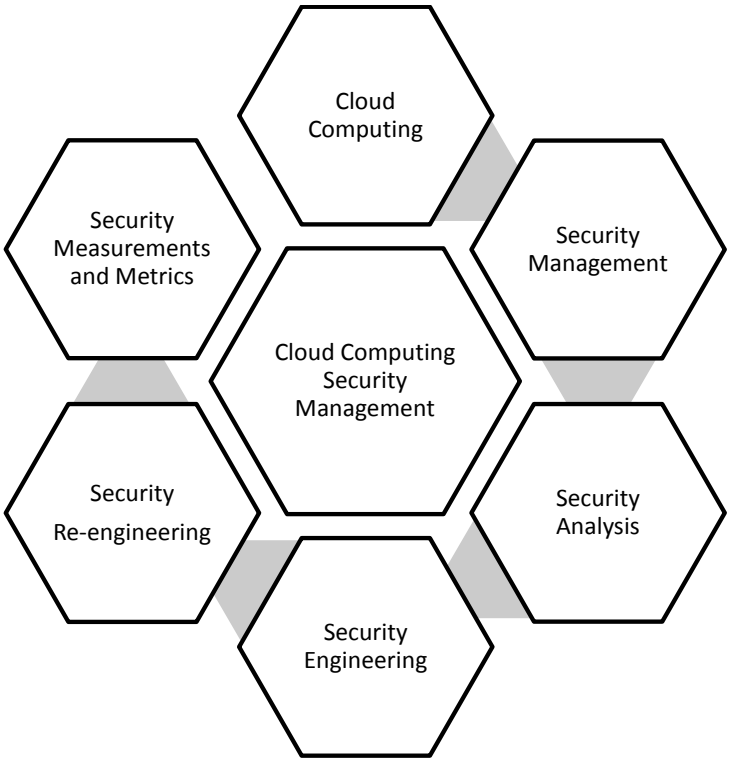


Figure 3-1. Relevant research areas to the cloud security management problem

3.1 Introduction

The main responsibility of a security management system is to help security administrators and engineers in capturing and defining IT assets' security, enforcing specified security details, monitoring the security status of these assets, and improving assets' security to meet target security objectives. These security objectives may change overtime according to business needs. This thus implies changing related security requirements, policies, controls and security control configurations. As we stated in our analysis of the cloud computing security problem (Chapter 2), it is too hard to depend on manual approaches that require deep involvement of stakeholders (cloud providers, service providers or service consumers) to deliver the aimed security level. Thus, any cloud computing security management approach must focus on automating these security management tasks including defining security, enforcing security, and monitoring and improving security. A cloud computing security management approach must address the loss-of-control and lack-of-trust problems because it is the best place to incorporate cloud consumers' security. It also should take into consideration multi-tenancy, as a key factor contributing to the cloud computing security problem. This because multi-tenancy has a big impact on how to capture, enforce, and monitoring tasks. For example, instead of working only with one set of security requirements, with multi-tenancy we have different sets of security requirements for different tenants. These need to be captured, enforced, and monitored on a shared service instance.

We have determined four main relevant research areas to our research problem (cloud computing security management), including the security management area, security analysis, security engineering, and security monitoring. Two more areas are also relevant to our research problem, cloud computing security as the underlying problem domain, and security reengineering/retrofitting. The latter is required when addressing cloud services with built-in security capabilities that hamper (conflict) with the adoption of our security management platform in automating service security management. Below we discuss the key points and questions that we need to get answers for in each research area in order to specify what efforts could help building our cloud computing security management approach.

- *Cloud Computing Area*: We need to study the cloud computing model details and determine what factors contribute to the cloud computing security problem? What are the key requirements that should be addressed when developing such a security management model for the cloud computing model? This part was discussed in detail in our analysis of the cloud computing security problem (Chapter 2). Thus, we are not going to discuss it again here.
- *Security Management Area:* We need to study what are the existing security management standards? What are the bases and assumptions that these standards are built on? What are

the existing security management systems? What are the core models and paradigms adopted in developing these systems? What are the key problems and limitations of these security management standards and systems when applied to the cloud computing model?

- *Security Analysis Area*: What are the main security analysis tasks? What are the main security vulnerabilities' repositories? What are the existing web applications security analysis efforts? What vulnerability categories are covered by these efforts? What are the main limitations of these efforts? How far do these efforts support automation of the security analysis tasks? How are these efforts extensible to support discovery of existing as well as new vulnerabilities that emerge at runtime?
- *Security Engineering Area*: We need to capture, inject, and update cloud services' security for different tenants at runtime taking into consideration different multi-tenancy models. We need to study what are the existing security engineering efforts? What are the key limitations of these efforts that arise from applying these techniques on cloud-hosted services? How do these efforts fit with the cloud computing multi-tenancy requirements? How much automation do these efforts provide to facilitate the automated integration of security with cloud services?
- *Security Reengineering (Retrofitting) Area*: We need to modify legacy applications' security capabilities. Thus, we need to study what are the existing security reengineering (retrofitting) efforts? What are the key limitations of these efforts that arise from applying these techniques to the cloud services? How much automation is possible with these approaches to facilitate the modification of software systems and realizing new system modifications?
- *Security Monitoring Area*: What security monitoring platforms do exist? How extensible these platforms in terms of security metrics specification and realization? How easy these security metrics could be specified? How these platforms fit with the cloud and multi-tenancy model? How can we capture different tenants' security metrics, and how can we realize these metrics? How can we plug in security probes that collect measurements required to assess the security status specified by different tenants?

3.2 Security Management

The area of security management is one of the core areas in IT security where all enterprise IT systems and operated security controls are aligned and integrated together. We have determined two key groups of efforts in this area: security management standards, and security management systems. The first group focuses on defining standard processes that should be followed when developing enterprise security model. The latter one focuses on how to help security administrators with their IT security management tasks.

3.2.1 Security Management Standards

Information security management systems (ISMS) are defined as systems that deliver a holistic "model for establishing, implementing, operating, monitoring, reviewing, maintaining and improving the protection of information assets" [1, 5, 68]. We have identified two key security management standards. The first one is the Federal Information Security Management Act introduced by the National Institute of Standards and Technology - NIST-FISMA [1]. The second is the International Organization for Standardization and the International Electro-technical Commission - ISO/IEC – ISO27000 [5]. Below we summarize these two standards highlighting the main assumptions and bases for each one.

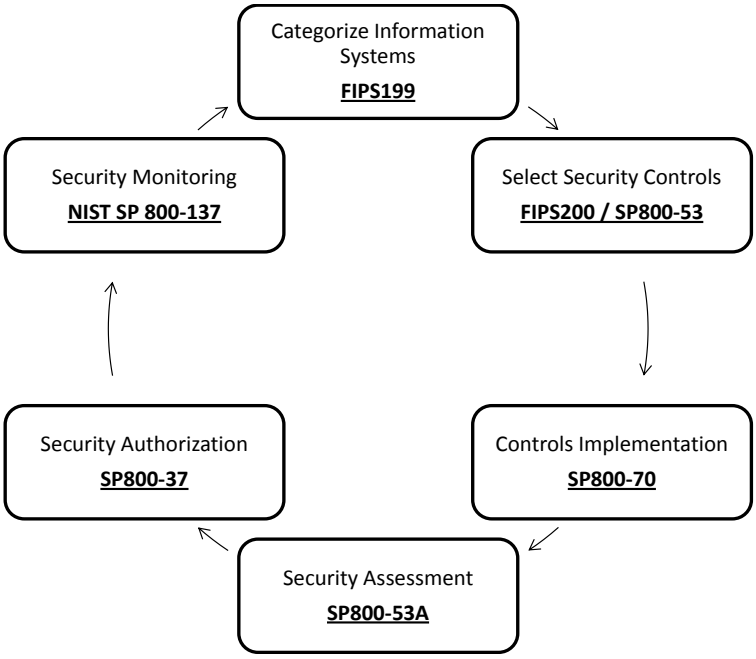


Figure 3-2. NIST-FISMA main phases, flow, and standards

3.2.1.1 NIST-FISMA Standard

This was originally declared as an e-Government Act in 2002 [1]. The first phase of the FISMA implementation project was planned to run from 2003 to 2012. The FISMA standard delivers a set of guidelines to be used in developing agency-wide security management program that helps in categorizing information systems, capturing security objectives, enforcing specified security, and monitoring the security status of agency assets. The FISMA standard includes a set of guidelines and standards that help implementing the enterprise information security management program as follows:

– *FIPS199:* Federal Information Processing Standards199 (FIPS199) standard for categorizing information and information systems by mission impact. It focus on how to assess the impact

of a security breach of one or more of the security objectives (including confidentiality, availability, and reliability) assigned to a given information system.

- *FIPS200:* A standard that defines a minimum set of security requirements that should be applied on information and information systems. Based on the security categorization of a given information system (in FIPS199), a set of minimum security requirements and security controls is selected from multiple sets of predefined security control baselines – i.e. if an information system is assigned a low security impact, this means that the low impact security requirements and controls baseline is selected. This set represents the minimum security capabilities that enterprise security engineers need to implement. This standard also includes applying security risk analysis that may result in a new set of security requirements that should be incorporated with standard set of security controls to be applied.
- *SP800-70:* A standard to help security administrators in selecting appropriate security controls for information systems. Different information systems may have different natures that may require using specific rather than enterprise-wide, common security controls. The objective of this standard is to guide the selection process of security controls specific to certain information systems and controls to be used enterprise-wide.
- *SP800-53A:* A guidance for assessing security controls in information systems and determining security controls' effectiveness. This guideline defines how to select security controls to be assessed, method of the assessment, metrics that could be used, and how the assessment could be conducted.
- *SP800-37:* A standard for the security authorization of information systems. This guideline specifies who should be responsible for authorizing the security management plan developed and how the identified risks are addressed /mitigated.
- *SP800-137:* A standard for monitoring the security controls and the security authorization of information systems. This guideline defines for each security controls' family (FISMA standard divides the security controls into a set of 17 security controls families), a set of security metrics that should be measured in the course of monitoring the security status of enterprise IT systems, frequency, nature of the metric, formula, unit of measure, etc.

3.2.1.2 ISO27000 Standard

The ISO27000 standard [5, 69] provides a model to guide the definition and operation of information systems security management process. The ISO27000 targets all types of organizations other than federal agencies as intended in the FISMA standard. The ISO27000 standard has a series of security standards that address different areas in the information systems security management framework as follows:

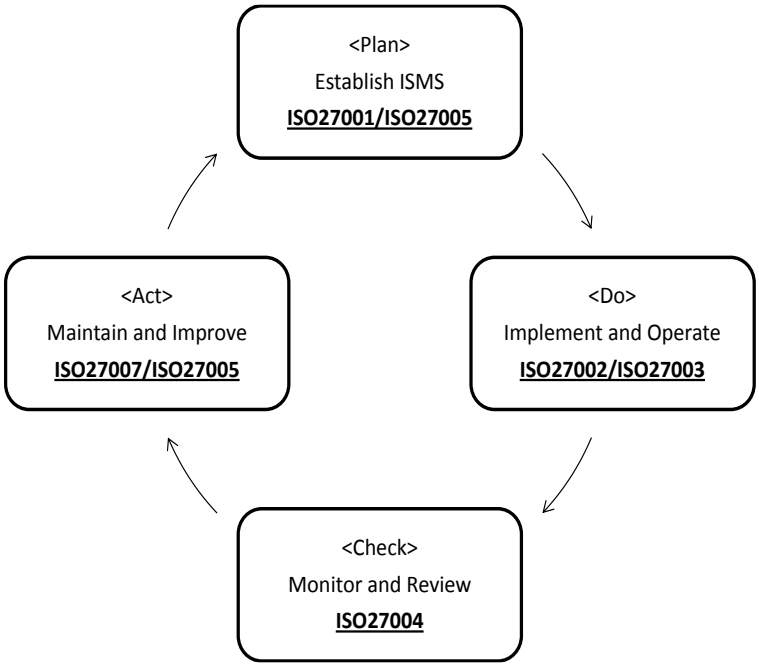


Figure 3-3. ISO27000 main phases, flow, and standards

- *ISO27001:* This standard gives an overview of the specification of any ISMS based on the ISO27000 standard. It discusses how ISO27000 standard is aligned with the Plan-Do-Check-Act (PDCA) management model. Moreover, It summarizes the key terminologies exist in the security management area and gives a summary of security controls' objectives that should be operated.
- *ISO27002:* This standard focuses on security controls' implementation guidance to help organizations during the ISMS implementation, reviewing and authorization phases. It covers how these phases could be done to address different targets or categories of security including human resources, physical security, communication security, access control, information systems, etc. This is similar to the security controls' families introduced in the NIST-FISMA standard and the security requirements families introduced in the Common Criteria model for software security evaluation [70].
- *ISO27003:* This standard gives guidance and details on implementing different ISMS phases including plan, do, check, and act (PDCA) phases.
- *ISO27004:* This standard addresses and defines the ISMS measurements and metrics that could be used, stakeholders involved and their responsibilities, measurement operations, data analytics of the measurement results, and further improvement actions that could be taken in case of security deviations.
- *ISO27005:* This standard addresses the security risk management process. It details the proposed methodology for information security risk management including risk analysis, treatment, and acceptance.

– *ISO27006:* This standard provides guidelines to help organizations in the accreditation process of the ISMS ISO27000 certification. It documents the key requirements that should be satisfied and how it could be addressed.

3.2.1.3 Differences between NIST-FISMA and ISO27000

We have determined multiple similarities and discrepancies between ISO27000 and NIST-FISMA standards [71, 72]. The similarities between both standards include the general approach, phases of security management, complexity of both standards to implement and satisfy, relatively similar concepts, risk management activities, list of security controls (NIST specifies links to ISO27000 security controls). On the other hand, we found a set of differences between both as well. NIST-FISMA targets federal agencies while ISO27000 target commercial organizations; however, we did not figure out problems to apply NIST as a security management standard to commercial organizations. NIST-FISMA focuses mainly on one or more IT systems. The ISO27000 has organizational-wide focus. NIST uses the IT systems categorization to set the security controls baseline to apply (as a default set) while ISO27000 assumes that the set of security controls provided in the standard are available to be picked up and used according to the situation. In our opinion, this helps in the security controls selection phase by minimizing the scope of security controls to select from (minimize the possibility of error or missing security). This security controls baseline could be customized later, according to the identified and assessed risks. In this thesis we base our approach on NIST-FISMA.

3.2.1.4 Security Management Standards and Cloud Computing

Both ISO27000 and NIST-FISMA standards assume that the asset (IT system) owner has full control over the security management process – i.e. assets are mostly hosted internally inside their network perimeter or at least they can specify and monitor the security of their assets if hosted on a service provider. Thus, both standards, with their current specifications, do not fit well with the cloud computing model. Nor do they fit well with the multi-tenancy model, where tenants do not have any control on their outsourced assets. This is shown in the responsibility matrix summarized in Figure 3-4. Here, service consumers do not have any participation in securing their cloud services – this is a well-known security problem in the cloud computing model "loss-of-control" problem. Multi-tenancy adds a new complex dimension to the security problem. These security management standards are not designed taking into consideration the service sharing concept introduced by multi-tenancy – i.e. how to capture, enforce, and monitor service security status for different tenants given that these security requirements may change overtime. In addition, the set of service tenants evolves at runtime. New tenants may register to use the service at runtime. At the same time, other tenants may unregister from the service.

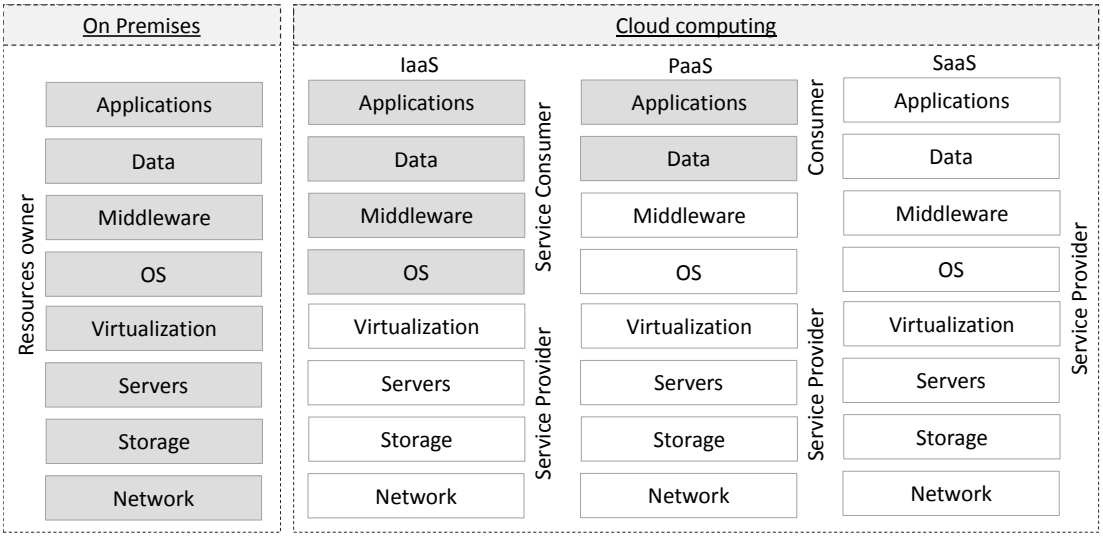


Figure 3-4. Comparison of responsibility matrix between on-premise and cloud

3.2.2 Security Management Systems

The area of security management systems has lot of efforts even though relatively few efforts deliver full implementation of the security management process. Many focus on detailing security management standards (ISO and NIST) [69, 73]. The rest of these efforts that introduce a working security management approach could be categorized as policy-based, ontology-based, and model-based approach. Below we summarize many of these key efforts.

3.2.2.1 Policy-based Security Management

The adoption of security policies as a high-level mean to capture security controls' configurations has been widely used in the area of information security management to automate the security controls' configuration process. These efforts focus on how to capture different types of security policies using security policy specification languages such as [74-76] and how to automate the configuration of different heterogeneous security controls developed by different security vendors.

POSTIF [77] is a security management framework that focuses on automated configuration of different heterogeneous security controls in order to realize the specified security policies. The framework is based on the common information model (CIM) introduced by the DMTF [78]. The proposed framework focuses mainly on automation of intrusion detection systems' configurations. The security policies are used to specify high-level security controls' configurations. We could not find implementation details of this approach.

Faheem et al [79, 80] introduce an abstract multi-agent based system for managing network security policies. The proposed framework is made of three layers: the core security policies layer that captures different security policies; the multi-agent layer that has a set of interacting

agents that collaborate to refine the specified security policies into security controls' configurations; and security products layer which is a layer of enterprise deployed security controls. Their case study was on an intrusion detection system developed internally in their research labs. The proposed framework is based on mobile agents that have severe problems with security. In giving permission to software entities to move around in the enterprise network increases the possibility of the exposure of malicious activities (malwares and Trojan horses).

3.2.2.2 Ontology-based Security Management

The ontology concept has been frequently used in the information security management domain as a mean to formalize the concepts, entities, and relationships existing in this domain [81]. Bellow we summarize some of the key trials in this area.

Tsoumas et al [7] introduce an ontology-based information systems security management system. They built their own risk analysis security ontology based on the common information model (CIM) [78]. They map the IT asset concept (the core entity in security risk management) to the CIM CIM_ManagedElement concept. This in turn simplifies the enforcement and monitoring process. After linking assets to risks, they developed countermeasures ontology and then linked this to threats that each countermeasure can help in resolving. The countermeasures' ontology is as follows: CM_ID, Target (asset), subject (the enforcer of the countermeasure), countermeasure group, countermeasure sub groups, actions (that the countermeasure can take), constraints (time, location, subject), type (managerial, operational, technical), security attributes to preserve (security objectives like confidentiality, integrity,...etc), type of control (protective, defective, or corrective), risk mitigation factor (low, medium, high), and control purpose (security, audit). This also simplified the adoption of the Web-based enterprise management standard (WBEM) [82] introduced by the Distributed Management Task Force (DMTF) organization to address the distributed nature of systems management problem (including security management). The captured enterprise security knowledge is then converted into ponder-based policies [75] (Ponder is a security policy specification language) that are used mainly for defining access control policies.

Xu et al [83] introduce a hybrid network security management approach based on policy-based management and ontology-based management. The ontology is used to help in reasoning about specified security policies while applying the policy-based PDP and PEP management model (PDP: policy definition point; PEP: policy enforcement point) for security policies enforcement. Each agent deployed on a host can communicate with other network agents sharing the same ontology to reason about the operated security policies.

Uszok et al [84] introduce a security management architecture based on KAoS policies language. The architecture has three main layers: (i) policy specification layer represented by a user interface where security administrators can define their own security problems; (ii) policy reasoning layer; (iii) policy enforcement layer (guards). The policy specification is based on an extensible ontology to recognize domain specific concepts. KAoS can help in defining authorization and obligation policies. The reasoning layer takes into account issues like precedence, temporal conditions, historical states, policy triggers, and context information. For the policy enforcement layer, the authors developed guards (agents) to be deployed for applications. These agents cache the policies and act as PDP for the applications. In case of any security event raised by the application using Action Instance Description (AID), a java object encapsulates event details; the guard decides the correct action based on the cached policies. These guards can be extended to monitor application status using AID entities.

3.2.2.3 Model-based Security Management

Albuquerque et al [8] introduce a security management approach based on the model-based management model. The authors introduce a hierarchical system model which represents the IT systems on three abstract, interrelated levels: (i) roles and objects which summarize details of the *who* of the stakeholders and *what* assets to be secured; (ii) subjects and resources which summarize users or services and resources; and (iii) diagram of abstract systems which capture the system building blocks. The high-level security policies are mapped on the highest system model and automatically refined down with the refined system models to generate the low-level security policies. Similar work was introduced by Lang et al [85], OpenPMF - Open Policy Management Framework, a model-driven security management approach based on model-driven security.

3.2.2.4 Security and Service Level Agreement

As a result of outsourcing IT assets for hosting on third-party platforms, an increasing need for security SLA emerge; however, we have found most of the existing SLA efforts focus on capturing SLA terms related to performance, reliability, and availability. The area of security SLA is relatively hard to approach because no one will be able to prove a certain security level to negotiate and agree on with the customers. However, no one would like to announce security breaches on their platforms because this will impact their reputation. Shirlei et al [13] introduced a proposal for security SLA (Sec-SLA) which capture customers' security requirements in terms of security metrics that could be regularly measured, analysed, and reported for customers.

3.2.3 Information Security and Risk Management

From the discussion above, we conclude that existing security management standards target mainly enterprise assets' security management where tenants own and control the existing infrastructure, network, and applications. Thus, they do not help with services' outsourcing. They also do not take into consideration the multi-tenancy and how to capture and enforce different tenants' security requirements. Existing security management systems focus mainly on (i) how to capture security details using policies directly, using ontology, or using models; (ii) how to convert these security details (requirements) into security policies; (iii) and how to map these polices into security controls' configurations. Thus, it is clear that the monitoring and feedback components of the security management process are missing in these efforts.

From our analysis of the security management area and existing security management systems and standards, we have figured out a misunderstanding in some of the concepts related to ISMSs. Mainly, we found a mix between the security management and the security risk management. We have investigated the differences and relationships between the ISMS and ISRMS (Information Security Risk Management Systems). The ISRMSs focus on risk identification, treatment, acceptance, communication, and monitoring and reviewing. This is in comparison to the ISMS we discussed above shows that the ISRMS is a part of the ISMS as we show in Figure 3-5. Implementing security controls specified in the risk mitigation actions, integrating security controls with the target IT systems, developing and deploying security probes are the other key phases of an ISMS.

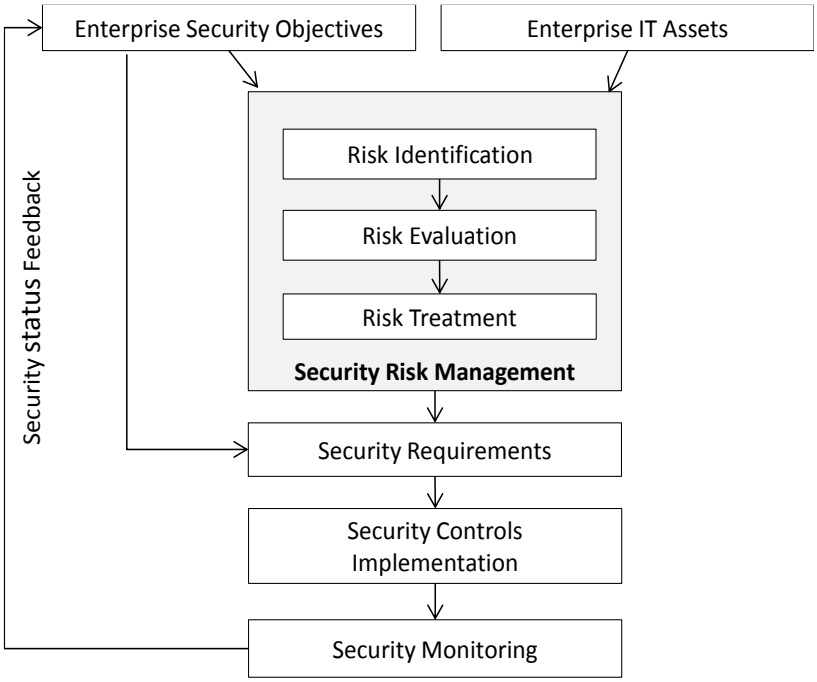


Figure 3-5. Relationship between ISMS and ISRM

3.3 Security Analysis

The security analysis task is one of the very complicated tasks in both security engineering and management domains. The security analysis task includes threat analysis, security vulnerability analysis, and security attack analysis. These tasks are integrated together while conducting security analysis. The output of the security analysis tasks represents the main source of security requirements to be realized by any ISMS. A key limitation of the existing security risk analysis efforts is that they mainly focus on introducing a risk analysis methodology to be followed by security administrators or at the maximum help in the documentation and assessment process. They do not help in automating the security risk analysis. Thus, we had to investigate in other security analysis areas that contribute to the security analysis including architecture risk analysis that helps in identifying security threats in a given software system, and security vulnerability analysis that helps in identifying system security vulnerabilities. Both constitute the main sources of information required to build a complete security risk model. Below we discuss effort in these three main areas.

3.3.1 Security Risk Analysis

Security risk analysis is one of the key steps in the ISMSs. The main target of the security risk analysis task is to identify possible threats and attacks against a target IT system, that need to be secured, and could be exploited by attack agents to breach systems' security. Then, security experts use these vulnerabilities to develop the possible threats and attack graphs that could be fired by attackers against systems. The outcome of the security risk analysis task is used to develop risk treatment plan where security experts specify how to mitigate or prevent the identified risks. These treatment plans contain a set of security requirements that need to be enforced in order to mitigate reported risks and meet customers' security objectives.

The existing security risk analysis and assessment efforts can be categorized into two main categories: tool-based analysis and workshop-based analysis [9]. The tool-based analysis approaches introduce toolsets that help in capturing enterprise assets and security details and automatically conduct the security risk analysis task. In the workshop-based analysis, the stakeholders conduct brainstorming and interviewing sessions. Another possible categorization of the security risk analysis methods is either qualitative or quantitative. The latter category uses mathematical formulas to assess identified risks while the earlier depends on subjective assessment bands (high, medium, low). Syalim et al [86] introduce a comparison between four key security analysis methodologies including Mehari, Magerit, NIST800-30 and Microsoft's security management. The key limitation of the security risk analysis efforts is the focus on introducing a risk analysis methodology to be followed by security administrators or at the

maximum help in the documentation and assessment process. Thus, they do not help in automating the security risk analysis. Below we discuss key security risk analysis efforts:

Operationally Critical Threat, Asset and Vulnerability Evaluation (OCTAVE) [9] is a workshop-based risk assessment approach. OCTAVE has three main phases. Each phase has a set of processes and activities. *First*, the security analysis team builds a repository of critical enterprise assets. *Next*, they develop a threat profile for these assets. *Then*, the security analysis team performs vulnerability analysis of the key components related to the critical assets. *Finally*, this team performs impact and probability evaluation of the identified threats on critical assets. Furthermore, they develop protection plan to mitigate, reduce, and prevent the identified risks.

Information Security Risk Analysis Method (ISRAM) is a seven-step quantitative risk analysis approach based on conducting surveys that contain questions about risk factors (type of attachment, number of emails, number of files to be downloaded per day) to help in assessing the likelihood and impact of the given list of risks.

Construct a platform for Risk Analysis of Security Critical Systems (CORAS) [10] is a model-based method for security risk analysis. The security analysis team conducts an initial risk analysis to identify initial list of threats and vulnerabilities. This is followed by a deeper analysis by the security team. A brainstorming workshop is conducted to identify any unwanted security incidents. This is followed by another risk estimation workshop to estimate the likelihood of the identified risks. *Finally*, they conduct a workshop to develop risk treatment plan including a cost-benefit analysis.

Saripalli [11] [87] introduces different security risk analysis methods for the cloud computing model adopting the existing security management standards such as ISO27000. However, they consider applying these standards from the service (cloud platform) provider perspective not from the cloud consumers' perspective. Moreover, these efforts did not consider hosting of external services that have been developed by other service providers where the cloud platform provider does not have any information about their security issues.

In summary, the existing security risk analysis efforts focus mainly on how to conduct and document the outcomes of the security risk analysis process through a set of well-defined steps, some with tool support. However, they do not help in automating the analysis process itself.

3.3.2 Architecture Security Analysis

Existing efforts in architecture security risk analysis can be categorized into two main groups: scenario-based approaches and metrics-based approaches. Both have limitations related to

approach formality in describing metrics or scenarios, extensibility to capture new metrics or scenarios to be assessed, and in automating the architecture risk analysis process. A key notice from the existing efforts is that they focus mostly on scenario-based analysis. A possible justification of this tendency is that developing security metrics is a hard problem. However, it limits the capabilities of the approach compared to user-defined or tool-supported scenarios.

3.3.2.1 Scenario-based Analysis

Kazman *et al.* [88], Dobrica *et al.* [89], and Babar *et al* [90] introduce comprehensive software architecture analysis methods for different milestones of the software architecture development. They introduce a set of criteria that can be used in developing or evaluating an architecture analysis method including identification of the goals, properties under examination, analysis support, and analysis outcomes. Babar *et al.* compare and contrast eight different existing architecture analysis approaches. A common weakness of all these approaches is the lack of extensible tool support.

Kazman *et al.* [91] introduce architecture trade-off analysis model, ATAM, to identify trade-offs between quality attributes of a given system and report sensitivity points in its architecture. The approach is based on collaboration of stakeholders to define scenarios to be used in evaluating different architectures. The analysis is expected to be done manually.

Faniyi *et al.* [92] extend the ATAM approach to support architecture analysis in unpredictable environments such as cloud computing platforms. They improve the scenario elicitation process using security testing with implied scenarios (unanticipated scenarios of components' interactions). This generates potential scenarios that may lead to security attacks. Although this improved the scenario elicitation process, it still requires manual analysis. A further extension to our signature-based architecture security analysis approach could be to integrate this approach as a source of attack and metrics signatures' specifications.

Halkidis *et al.* [93] introduce an architectural risk analysis approach based on locating the existing security patterns in the architecture of system under test using architecture annotation. Then, they use Microsoft STRIDE model [94] to generate a set of possible attacks along with their likelihood. These security attacks can be mitigated using security patterns. Thus, the lack of specific security patterns in a given system architecture means possibility of violating certain security objectives in the underlying system architecture. However, their approach does not support developing custom security scenarios to be analyzed in the target system.

Admodisastro *et al.* [95] introduce a scenario-driven architectural analysis approach for black-box component-based systems. Their analysis framework is extensible to support different pluggable analyzers that perform structure checking, quality checking, and

conformance checking. However, their proposed framework is high-level and lacks details of its realization system.

Alkussayer *et al.* [96, 97] introduce a scenario-based security evaluation framework of software architecture. They use mappings between security goals and requirements, security patterns, and security threats to identify security scenarios used in evaluating (and may be improving) a given system architecture.

3.3.2.2 Metrics-based Analysis

Metrics-based analysis techniques focus on developing a set of security metrics that could be used in assessing the security strength of a given software system architecture against possible attacks and how far a given attack impacts system operation.

Antonino *et al.* [98] introduce an indicator-based approach to evaluate architecture-level security in Service-Oriented Architecture (SOA). They use reverse engineering to extract security-relevant facts. Then, they use system-independent indicators and a knowledgebase maintaining a list of security goals and indicators relevant for each security goal. Although the approach is extensible, it does not support automated security analysis. Sant'anna *et al.* [99] describe a concern-driven quantitative framework for assessing architecture modularity. They introduce a set of predefined modularity metrics that are used to assess a given system architecture.

Alshammari *et al*. [100, 101] introduce a hierarchical security assessment model for object-oriented programs. They define a set of dependent metrics that capture security attributes of a given system. The proposed metrics are well organized; however, they are not extensible (i.e. are predefined metrics). They also do not consider security architecture-level details.

Heyman *et al.* [102] introduce an approach to identify security metrics to measure or assess based on mapping user security requirements on security objectives. For each security objective, they define security patterns that are expected to satisfy such objectives. Each security pattern has a set of security metrics that are satisfied by a pattern. The metrics specification approach is informal so it does not enable automating the analysis phase.

Sohr *et al*. [103] describe an architecture-centric security analysis approach. They reverse engineer system architecture from source code using the Bauhaus tool. Then, they perform manual analysis to identify security flaws existing in the given system architecture.

Liu *et al*. [104] introduce a service-oriented framework to analyze attack-ability of a given software. They develop a new language to capture system architecture and security details.

Using this model, they defined a set of built-in security metrics to assess the security architecture of a given system.

In summary, the existing architecture security analysis efforts requires deep involvement from the security experts in specify possible attack scenarios as well as analyzing the software architecture searching for matched entities. The metrics-based efforts depends on a set of predefined, well-known metrics, which in most of the time require manual analysis.

3.3.3 Security Vulnerability Analysis

Existing efforts in vulnerability analysis can be categorized according to the analysis mechanism used into static analysis, dynamic analysis, and hybrid analysis based approaches. Most of these efforts are designed to analyse against specific vulnerability types mainly SQL Injection attacks and Cross-Site Scripting as the most frequently reported vulnerabilities. Jimenez *et al.* [105] review various software vulnerability prevention and detection techniques. Broadly, static program analysis techniques work on the source code level. This includes pattern matching that searches for a given pattern inside software source code - e.g. calls to specific functions. Data flow and taint analysis helps identifying data coming from untrusted sources to mark as tainted i.e. should not be used before being sanitized or filtered. Model checking can detect vulnerabilities based on extracting a system model from the source code and developing a set of constraints on the model that should not occur. An issue is that model checking approaches often suffer from a state explosion problem and generate only a counterexample. Dynamic analysis techniques analyze a system as a black box, avoiding being overwhelmed with system details. Fuzzy testing provides random data as input to the application in order to determine if the application can handle it correctly or not. Dynamic techniques are however limited in code coverage.

3.3.3.1 Static Vulnerability Analysis

NIST [106] is conducting a security analysis tools assessment project (SAMATE). A part of this project is to specify a set of weaknesses that any source code security analysis approach should support including SQL Injection, Cross-Site Scripting, OS Command Injection, etc. They have also developed a set of test cases that help in assessing the capabilities of a security analysis tool in discovering such vulnerabilities.

Halfond *et al.* [107] introduce a new SQL Injection vulnerability identification technique based on positive tainting. They identify “trusted” strings in an application and only these trusted strings are allowed to be used as parts of an SQL query, such as keywords or operators.

Lei *et al.* [108] trace the memory size of buffer-related variables and instrument the code with corresponding constraint assertions before the potential vulnerable points by constraint based analysis. They used model checking to test for the reachability of the injected constraints.

Dasgupta *et al.* [109] introduce a framework for analyzing database application binaries to automatically identify security, correctness and performance problems especially SQLI vulnerabilities. They adopt data and control flow analysis techniques to extract SQL statements, parameters, tables and conditions and finally analyze such details to identify SQLI vulnerabilities.

Martin et al [110, 111] introduce a program query language PQL that can be used to capture definition of program queries that are capable to identify security errors or vulnerabilities. PQL query is a pattern to be matched on execution traces. They focus on Java-based applications and define signatures in terms of code snippets. This limits their capabilities in locating vulnerabilities' instances that match semantically but not syntactically.

Wassermann *et al.* [112] introduce an approach to find XSS vulnerabilities based on formalizing security policies based on W3C recommendation. They conduct a string-taint analysis using context free grammars to represent sets of possible string values. They then enforce these security policies that guarantee that the generated web pages include no untrusted scripts. Jovanovic *et al.* [113] introduce a static analysis tool for detecting web application vulnerabilities. They adopt flow-sensitive, inter-procedural and context-sensitive data flow analysis. They target identifying XSS vulnerabilities only.

Ganesh et al [114, 115] introduce a string constraint solver to check if a given string can have a substring with a given set of constraints. They use this technique to conduct white box and dynamic testing to verify if a given system is vulnerable to SQLI attacks using strings generated by the string constraint solver.

3.3.3.2 Dynamic Vulnerability Analysis

Bau et al [116] perform an analysis of the black-box web vulnerability scanners. They conducted an evaluation of a set of eight leading commercial tools to assess the supported classes of vulnerabilities and their effectiveness against these target vulnerabilities. A key conclusion of their analysis is that all these tools have low detection rates of advanced (second-order) XSS and SQLI. The average percentage of discovered vulnerabilities equals 53%. The analysis shows that these tools achieve 87% in session management vulnerabilities and 45% in the cross-site scripting vulnerabilities.

Kals et al [117] introduce a black-box vulnerability scanner that scans websites for the presence of exploitable SQLI and XSS vulnerabilities. They do not depend on a vulnerability

signature database, but they require attacks to be implemented as classes that satisfy certain software interfaces. Thus such attacks can be called from their vulnerability scanner.

Weinberger et al [118, 119] introduce an analysis of a set of 14 frameworks that provide XSS sanitization techniques. They identify a set of limitations in these efforts including lack of context-sensitive sanitization that result in developing customized sanitizer. Such sanitizers need to be validated for their correctness, and resistance to client-side code "DOM-based XSS".

Felmetsger et al [60] use an approach for automated logic vulnerabilities detection in web applications. They depend on inferring system specifications of a web application's logic by analyzing system execution traces. They then use model checking to identify specification violations. The extraction of security properties' specifications to be validated is a key limitation in this approach. Moreover, they assume that these traces represent correct system behavior, which is not always correct (system bugs may result in incorrect/inconsistent traces).

3.3.3.3 Hybrid Vulnerability Analysis

Monga et al [120] introduce a hybrid analysis framework that blends static and dynamic approaches to detect vulnerabilities in web applications. The application code is translated into an intermediate model. This static model is filtered to focus only on dangerous statements. This reduces model size where dynamic analysis will be conducted, mitigating the performance overhead of the dynamic taint analysis approach. This approach, as most taint analysis approaches (either static or dynamic), targets only injection-related vulnerabilities. Balzarotti et al [121] introduce composition of static and dynamic analysis approaches "Saner" to help validating sanitization functions (addressing the input validation related attacks) in web applications. The static analysis is used to identify sensitive source and sink methods. The dynamic analysis component is used to analyse suspected paths only.

In summary, the existing security vulnerability analysis efforts focus on specific vulnerability types such as SQLI, XSS, etc. These efforts are not generally extensible enough to support analysis against new attacks. Existing vulnerability signatures such as those in the National Vulnerability Database (NVD) and Common Weaknesses Enumeration Database (CWE) are informal which hamper their adoption in developing automated vulnerability analysis tools.

3.4 Security Engineering

Existing security engineering efforts focus on capturing and enforcing security requirements at design time, supporting adaptive security, and multi-tenant security engineering. On the other hand, most industrial efforts focus on delivering security platforms that can help software developers in implementing their security requirements using readymade standard security

algorithms and mechanisms. Some of the key limitations with the existing security engineering efforts include: (i) these efforts focus mainly on design-time security engineering – i.e. how to capture and enforce security requirements during software development phase; (ii) limited support to dynamic and adaptive security and require design-time preparation; and (iii) no support for multi-tenancy, most of the existing efforts focus on getting services (including cloud services) to reflect one set of security requirements without considering different tenants' security requirements. Benjamin et al [122] introduce a detailed survey of the existing security engineering efforts; however they did not highlight limitations of these approaches.

3.4.1 Design-time Security Engineering

Software security engineering aims to develop secure systems that remain dependable in the face of attacks [123]. Security engineering activities include: identifying security objectives that systems should satisfy; identifying security risks that threaten system operation; elicitation of security requirements that should be enforced on the system to achieve the expected security level; developing security architectures and designs that deliver the security requirements and integrates with the operational environment; and developing, deploying and enforcing the developed or purchased security controls. Below, we summarize the key efforts in the security engineering area.

3.4.1.1 Early-stage Security Engineering

The early-stage security engineering approaches focus mainly on security requirements engineering including security requirements elicitation, capturing, modelling, analysing, and validation at design time from the specified security objectives or security risks. Below we discuss some of the key existing security requirements engineering efforts.

Knowledge Acquisition in automated Specification (KAoS) [124] is a goal-oriented requirements engineering approach. KAoS uses formal methods for models analysis [125]. KAoS was extended to capture security requirements [16] in terms of obstacles to stakeholders' goals. Obstacles are defined in terms of conditions that when satisfied will prevent certain goals from being achieved. This is helpful in understanding the system goals in details but it results in coupling security goals with system goals.

Secure i* [126, 127] introduces a methodology based on the i* (agent-oriented requirements modelling) framework to address the security and privacy requirements. The secure i* focuses on identifying security requirements through analysing relationships between users, attackers, and agents of both parties. This analysis process has seven steps organized in three phases of security analysis as follows: (i) attacker analysis focuses on identifying potential system abusers

and malicious intents; (ii) dependency vulnerability analysis helps in detecting vulnerabilities according to the organizational relationships among stakeholders; (iii) countermeasure analysis focus on addressing and mitigating the vulnerabilities and threats identified in previous steps.

Secure TROPOS [128-130] is an extension of the TROPOS requirements engineering approach that is based on the goal-oriented requirements engineering paradigm. TROPOS was initially developed for agent-oriented security engineering (AOSE). TROPOS introduces a set of models to capture the system actors (actors' model) and their corresponding goals (goal model: hard goals represent the actor functional requirements and soft-goals represent the actor non-functional requirements). These goals are iteratively decomposed into sub-goals until these sub-goals are refined into tasks, plans, and resources. Secure TROPOS is used to capture security requirements during the software requirements analysis. Secure TROPOS was appended with new notations. These included: (i) security constraints: restriction related to certain security issue like: privacy, integrity...etc.; (ii) security dependency: this adds constraints for the dependencies that may exist between actors to achieve their own goals and defines what each one expects from the other about the security of supplied or required goals; and (iii) security entities: are extensions of the TROPOS notations of entities like goals, tasks, and resources as follows: secure goal: means that the actor has some soft-goal related to security (no details on how to achieve) this goal will be achieved through a secure task; secure task: is a task that represents a particular way of satisfying a secure goal; secure resource: is an informational entity that's related to the security of the system; and secure capability: means the capability of an actor to achieve a secure goal. In our SecDSVL (Chapter 6) we capture these security details in abstract level and at runtime.

Misuse cases [131, 132] capture use cases that the system should allow side by side with the use cases that the system should not allow which may harm the system or the stakeholders operations or security. The misuse cases focus on the interactions between the system and malicious users. This helps in developing the system expecting security threats and drives the development of security use cases.

3.4.1.2 Later-stage Security Engineering

Efforts in this area focus on how to map security requirements (identified in the previous stage) on system design entities at design time and how to help in generating secure and security code specified. Below we summarize the key efforts in this area organized according to the approach used or the underlying software system architecture and technology used.

UMLsec [14, 133, 134] is one of the first model-driven security engineering efforts. UMLsec extends UML specification with a UML profile that provides stereotypes to be used in annotating system design elements with security intentions and requirements. UMLsec provides

a comprehensive UML profile but it was developed mainly for use during the design phase. Moreover, UMLsec contains stereotypes for predefined security requirements (such as secrecy, secure dependency, critical, fair-exchange, no up-flow, no down-flow, guarded entity) to help in security analysis and security generation. UMLsec is supported with a formalized security analysis mechanism that takes the system models with the specified security annotations and performs model checking. UMLsec [135] has recently got a simplified extension to help in secure code generation.

SecureUML [15] provides UML-based language for modeling role-based access control (RBAC) policies and authorization constraints of the model-driven engineering approaches. This approach is still tightly coupled with system design models. SecureUML defines a set of vocabulary that represents RBAC concepts such as roles, role permissions and user-assigned roles.

Satoh et al. [136] provides end-to-end security through the adoption of model-driven security using the UML2.0 service profile. Security analysts add security intents (representing security patterns) as stereotypes for the UML service model. Then, this is used to guide the generation of the security policies. It also works on securing service composition using pattern-based by introducing rules to define the relationships among services using patterns. Shiroma et al [137] introduce a security engineering approach merging model driven security engineering with patterns-based security. The proposed approach works on system class diagrams as input along with the required security patterns. It uses model transformation techniques (mainly ATL - atlas transformation language) to update the system class diagrams with the suitable security patterns applied. This process can be repeated many times during the modeling phase. One point to be noticed is that the developers need to be aware of the order of security patterns to be applied (i.e. authentication then authorization, then…)

Delessy et al. [138] introduce a theoretical framework to align security patterns with modeling of SOA systems. The approach is based on a security patterns map divided into two groups: (i) abstraction patterns that deliver security for SOA without any implementation dependencies; and (ii) realization patterns that deliver security solutions for web services' implementation. It appends meta-models for the security patterns on the abstract and concrete levels of models. Thus, architects become able to develop their SOA models (platform independent) including security patterns attribute. Then generate the concrete models (platform dependent web services) including the realization security patterns. Similar work introduced by [139] to use security patterns in capturing security requirements and enforcement using patterns.

Hafner et al. [140] introduce the concept of security-as-a-service (SeAAS) where a set of key security controls are grouped and delivered as a service to be used by different web-based

applications and services. It is based on outsourcing security tasks to be done by the SeAAS component. Security services are registered with SeAAS and then it becomes available for consumers and customers to access whenever needed. A key problem of the SeAAS is that it introduces a single point of failure and a bottleneck in the network. Moreover, it did not provide any interface where third-party security controls can implement to support integration with the SeAAS component. The SECTET project [141] focuses on the business-to-business collaborations (such as workflows) where security need to be incorporated between both parties. The solution was to model security requirements (mainly RBAC policies) at high-level and merged with the business requirements using SECTET-PL [142]. These modeled security requirements are then used to automate the generation of implementation and configuration of the realization security services using WS-Security as the target applications are assumed to be SOA-oriented.

3.4.1.3 Security Engineering Processes

Different proposals have been developed trying to align and incorporate security engineering activities with the software development lifecycle. These processes such as Security Quality Requirements Engineering (SQUARE) [65], SREP [143] and Microsoft SDL specify the steps to follow during software engineering process to capture, model, and implement system security requirements. Such processes are aligned with system development processes. They focus on engineering security at design time making assumption about the expected operational environment of the application under development. This leads to lot of difficulties when integrating such systems and their implemented security with the operational environment security as software systems depend on their built-in security controls.

3.4.1.4 Widely Deployed Security Platforms

We have determined different industrial security platforms that have been developed to help software engineers realizing security requirements through a set of provided security functions and mechanisms that the software engineers can select from. Microsoft has introduced more advanced extensible security model - Windows Identity Foundation (WIF) [144] to enable service providers delivering applications with extensible security. It requires service providers to use and implement certain interfaces in system implementation. The Java Spring framework has a security framework – Acegi [145]. It implements a set of security controls for identity management, authentication, and authorization. However, these platforms require developers' involvement in writing integration code between their applications and such security platforms. The resultant software systems are tightly coupled with these platforms' capabilities and mechanisms. Moreover, using different third-party security controls requires updating the system source code to add necessary integration code.

3.4.2 Adaptive Application Security

Several research efforts try to enable systems to adapt their security capabilities at runtime. Elkhodary et al. [146] survey adaptive security systems. Extensible Security Infrastructure [17] is a framework that enables systems to support adaptive authorization enforcement through updating in memory authorization policy objects with new low level C code policies. It requires developing wrappers for every system resource that catch calls to such resource and check authorization policies. Strata Security API [18] where systems are hosted on a strata virtual machine which enables interception of system execution at instruction level based on user security policies. The framework does not support securing distributed systems and it focuses on low level policies specified in C code.

The SERENITY project [19, 147, 148] enables provisioning of appropriate security and dependability mechanisms for Ambient Intelligence (AI) systems at runtime. The SERENITY framework supports: definition of security requirements in order to enable a requirements-driven selection of appropriate security mechanisms within integration schemes at run-time; provide mechanisms for monitoring security at run-time and dynamically react to threats, breaches of security, or context changes; and integrating security solutions, monitoring, and reaction mechanisms in a common framework. SERENITY attributes are specified on system components at design time. At runtime, the framework links serenity-aware systems to the appropriate security and dependability patterns. SERENITY does not support dynamic or runtime adaptation for new unanticipated security requirements neither adding security to system entities that was not secured before and become critical points.

Morin et al. [149] propose a security-driven and model-based dynamic adaptation approach to adapt applications' enforced access control policies in accordance to changes in application context – i.e. applying context-aware access control policies. Engineers define security policies that take into consideration context information. Whenever the system context changes, the proposed approach updates the system architecture to enforce the suitable security policies.

Mouelhi et al. [7] introduce a model-driven security engineering approach to specify and enforce system access control policies at design time based on AOP-static weaving. These adaptive approaches require design time preparation (to manually write integration code or to use specific platform or architecture). They also support only limited security objectives, such as access control. Unanticipated security requirements are not supported. No validation that the target system (after adaptation) correctly enforces security as specified.

3.4.3 Multi-tenancy Security Engineering

The area of multi-tenant SaaS applications' security engineering is relatively new. Existing multi-tenancy security solutions from industry and academia are still under development. Michael et al. [150] discuss the limitations of security solutions proposed by different commercial cloud platforms. Salesforce.com has introduced a simplified solution to support their CRM integration with tenants' security solutions. They focus on the Identity and Access Management (IAM) area only. Tenants who are interested in integrating with Salesforce.com have to implement web services interfaces with predefined signatures in order to integrate with Salesforce.com.

Enabling applications to support multi-tenancy either during application development or by adapting existing web applications to support multi-tenancy has been investigated by [151-154]. Cai et al. [22, 23] propose an approach to transform existing web applications into multi-tenant SaaS applications. They focus on the isolation problem by analyzing applications to identify the possible isolation points that should be handled by the application developers.

Guo et al. [24] developed a multi-tenancy enabling framework. The framework supports a set of common services that provide security isolation, performance isolation, etc. Their security isolation pattern considers the case of different security requirements for different tenants while still using a predefined, built-in, set of security controls. It depends on the tenant's administration staff to manually configure security policies and map their users and roles to the application predefined roles.

Pervez et al. [25] developed a SaaS architecture that supports multi-tenancy, security and load dissemination. The architecture is based on a set of services that provide routing, logging, security. Their proposed security service delivers predefined authentication and authorization mechanisms. No control by service consumers on the security mechanisms used. No isolation is provided between the authentication and authorization data of different tenants.

Xu et al. [26] propose a new hierarchical access control model for the SaaS model. Their model adds higher levels to the access control policy hierarchy to be able to capture new roles such as service providers' administrators (super and regional) and tenants' administrators. Service provider administrators delegate the authorization to the tenants' administrators to grant access rights to their corresponding resources.

Zhong et al. [155] propose a framework that tackles the trust problem between service consumers, service providers and cloud providers on being able to inspect or modify data under processing in memory. Their framework delivers a trusted execution environment based on encrypting and decrypting data before and after processing inside the execution environment

while protecting the computing module from being access from outside the execution environment.

Menzel et al. [156, 157] propose a model-driven platform to compose SaaS applications as a set of services. Their approach focuses on enabling cloud consumers to compose their system instances and define their security requirements to be enforced on the composed web services. However, tenants' instances must be deployed on separate VMs and there is no means to update or reconfigure the defined security except manual. These efforts deliver security using specific solutions and architectures. However, they do not give tenants any type of control on their assets' security; do not support multi-tenant security; and do not support runtime enforcement or updating of enforced security.

In summary, the existing efforts in this area focus mainly on design time security engineering which is not feasible in multi-tenant cloud-based applications where tenants' security requirements are not known at design time. The existing adaptive security engineering efforts require deep design time preparation, which is mostly not feasible for legacy applications. Moreover, the existing multi-tenant security engineering efforts do not consider the possibilities of integrating tenant third-party security controls at runtime.

3.5 Security Re-engineering

Although a lot of security engineering approaches and techniques do exist as we discussed in the last section, the efforts introduced in the area of security re-engineering and retrofitting are relatively limited. This comes, based on our understanding, from the assumption that security should not be considered as an afterthought and should be considered from the early system development phases. Thus, research and industry efforts focus mainly on how to help software and security engineers in capturing and documenting security in system design artifacts and how to enforce using model-driven engineering approaches. Security maintenance is implicitly supported throughout updating design time system or security models. In the real world, system delivery plans are dominated by developing business features that should be delivered. This leads to systems that miss customers expected or required security capabilities. These existing legacy systems lack models (either system or security or both) that could be used to conduct the reengineering process. The maintenance or reengineering of such systems is hardly supported by existing security (re)engineering approaches. Below we summarize the key efforts we found in relevant research areas including security retrofitting, software maintenance and change impact analysis, dynamic software updating, and concept location areas.

3.5.1 Security Retrofitting Approaches

Research efforts in the security retrofiting area focus on how to update software systems in order to extend their security capabilities or mitigate security issues. Al Abdulkarim et al [158] discussed the limitations and drawbacks of applying the security retrofitting techniques including cost and time problems, technicality problems, issues related to the software architecture and design security flaws.

Hafiz et al. [159, 160] propose a security on demand approach which is based on a developed catalog of security-oriented program transformations to extend or retrofit system security with new security patterns that have been proved to be effective and efficient in mitigating specific system security vulnerabilities. These program transformations include adding policy enforcement point, single access point, authentication enforcer, perimeter filter, decorated filter and more. A key problem with this approach is that it depends on predefined transformations that are hard to extend especially by software engineers.

Ganapathy et al. [161, 162] propose an approach to retrofit legacy systems with authorization security policies. They used concept analysis techniques (locating system entities using certain signatures) to find fingerprints of security-sensitive operations performed by system under analysis. Fingerprints are defined in terms of data structures (such as window, client, input, Event, Font) that we would like to secure their access and the set of APIs that represent the security sensitive operations. The results represent a set of candidate joinpoints where we can operate the well-known "reference monitor" authorization mechanism.

Padraig et al. [163] present a practical tool to inject security features that defend against low-level software attacks into system binaries. The authors focus on cases where the system source code is not available to system customers. The proposed approach focuses on handling buffer overflow related attacks for both memory heap and stack.

Welch et al. [164] introduce a security reengineering approach based on java reflection concept. Their security reengineering approach is based on introducing three meta-objects that are responsible for authentication, authorization, and communication confidentiality. These meta-objects are weaved with the system objects using java reflection. However, this approach focuses only on adding predefined types of security attributes and do not address modifying systems to block reported security vulnerabilities.

3.5.2 Software Maintenance

Another key area that could be used in addressing the security reengineering problem is the software maintenance and reengineering. System reengineering "preventive maintenance" [165]

targets improving system structure to easily understand and help in reducing cost of future system maintenance. The re-engineering process includes activities such as source code translation, reverse engineering, program structure improvement, and program modularization. System maintenance [166] includes any post-delivery modification to existing software. Runtime system adaptation is similar to system maintenance where we can handle post-delivery "unanticipated" requirements, but this should happen while the system is running. These concepts target adding, removing, replacing or modifying a system feature or structure either at design time or at runtime. Engineering approaches that depend on aspect-oriented software development enable systems to extend, may be replace, system functionality even at runtime but they do not support leaving out certain patterns that may be buggy, unsafe or insecure.

Software maintenance requires deep understanding of target applications in order to analyse the impact of a given system modification on other system entities "change impact analysis". Existing software maintenance efforts focus mainly on facilitating the impact analysis task as a crucial part of change realization [167]. Specifying which entities to be changed and propagating changes to the target system are not often considered. Many existing impact analysis approaches assume that the entities to be modified – the "change set" - are known beforehand. Thus, they usually focus on identifying entities – the "impact set" - that will be impacted by modifying entities included in the change set.

Xiaobing et al. [168] introduce a static analysis approach to identify the impact set of a given change request based on the change type (modify, add and delete) and the entity to be modified (class, method, attribute). They construct a dependency graph of system classes, methods, and members (OOCMDG). Given an entity with change type CT, then using the OOCMDG and a set of impact rules they define the other impacted entities in a given application. Types of changes are limited to classes and methods. Statement-level modifications are not considered. The types of modifications required on the identified impact set are not known. Petrenko et al. [169] introduce an interactive process to improve the precision of the identified impact analysis using variable granularity analysis guided by developers. The proposed approach depends on developers' deep involvement during the impact analysis process to control the precision of the change set.

Hassan et al. [170, 171] introduce an adaptive change impact analysis approach based on adaptive change propagation heuristics. The approach combines different heuristics-based approaches including history-based impact analysis (given a change request to modify entity (A), what are the entities that are often modified with); containment-based impact analysis (modifying entity (A) means other entities in the same container may be changed as well. Container may be a component or a source file); call-use-depends impact analysis (uses the

dependency graph to identify entities that refer to the modified entity); code ownership impact analysis (modifying entity (A) will return other entities that are owned by the same developer). The best heuristics table maintains for each entity in the system, the best heuristics approach that helps in conducting more accurate impact analysis. However, the approach did not explain how these best heuristics are automatically selected and updated at runtime.

It is worth mentioning here that we could not find relevant work that addresses the change propagation as the next step of the software maintenance problem. The system refactoring area has a similar scope to maintenance but with limited system modification, focusing on identifying code regions to be refactored – i.e. "bad smells". Some of the refactoring problems include how to specify and locate code snippets to be refactored, and updating system models to maintain consistency between the updated (refactored) source code and system models [24]. Wloka et al [172] introduce an aspect-aware refactoring approach where refactoring takes into account updating the defined aspects and pointcuts model. Most refactoring tools identify known refactoring patterns [173]. They depend on user involvement to define syntactic bad smells or use aspect mining tools to propose candidates that need to be refactored.

3.5.3 Dynamic System Updating

Dynamic system updating efforts aim to facilitate system updates at runtime. Such efforts have been used also in adding new features and updating system at runtime. Most of these efforts are based on the aspect oriented programming concept. Existing AOP languages e.g. AspectJ support two types of crosscutting concerns: dynamic crosscutting concerns that impact system behaviour by injecting code "advice" to run at well-defined points (normally limited to updating methods – removing, modifying and replacing); and static crosscutting concerns that impact the static structure and signature of program entities (normally limited to adding new declarations and methods, rather than modifying existing system entities like classes, methods and fields). These are key limitations in adopting AOP for software reengineering and maintenance.

Pukall et al. [174] introduce an approach using AOP HotSwaping and object wrapping. It is based on role-based adaptation. Given a system change (adaptation), the involved entities are categorized into caller and callee. The callee is extended by a wrapper class. The caller method is replaced with a new method that uses the new wrapper class. The approach suffer from: memory and performance impact on the updated system; out of synchronization with the original source code; requires modifying the callers in all classes (at runtime); and has limited support for class hierarchy change.

Villazon et al. [175] introduce an approach to support runtime adaptation based on AspectJ - HotWave (Hotswap and reWave) – as an aspect weaver. This approach is limited to dynamic

AOP and static crosscuts are not supported. Nicorra et al [176] introduced PROSE, an AOP-based code replacement approach. PROSE does not support schema changes, or "inter-type declarations" such as the replacing of a method, and does not allow the addition of new class members (i.e., methods, fields) in the original code.

3.5.4 Concept Location Techniques

Concept location techniques help in identifying and locating source code blocks that realize a given system feature or concept. This area is also relevant to our security reengineering problem where we need to locate code blocks with certain signatures as we going to explain in next chapters. Efforts in capturing code signatures include point-cut designators, feature location, and aspect mining. Feature location is a key step in system reengineering and maintenance to understand the target system and identifying implemented features. Feature location approaches can be categorized into static-based, dynamic-based, and runtime-based approaches. Below we summarize the key efforts in the area of concept location:

Reiss [177], Shepherd et al [178], Marcus et al [179] use natural language and ontology-based queries and information retrieval approaches in searching source code looking for certain concepts. The adoption of natural language impacts approach accuracy and soundness. Poshyvanyk et al [180] use AI techniques *e.g.* decision making and uncertainty to locate system features. These help in understanding target systems but they do not assure high soundness, a key requirement in system maintenance [181]. Zhang et al [182] introduce PRISM to help extracting aspects. It is similar to our signature approach while it has limited signature specification capabilities.

In summary, the existing software and security re-engineering efforts require deep understanding and involvement of the software and security engineers to effect a given system modification. Many focus on retrofitting an application with specific security patterns using tools with a set of predefined patterns and modification steps required to realize such patterns. Furthermore, the existing signature matching efforts are not formal enough to help in automating the software analysis process.

3.6 Security Measurement and Metrics

There is no mean that could be used to help proving that a given system is completely (100%) secure [183]. Security is like a game between the security officers and malicious users – mind-against-mind. This means that there is no limit to attackers' malicious actions to breach assets' security. Thus, it is definitely hard to show that the system is secure against existing as well as new security vulnerabilities. Security metrics represent a good solution to the security

assessment problem. Different types of security metrics do exist either *offline security metrics* such as comparing system security with other systems, how many vulnerabilities found, attack surface, planned attacks reported, strength of the applied security controls; and *online security metrics* that assess the current security status and how the operated security is capable to defend against different attacks. NIST [184] characterizes security metrics into three types as follows:

- *Implementation Metrics:* These metrics are intended to demonstrate progress in implementing information security solutions and related policies and procedures;
- *Effectiveness and Efficiency Metrics:* These metrics are intended to monitor if the implemented security controls are implemented correctly, operating as intended and meet the desired outcomes. Effectiveness focuses on the robustness of the security controls while efficiency focuses on the capability of the security controls to mitigate the security objectives;
- *Impact Measures:* These are used to articulate the impact of IT security on enterprise mission including cost savings and public trust.

System monitoring approaches can be categorized into external monitoring which resides in the system infrastructure and collects measure from the interactions between the system and its underlying infrastructure; or internal monitoring which depends on instrumenting the system binaries or source code with monitoring code snippets that can collect measurement related to certain internal system events. Below we summarize key efforts in relevant areas including security monitoring, SLA monitoring, software requirements monitoring, and metric specification languages.

3.6.1 Security Monitoring

Existing efforts in information security monitoring focus on proposing guidelines or processes to be followed when defining metrics or collecting measurements. Chandra et al. [27] introduce a methodology to help in identifying the required security metrics in a given system. This methodology has a set of steps to follow including: specifying metric requirements, identify vulnerabilities, identifying software characteristics, analysing security model, categorizing security metrics, specifying security metric measures, designing metric development process, developing security metrics, and finalizing metrics suite. Similar efforts introduced for the cloud computing model in [185].

Savola et al. [28-31, 186] introduce an iterative process for security metrics development based on a set of refinements of system security requirements down to the set of on-line and off-line security metrics to be applied. These security metrics are categorized by related security objective (authentication, authorization, confidentiality, integrity and availability).

Muñoz et al. [187] introduce a cloud computing dynamic monitoring architecture for the security attributes along with a language to capture monitoring rules. The proposed architecture is made up of three main layers: the local application surveillance (LAS) which collects measures from each application instance in virtual execution environment; intra-platform surveillance (IPS) which collects measurements of different LAS elements and start analysing them to detect violations occurred from the interactions with other systems on the same virtual machine or different virtual machines; and global application surveillance (GAS) which analyses the results of different IPS for every specific application (taking into consideration its different instances). The key problem of this approach is that it focuses on how to help the service provider administrator but it did not consider the involvement of the service tenants in developing and enforcing their own security metrics. Moreover, the new proposed language is hard to learn and use in developing complex metrics.

The SERENITY Project [188, 189] introduced the EVEREST security monitoring platform. The SERENITY framework helps adding security patterns to systems at runtime (given that these systems have been already prepared at design time to integrate with SERENITY). The main objective of the EVEREST security monitoring platform is to assess the conditions of the operation of the security pattern realization components when integrated with the target system at runtime. These conditions are specified as a set of Event-Calculus [190] (first-order temporal formal language) assertion rules within the security and dependability patterns. When a security pattern is selected, the specified rules are fed into EVEREST to make sure that they are satisfied by events collected from the system at runtime. A key problem with this approach is that the event calculus is hard to develop by service tenants. An extension of this approach was introduced in the area of SLA management as we going to discuss in the next subsection. Lorenzoli et al. [191] introduce an extension of this framework (EVEREST+) that helps in delivering SLA violation prediction capabilities based on the measurements and results got from the EVEREST framework. Similar work introduced by Spanoudakis et al [192]. They introduce a security monitoring approach based on event-calculus captured as parameterized monitoring patterns classified based on the related security objectives confidentiality, integrity and availability.

Patzina et al. [193] introduce an approach that targets automatic generation of security monitors. The approach is based on using Live Sequence Charts (LSCs) by system developers to capture use and misuse cases of the system. These LSCs are translated into monitor petri nets (MPNs) dialect (a modified definition of petri nets). These MPNs are then used to generate the required security monitors. Although the authors claimed that the introduction of MPNs simplified the generation of the security monitors, we see that this step adds more complication

and overhead to the process. Using LSCs directly could help to automatically generate security monitors.

3.6.2 SLA Monitoring

The service level agreement (SLA) management becomes a very important research area with the wide-adoption of the service outsourcing for hosting on external third-party platforms (such as the cloud computing model) where customers do not have control on such services. This increases the need to measure the quality of the delivered services (QOS) in terms of performance, availability, reliability, security, and so forth. The service providers and consumers conduct SLAs that define the QOS attributes that should be guaranteed by the service provider and penalties to be applied on the service provider in case of any violation to any of these QOS terms. Hence, it is very important to monitor the QOS terms specified in order to take proactive actions before such violations occur or corrective actions in case of such violations happened. However, we could not find efforts in the area of SLA that focus on how to specify, monitor, and enforce security SLA terms. Below, we summarize some of the key relevant SLA efforts we determined in this area.

Skene et al. [194-197] introduce a SLA specification language, SLang, to help in capturing SLA terms (including performance, reliability, and throughput) developed in UML. The SLang is supported with OCL that helps in capturing SLA constraints (invariants) that are used in assessing the satisfaction or violation of the specified service level agreements. They used the timed automaton to help in detecting violation of these SLA terms. This automaton is automatically generated from the specified OCL signatures.

Michlmyar et al. [198, 199] introduce a comprehensive QOS monitoring approach that is based on both client and server side monitoring of the QOS attributes. The proposed approach was integrated with the VRESCo platform (a runtime environment for SOA-based computing). They have developed their own SLA specification schema that is used in developing SLA terms in XML. The approach depends on the nature of the web service to deploy interceptors of requests and responses and trigger the QOS monitoring component.

Comuzzi et al. [200] introduce an approach for monitoring SLA terms as a part of the SLA@SOI project that targets developing SLA management framework for the cloud computing model. The proposed approach is based on the EVEREST monitoring framework. This uses event-calculus to express rules and patterns of interest that should be monitored. Thus a part of the proposed solution is to extract from the SLA terms patterns to be monitored expressed in event-calculus. The proposed approach is event-based. Measurements are sent to reasoning component to assess possible violations of the specified SLA terms. Similar efforts

[186] were introduced in the area of service selection that take into consideration different QOS attributes when selecting between different services.

3.6.3 Requirements Monitoring

Efforts in this area focus on how to monitor and gather measurements of the software system execution to assess whether the specified requirements are satisfied or not. Most of the existing efforts in this area depend on goal-oriented requirements engineering approaches, such as KAOS, where system requirements are formally expressed as refinements of high-level goals and then these formalizations are used to guide the generation of low-level requirement monitoring code that helps assessing the satisfy-ability of system requirements.

Lahmar et al [201] introduce a new non-functional properties monitoring approach based on component transformation that transform component into monitor-able components delivering both polling and subscription monitoring models. Each component defines the set of required properties. These properties must be offered by the referenced components. Therefore, the proposed approach uses these required properties to extend these referenced components with monitoring components as extensions to deliver these properties.

Ramirez et al [202] introduce an adaptive requirements monitoring approach that tries to address the performance overhead incurred from the application of extensive system monitoring. This is done using the application of configurable (adaptable) monitoring components with adaptable monitoring frequency "adaptive sampling". These can be turned on and off according to the current utility functions specified, in order to assess violations of the requirements satisfaction as well as the accuracy and cost of the monitoring components.

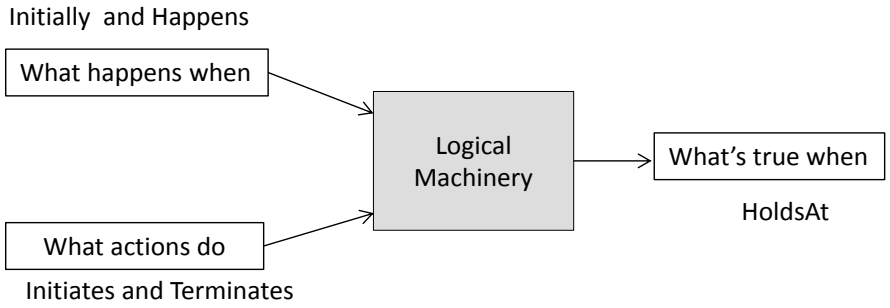


Figure 3-6. Event Calculus Model [190]

3.6.4 Security Metrics Specification Languages

Event-Calculus-Assertions [190] is a first-order predicate calculus that is used to develop formal specification/model and reason about system properties that could be specified in terms of a set

of events and their effects. The occurrence of these events impacts the satisfaction of specified system properties. Event calculus, as shown in Figure 3-6, is based on two basic constructs *events* and *fluents*. Event represents something that occurs at a specific point in time. An event may result in a change in the status. This state is represents by fluents. EC has a set of predicates that represent occurrence of an event (*Happens*), start hold of a fluent (*Initiates*), termination of the hold of a fluent (*Terminates*), fluent terminates between t1 and t2 (*Clipped*), and fluent holds at time t1 (*HoldsAt*).

The Performance Metric Specification Language (PMSL) [203, 204] is developed to capture high-level user-defined parallel-systems performance metrics. Metrics developed by the PMSL are fed in the G-PM performance analysis tool. PMSL is a declarative functional language. PMSL does not support control flow or state altering constructs. The PMSL provides a couple of set operations and aggregation functions. The list of measurable objects to be monitored is limited to predefined list defined and built-in the PMSL.

The Goanna Metric Specification Language (GMSL) [205] is developed to assess programs source code quality using a set of user-defined static source code metrics. Metrics specified are evaluated against source code AST using a model-checker. The grammar of the GMSL is based on Extended Backus Naur Form (EBNF) and supported with a set of aggregation functions.

In summary, the existing security and requirements monitoring efforts introduce proposed methodologies and processes to be followed in developing security metrics required in assessing the security of a given system. Relevant efforts in the requirements' monitoring focus on verification of certain system properties at runtime using formal mathematical languages such event calculus. Moreover, the existing metrics' specification efforts are either formal (hard to use) or domain specific (does not help in specifying customized security metrics).

3.7 Research Gaps Summary

In this chapter we have reviewed, analyzed, and summarized the key efforts, we found, in research areas relevant to the research problem we address in this thesis "cloud computing security management". Table 3-1 summarizes the key research branches in each area, key facts, and the main research gaps in these efforts project on the research problem.

- *Security Management Area:* The area of security management has different security management standards NIST-FISMA and ISO27000. Both are not designed for security management of outsourced cloud assets that are out of the asset owner control and shared with different tenants. Moreover, it has different information security management systems (ISMS); however, these efforts focus mainly on refining security objectives down to requirements and security policies, and automating the configuration of security controls

using these security policies. They do not address the multi-tenancy problem. Moreover, these efforts did not address the security monitoring and improvement aspects. Furthermore, some of these efforts depend on manual involvement of engineers which is very hard to have in case of cloud-hosted assets. Another key limitation of these efforts is that they do not consider integration of the operated security controls with the target IT systems (usually done manually). In this research project, we consider the security controls' configuration as out of scope for two reasons: (i) it is already covered by existing efforts; and (ii) we consider the case where different tenants may operate their own controls which may be out of control.

- *Security Analysis Area*: We have figured out hundreds of research efforts in this area either as risk management and assessment, architecture risk analysis, and vulnerability analysis. These efforts focus mainly on how to conduct and document outcomes of the security risk analysis process. Thus, we assume that this part of the security management process is out of scope in this project – i.e. security engineers can use any of these approaches during the security risk analysis process. However, we expect that the final outcome is to be modeled in our tool. The existing architecture risk analysis and vulnerability analysis efforts focus on specific, well-known threats, attacks, and vulnerabilities such as man-in-the-middle and injection attacks, attack surface and compartmentalization metrics, SQLI vulnerabilities, XSS, OS Command Injection, Input sanitization. Furthermore, there is no online analysis tool that can investigate for new vulnerabilities without a need for new security patches that may take weeks to be installed. This is very critical for cloud applications as they are mostly publicly accessible for end-users who may use these vulnerabilities to breach applications and data security.
- *Security Engineering Area*: The area of security engineering has so many approaches and methodologies, and relatively few efforts in the area of adaptive security engineering. The key limitations we found in this area with regard to our research problem are: they focus mainly on design time security engineering which is not feasible in multi-tenant cloud applications where tenants' security requirements become known at runtime. Moreover, these requirements are highly expected to change as a consequence of business and security changes. The existing adaptive security engineering efforts require deep design time preparation, which is mostly not feasible for legacy applications. Moreover, these efforts do not address the problem of integrating third-party security controls (at runtime) with the target application.
- *Security Retrofitting Area*: The area of software and security re-engineering has relatively few efforts. Most of these efforts require deep understanding and involvement of software and security engineers. Many focus on retrofitting an application with specific security patterns using tools with built-in patterns and modification steps required to realize such

patterns. Furthermore, the existing signature matching efforts are either not formal enough or work on function level signatures only (such as pointcut in AOP).

- *Security Monitoring Area*: The area of security monitoring is relatively new. Most of these efforts still proposing methodologies and processes to be followed in developing security metrics required in assessing the security of a given system. Relevant efforts in the requirements' monitoring focus on verification of certain system properties or invariants at runtime using event calculus for example. Event calculus is hard to use, and still limited when writing security metrics that perform aggregation functionalities. Furthermore, these efforts do not consider the multi-tenancy dimension – i.e. how to define, develop probes, deploy, and analyze results of different metrics for different tenants.

Table 3-1. Key research areas, efforts, and gaps

Area	Existing Efforts	Limitations
Security Management	- Security Management Standards - Security Management Framework	- No Multi-tenancy Support - Security integration within IT system is limited - Focus mainly on security controls' configuration, no monitoring nor feedback
Defining Security	- Risk analysis tools - Architecture Risk Analysis - Security Vulnerability Analysis	- Mainly focus on risk documentation - Limited to specific vulnerability or attack types - No support for online security analysis
Enforcing Security	- Design time security Engineering - Multi-tenant Security Engineering - Adaptive Security Engineering	- Focus on design time security engineering - Adaptation requires design time preparation - Adaptive approaches depend on specific architecture and technologies (SOA, CBSE)
Monitoring Security	- Security Monitoring Framework - Requirements Monitoring - SLA Monitoring - Security Metrics' specification languages	- Security monitoring approaches deliver methodologies; no tool support. - Requirements monitoring approaches depend on formalized event-calculus; hard to express by engineers and service consumers. - Approaches depend on system events are limited to reactive actions - No formal and familiar metrics specification language.

Part 2

Adaptive, Model-based Cloud Computing Security Management

Chapter 4
Adaptive, Model-based Cloud Computing Security Management

In chapter 2 we have discussed key security challenges in the cloud computing model, and in chapter 3 we reviewed and identified research gaps in relevant areas. The conclusion was that the cloud computing model lacks a strong security management framework that can handle the large number of cloud services and security solutions and takes into consideration the multi-tenancy and elasticity, lack-of-trust and loss-of-control, and multiple stakeholders involved with the cloud model. Moreover, we concluded that the existing efforts are limited and do not fit well with the cloud computing security problem. In this chapter, we introduce the core idea of our approach and the big picture of the developed solution. This chapter is organized as follows. In Section 2 we introduce an overview of the IBM MAPE-K autonomic computing model as the reference model for our approach. In Section 3 we introduce the big picture of our approach, including the core idea, high-level architecture and main components.

4.1 Introduction

The cloud computing model is a good example of an adaptive computing platform. Computing resources utilized by different services and different tenants can be scaled up or down according to the current needs that are usually captured as a set of constraints, rules or utility functions that specify when to adapt the allocated resources. Different frameworks in both industry and academy [3, 194, 206] are currently under development to help adapting allocated resources according to predefined constraints. This dynamic nature of the cloud computing model along with the sharing of resources between tenants and public accessibility of the cloud platform reinforce the need for platforms that can change their operated security at runtime according to the current security risks and business objectives. The current cloud computing platform's security is still far from adaptive-ness – i.e. how to get cloud services to deliver multi-tenant, adaptive security has not been considered with an applicable solution yet. In this chapter, we discuss how to deliver a security management platform that can extend cloud computing platform with the core infrastructure components required to deliver multi-tenant, adaptive, and model-based cloud computing security. We base our approach on the IBM autonomic computing platform [207] with a slight modification, which is the ultimate goal of the adaptive computing models including cloud computing.

In the next sections we discuss IBM MAPE-K autonomic computing model. Then, we introduce our general approach we propose to deliver adaptive security model that meets the key challenges we have explained in details in the last chapters. Finally, we will introduce the "big picture" of our security management framework.

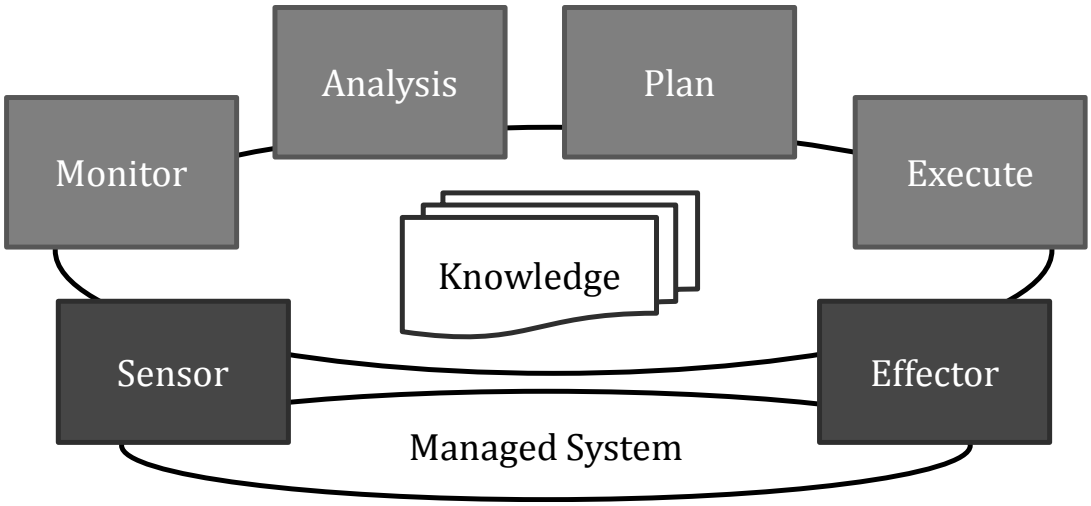


Figure 4-1. Autonomic computing model [209]

4.2 Autonomic Computing and MAPE-K Model

Software systems nowadays are getting more complicated, autonomous and real-time. This requires such systems to address unanticipated requirements that emerge at runtime without waiting for customizations and maintenance tasks that usually take several weeks. Administration of such complex systems is also a complicated task. Autonomic computing aims at simplifying the administration of such complex computer systems [208]. According to the autonomic computing paradigm, system administrators merely specify high level objectives (policies), which determine how the system may adjust its behavior at runtime in order to guarantee specified objectives/requirements. Administrators are consequently relieved from dealing with numerous details of the system. The autonomic computing system idea was originally introduced by IBM [209]. Autonomic computing is based on the MAPE-K model, show in Figure 4-1. This model proposes architecting any adaptive system into four components: Monitoring, Analysing, Planning, and Execution. All these components share a common knowledge repository of the managed system(s) and operational environment details and status, stakeholders' objectives, and possible adaptation patterns. Below we discuss MAPE-K components and possible realization techniques for each component with pros and cons of each approach.

4.2.1 Monitoring Component

The first phase of any adaptive or autonomic system is to monitor the underlying system and its context. The main responsibility of the monitoring component is to collect the context and the managed system's status information from the available sensors and filter collected information from irrelevant information. These measurements are fed into the analysis module to reason about the current system status and take predictive or corrective actions. Most of the monitoring efforts can be categorized as [207]:

- *Sensor interface*: this pattern is based on defining a specific interface to be used by all system types (classes/objects) that sense the current status of the environment. This approach is applicable when adaptive-ness is considered when designing the managed system itself.
- *Publisher/subscriber "middleware"*: this pattern assumes that we have context-provider or broker that publishes some context information and each adaptive system needs to register its interest in any of the available events or context domains. Thus, when new information is available, the publisher calls a certain function or fires a specific event. This approach is applicable when data is used by multiple clients and system adaptation requires information about its context.
- *Logging*: this approach depends on collecting execution traces that reflect certain system events in log files or logging database (audit trial) for further analysis by the analysis component. A key problem with this pattern is that it leads to lagging measurements not real-time measurements. Thus it fits more with the mitigation and recovery purposes.
- *Profiling*: a library of APIs that can be used to develop profiling tools used to monitor the events that arise within the system host – e.g. Java VM runtime tools, and Microsoft .NET profiler. This is interesting when dealing with monitoring of the interactions between the system and the underlying platform.
- *Reflection*: the adaptation system uses reflection to read information about the objects existing in its environment without having to alter its implementation. This approach is interesting when adding monitoring as afterthought or addressing an existing legacy system. We use this approach in the monitoring component of our security management platform.
- *Management protocols*: different protocols are existing related to the area of monitoring and serve different domains such as performance, manageability, etc. as follows: *first,* the application response measurement (ARM) [210] defines a set of APIs that can be used within application or its transactions in order to define the performance of certain application transactions. *Second*, web-based enterprise management (WBEM) [82] is a new standard developed by DMTF. WBEM is based on CIM: The common information model (CIM) [78] as a reference for the manageable objects; XML to represent data communications among

management and manageable objects; and HTTP to transfer the data among parties. *Third,* Simple Network Management Protocol (SNMP) is based on deploying monitoring agents (SNMP agents) on each managed device; SNMP Manager collects data from these agents; and the web server that hosts the management application (interface) to be used by the administrators. *Fourth,* Java management framework (JMX) was developed to help developing distributed management applications. The framework has three levels: (i) Instrumentation Level: this is responsible for the managed objects (MBeans) that define a standard interface to reflect set of functions (static or dynamic); (ii) agent level: this is the MBean server that delivers a registry of the MBean that allows clients to discover information and execute actions on MBeans; and (iii) remote management: this is the client of layer. It can communicate with the MBeans server through APIs.

Before we start developing a monitoring component, we need to answer a set of questions including: what are the QOS attributes to be monitored, what system objects to monitor, monitoring frequency for each object, required redundancy (avoid failure and noise), how to secure monitored data and avoid spams and attacks on it, and how to relate data monitored to business objectives (goals) in order to trigger the corresponding adaptation actions.

4.2.2 Analysis component

The analysis component receives the monitored data from the monitoring component for analysis in order to understand the current system status. Monitored data may be filtered to remove any noise or redundancy. Also correlation or aggregation of the monitored data may exist to formulate meaningful information about the underlying context or system behavior. This information is usually expressed in terms of metrics of interest. These metrics may assess system during design time using system models or at runtime using some utility functions imposed on the system. The analysis component in most of the time is merged with either the monitoring component or with the decision and planning component. Below, we discuss the most common ways in developing analysis components.

- *Rule-Based*: The monitored data or (metrics of interest calculated from such monitored data) are traced against a set of rules that define constraints (upper and lower bounds) [211, 212]. In case that any rule violated (in some cases fired), then a set of symptoms are reported. Such reported symptoms are linked to certain mitigation actions. We use this approach in our security monitoring approach.
- *Symptoms Database (Case-Based Reasoning)*: The logic of the analysis is formatted as symptoms. The current situation (case) is compared with the cases database. Then, the best matched case is retrieved and the related solutions or actions are applied. Other artificial

intelligent approaches such as neural networks, decision trees, and Game theory could be used to analyze system status against stakeholders' defined desired objectives.

- *Model-Based*: A lot of work has been introduced in this area [213, 214]. It is based on maintaining a model of the system and/or its operational environment (context). This model is updated with the monitored data. Then the current system model is: (i) Compared with the target model and the differences are used to guide the adaptation planning and execution steps; (ii) Validated against set of rules or constraints defined, so in case of rules violation, the system will take corrective actions; (iii) Used to activate a set of components. Each component has a set of rules, in case that these rules are matched then the component is integrated with the target system model to reflect current needs.
- *Artificial Intelligent and Adaptive Learning*: These methods use a set of artificial intelligent methods and rules generated through supervised learning [215] and applied as normal behavior rules. Any abnormal activities are used to retrain the analyzer.
- *Regression Analysis*: This is a statistical approach to help in investigating and understanding the relationships between variables [216]. This is usually used in ascertaining the causal impact of some variables on others. This is usually followed by statistical significance analysis to make sure that the estimated relationships are close to the truth. Regression analysis includes: linear regression and non-linear regression based on the nature of the dataset; interpolation: prediction within the range of the given data; or extrapolation: prediction out of the range of the given data.

4.2.3 Planning and Execution components

Given the system status and found deviations pinpointed and reported by the analysis component(s), the planning component generates a sequence of actions to be applied on the underlying system and/or managed objects (may be the current system environment as well) in order to adapt system behavior and meet the specified objectives (either as policies or as utility functions). The execution component should update the system behavior or structure accordingly and the underlying effectors should reflect such changes on the managed objects as well. Below we discuss a set of approaches that could help in realizing new changes.

4.2.3.1 *Architectural/Design Patterns*

Software architectural patterns help in expressing the fundamental structure (main components and their relationships) of the software systems [217]. It provides a set of predefined subsystems, responsibilities, and guidelines for organizing the relationships between them. Below is a list of patterns that could be used in with such approach:

- *Decorator Pattern* [218]: Helps in extending the responsibilities of an object, independent of other class objects, dynamically instead of using sub classing and also in cases where sub classing is not feasible (sealed or final class). However, this pattern requires design time preparation to use it. The decorator pattern is realized by introducing a decorator class that wraps/encloses the original class. The decorator class conforms to the interface of the original class and delegate calls to the enclosed class object.
- *Microkernel Pattern* [217]: The microkernel architectural pattern best fits with the design of adaptive systems that target addressing unanticipated requirements at runtime. The microkernel enables plugging in and out system features/components and facilitating the communication between these components. However, this pattern requires design time preparation of the software architecture under development.
- *Interception Pattern* [219]: The interceptor pattern helps in updating system behavior and capabilities at runtime according to the incoming request and its context information. The beauty of this pattern is that such update is realized without a need to modify the existing code, design time preparation, or even details of the application. Furthermore, it does not affect the current system features. Interceptor pattern usually developed with three components: *Interceptor interface* which defines the operations which are executed by a Dispatcher in specific events e.g. at the beginning or at the end of a request processing; *Dispatcher* is the class or method that is called by the interceptor to perform required actions. The interception is done in different possible ways e.g. the interceptor could call Dispatchers prioritized in a user-defined order; and *Context* is a data object that maintains context information either from the request or the current system status *e.g.* transaction id, caller, passed in parameters. The context object is sent to the interception handler. The context object details (data items) may be different from one interceptor to another according to the handler functionality. We use this pattern in our security monitoring and execution components as we discuss in chapter 6 and chapter 9.

4.2.3.2 *Middleware-Based Approaches*

The execution is implemented in the middleware layer so application does not need to be aware of the nature of the effectors (this is mostly used in distributed applications) [207, 220]. The middleware may implement one of the mentioned herein solutions to deliver its functionality:

- *Mobile Agents* [80]: A mobile agent is a composition of computer software and data which is able to migrate (move) from one computer to another autonomously and continue its execution on the destination computer. They can be used as communicators/ negotiators with existing applications/security solutions. Thus, we can deploy different mobile agent for different task or different application interface or methodology of interaction and reasoning.

– *Reflection Pattern* [217]: The reflection architectural pattern helps in changing structure and behavior of software systems dynamically. It supports both type structure (e.g. extending classes) and function calls adaptation. The reflection pattern has two parts: a meta-level which provides information about system properties including structure and behavior; and a base-level which includes application logic itself. Its implementation builds on the meta-level. Changes are usually done on the meta-level. This is subsequently reflected on base-level components' behavior.
– *Dynamic Aspect Weaving* [221]: Dynamic weaving focus on the ability to apply, replace or remove an aspect while the software system is running (in contrast with the static aspect weaving at development time). Dynamic aspect weaving includes: *(i)* Load-time weaving: Byte code transformations at class loader level (Subclass the Java class loader or replace it); *(ii)* JIT compiler weaving: Byte code unaltered but alteration takes place when JIT compiler is employed; *(iii)* Code Splicing: Weaving changes on running native code. Native code is replaced with branch to external function (known as jump-return hooks). Replaced code appended at the end of external function. Jump back to instruction after spliced location.

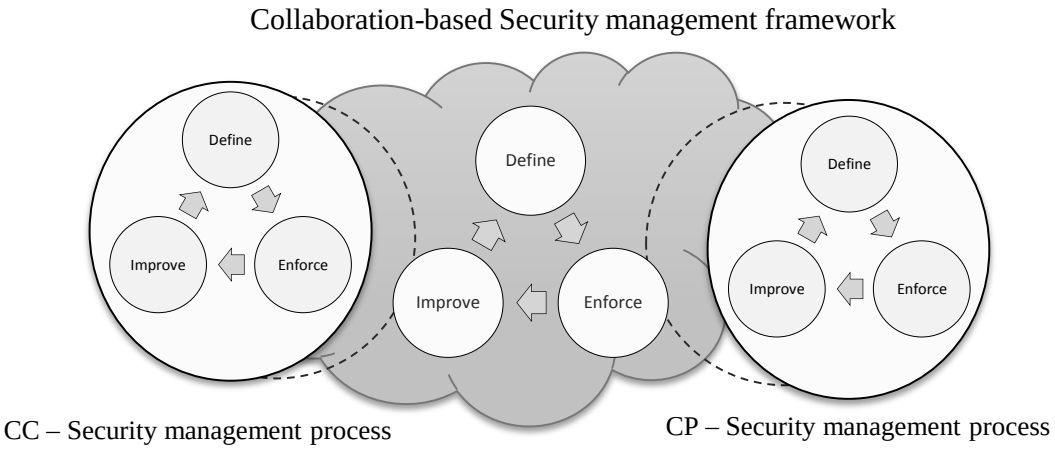


Figure 4-2. A concept diagram of our joint-collaboration cloud security management

4.3 Adaptive, Model-based Cloud Security Management – "Big Picture"

To satisfy the identified requirements and research gaps (questions) relevant to the cloud computing security problem as discussed in Chapters 2 and 3, we propose a novel approach based on extending the boundaries of the cloud consumers and providers' security management processes to include their cloud hosted services and cloud platforms respectively. This means that stakeholders can go through the security management process on their cloud hosted assets as if they have been hosting these assets inside their enterprise perimeters, as shown in

Figure 4-2. Moreover, they can use the same security specifications, security enforcement and monitoring and improvement approaches used internally and thus mitigate the loss-of-control and the lack-of-trust problems arise from adopting the cloud model. To deliver such capabilities, our framework has to introduce novel approaches to support capturing security requirements (including automated security analysis), enforcing security controls (through an automated security engineering approach), and monitoring the security of the hosted services (using automated security monitoring approach). Our framework should be deployed on cloud platforms where IT assets are located and used to manage the security of deployed services for corresponding tenants. Because none of the cloud stakeholders possesses the information required to secure a given service (going through the whole security management process), we adopt a joint-collaboration between cloud stakeholders in securing their cloud-hosted assets. Another obstacle to achieve this goal is that it is very hard to get the cloud consumers to have administrative access to the cloud platforms (may be malicious users) to manage the security of their assets by hand. Thus, we had to base our approach on abstract models that capture details of the cloud platform, services, and security. Our platform then takes the responsibility to realize these security specifications.

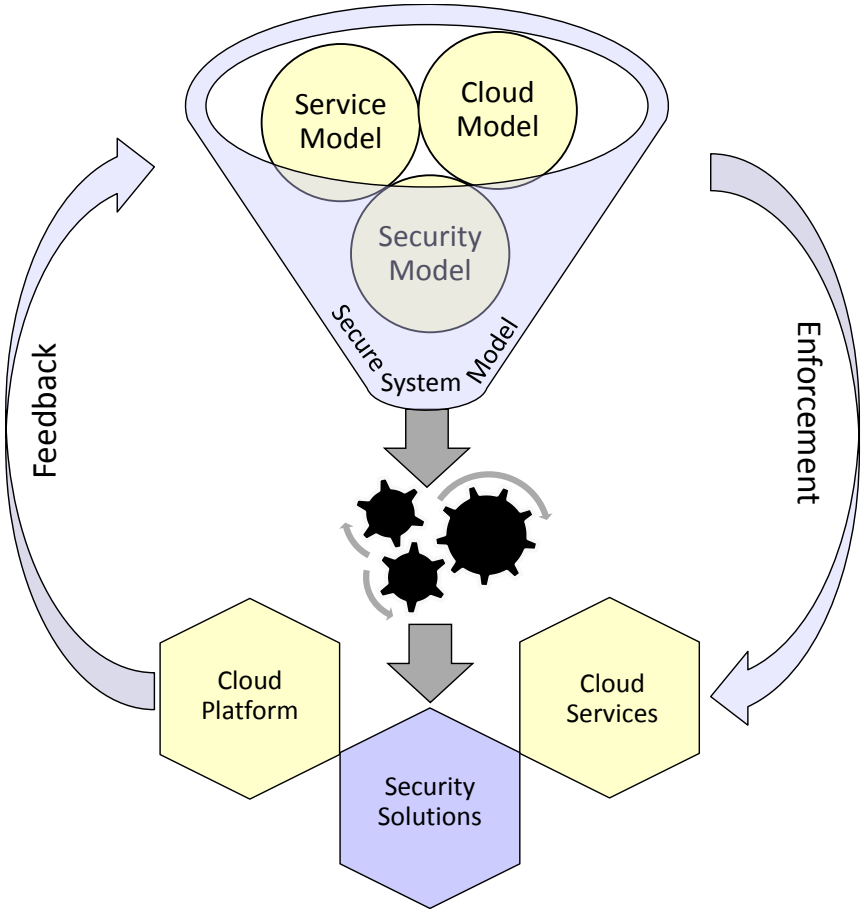


Figure 4-3. General Approach

Figure 4-3 shows that we get each stakeholder to summarize their information in models according to their roles: cloud providers model their platform details, service providers model their service details, and cloud consumers model their security model. These models are weaved in secure-system model (integrated model reflecting critical system entities and security details to be applied on these entities). This model is used as a reference in generating a security management plan that guides the configuration of security controls, integration of security controls within the target critical entities either in the service or in the cloud model. In our approach we move from top to bottom in the refinement process starting from models to real configurations "Enforcement". On the other side, we collect measurements for the services and security controls and consolidate such measurements into metrics reflecting security status "Feedback".

Figure 4-4 shows a high-level architecture of our adaptive-security management framework that we have been working on throughout this research project and we are going to discuss throughout this thesis. This framework is to be hosted on cloud platforms and used to manage the security of cloud services. Our approach architecture is inspired by the MAPE-K autonomic computing model introduced by IBM and discussed early in this chapter. Below we discuss the responsibilities of each of our approach.

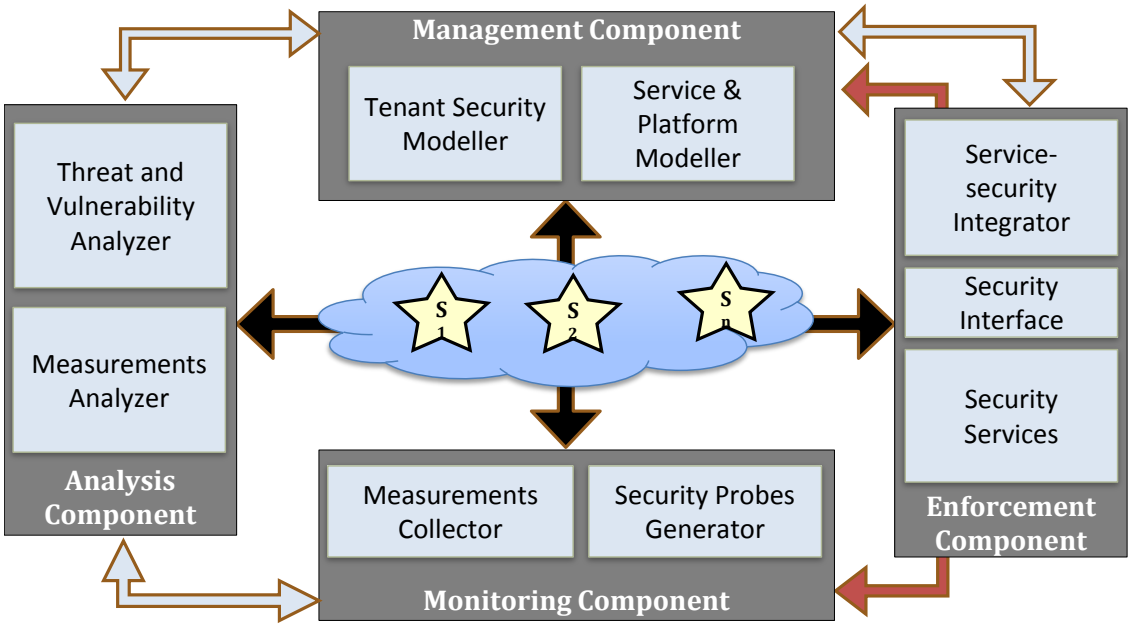


Figure 4-4. A high-level architecture of our security management approach

- *Management Component:* This is a model-based security management component that is responsible for capturing services and security details where service provider system engineers model their services' architecture, features and behavior and tenants' security engineers model and verify their own security objectives, requirements, architecture, and

metrics. Both models are then weaved together in a tenant secure-system model that guides the next steps of security enforcement and monitoring. This component represents the MAPE-K planning component where users define the policies or utility functions to be used to manage system adaptation.

- *Enforcement Component*: This component is responsible for integrating specified security details, modeled by different service tenants, with the target cloud services. The existing security management efforts, discussed in the related work chapter, focus mainly on automating security controls' configuration process. Thus, this point is out of our research scope. Actually, another reason is that these security controls may be deployed outside the cloud platform (inside tenant's network perimeter). Thus, our focus in this component is to support flexible integration of the security controls within the target cloud services. A common security interface was developed to facilitate the integration task. This interface defines a set of functionalities to be realized by the security vendors through a common security controls' adaptor. This enables security controls to easily integrate with our enforcement component which integrates with cloud services. This component represents the execute component in the MAPE-K model.
- *Monitoring Component*: This component is responsible for generating required security probes according to tenants' specified metrics (captured in the management layer). These probes are then deployed into the cloud services to capture system behavior and generate corresponding measurements/traces. Moreover, this component is responsible for collecting the measurements generated by these probes (according to metrics specified frequencies) and passing such measurements to the analysis component.
- *Analysis Component*: The analysis component is responsible for two main tasks: performing security analysis of the cloud services including vulnerability and threat analysis. The analysis component analyses the deployed services and their architectures to identify possible flaws and existing security bugs. This helps security engineers from both sides in developing their security models. Moreover, such issues are delegated to the security management component in order to incorporate in the security status reports for tenants as well as dynamically updating the security controls deployed to block the reported security issues. The analysis component also analyses the measurements reported by the monitoring component against a set of predefined metrics' stable ranges – e.g. number of incorrect user authentications per day should be less than 3 trials, so the analysis component should analyse the reported measures of incorrect authentications. This may also include taking corrective actions to defend against such probable attack. This represents the analysis component in the MAPE-K autonomic computing model.

4.4 Approach Evaluation

We have evaluated our approach using both experimental evaluation of each separate component and case studies from the cloud computing model using two or more components of our platform. In this section, we summarize the set of benchmark applications and set of evaluation metrics that we use throughout the thesis to evaluate the performance of our proposed platform components in terms of soundness, accuracy, and time. We introduce this here to avoid repetition in the next chapters. Below we summarize these benchmark applications and the evaluation metrics used.

4.4.1 Benchmark Applications

We have selected a set of real-world, large, widely-used, and commercial open source web applications developed using ASP.NET (currently we have a .NET parser) as our benchmark to evaluate our approach components including: the security engineering (chapter 6), security reengineering (chapter 7), security analysis (chapter 8), and security monitoring (chapter 9). In this section we introduce details of these benchmark applications. The other chapters reference this section in their evaluation sections.

The benchmark includes the following applications: *(i) Galactic-ERP*: An ERP system developed internally in our group for testing purposes. *(ii) PetShop*: A well-known reference e-Commerce application. *(iii) SplendidCRM*: An open source CRM that is developed with the same capabilities of the well-known open source SugarCRM system. It has been downloaded more than 400 times. *(iv) KOOBOO*: An open source enterprise content management system (CMS) used in developing websites. It has been downloaded more than 2000 times. *(v) BlogEngine:* An open source ASP.NET 4.0 blogging engine. It has been downloaded more than 46000 times. *(vi) BugTracer*: An open-source, web-based bug tracking and general purpose issue tracking application. It has been downloaded more than 500 times. *(vii) NopCommerce*: An open-source eCommerce solution. It has more than 10 releases. *(viii) Webgoat*: A security testing web-based application developed by OWSAP [40] for security analysis and testing purposes. This application is used mainly in the evaluation of the security analysis component. Except for Galactic, we do not have any previous experience with these applications. Table 4-1 shows a summary of these benchmark applications including number of downloads (which reflects how the applications are widely-used), size of the application in kilo-lines of code (KLOC), number of files, components, classes, methods, and time to build abstract syntax tree.

Table 4-1. Summary of benchmark applications statistics

Benchmark	Downloads	KLOC	Files	Components	Classes	Methods	AST Time
Galactic	–	16.2	99	2	101	473	187
PetShop	–	7.8	15	25	40	55	51
SplendidCRM	> 400	245	816	2	6177	6107	765
KOOBOO	> 2,000	112	1178	6	7851	5083	78
BlogEngine	> 46,000	25.7	151	13	258	616	163
BugTracer	> 500	10	19	8	298	223	93
NopCommerce	> 10 Rel.	442	3781	7	5127	9110	484
* Webgoat	-	15	105	2	125	165	150

Table 4-2. Evaluation results classification

		Actual Issue	
		Yes	No
Reported As Issue	Yes	TP	FN
	No	FP	TN

$$Precision = \frac{Valid\ Discovered\ Vulnerabilities\ (TP)}{Total\ Discovered\ Vulnerabilities\ (TP+FP)} \quad \text{Equation 1}$$

$$Recall\ = \frac{Valid\ Discovered\ Vulns\ (TP)}{Total\ vulns\ in\ a\ given\ system\ (TP+FN)} \quad \text{Equation 2}$$

$$False\ Alarm\ = \frac{False\ Positives\ (FP)}{False\ Positives\ (FP)+True\ Negatives(TN)} \quad \text{Equation 3}$$

$$F-Measure = 2\ \frac{Precision*Recall}{Precision+Recall} \quad \text{Equation 4}$$

4.4.2 Evaluation Metrics

To assess the effectiveness of our proposed components such as the security analysis, security re-engineering, and security monitoring components, we used a set of evaluation metrics to measure the soundness and completeness of the proposed technique. These metrics are precision rate, recall rate, false alarm rate, and F-measure. These metrics are based on the validity of the reported outcomes compared to the actual system status. Table 4-2 shows the different

combinations of reported outcomes and actual outcomes as follows: *True positive – TP:* valid outcome, the tool reported as an issue and it turns out to be actual issue*; False positive – FP:* invalid outcome, the tool reported as an issue although it is not an actual issue; *False negative – FN*: missed case, it is an actual issue, but the tool missed it; *True Negative –TN*: it is not an actual issue, and the tool did not report it. We next provide our definition of these metrics as used in our experiments. The *precision* metric is used to assess the soundness of the approach. A high precision rate means that the approach returns more valid results (true positive - TP) than invalid results (false positive - FP). Thus the maximum precision is achieved when no false positives (see Equation 1). The *recall* metric is used to assess the completeness of our approach. A high recall means that the approach returns most of the valid results (true positive - TP) than missed valid results (false negative - FN), see Equation 2. The low false alarm rate means how much invalid results reported by the tool compared to the total invalid results. The *F-measure* metric combines both precision and recall. It is used to measure the overall effectiveness of our approach (weighted harmonic mean). This metric depends on the importance of the recall rate and the precision rate, e.g. if we are interested in higher precision (more valid vulnerabilities) then we will give precision factor high weight, and vice-versa. We assume that the precision rate and recall rate are equally important, Equation 4.

4.5 Chapter Summary

In this chapter, we introduced a quick overview of the autonomic computing model introduced by IBM (MAPE-K model) and key techniques that could be used in realizing MAPE-K. Then we introduced the general idea of our approach which is based on getting cloud stakeholders involved in securing their assets through a joint-collaboration based approach. Finally, we introduced the big picture of our approach – the adaptive model-based security management framework. We explained our general approach and its main components. We discussed the main functionalities of every component of our proposed framework that we are going to discuss in detail. In chapter 5 we introduce our solution to align the existing security management standards to fit with the cloud computing model. In chapter 6 we discuss the security management and enforcement components using a novel model-driven security engineering at runtime approach. In chapter 7 we introduce how to address re-engineer legacy system that are already developed with built-in security capabilities to be managed by our security management platform. In chapter 8 we discuss one part of the analysis component which is a static security analysis. This is based on a novel security analysis approach based on formalizing security analysis signature as well as an extensible security analysis tool support. In chapter 9 we introduce monitoring component which covers how to capture metrics, generate probes, and collect measurements as well as analyzing the collected security measurements.

Chapter 5
Aligning Security Standards with Cloud Computing Model

To build our adaptive model-based cloud computing security management approach we introduced in the last chapter, we found it very crucial to base such an approach on a well-known and well-defined security management standard, such as ISO27000 or NIST-FISMA. However, such security management standards are far from covering the full complexity of the cloud computing model we discussed in the early chapters mainly multi-tenancy and outsourcing of IT assets. In this chapter, we introduce our proposed alignment of the NIST-FISMA standard to fit with the cloud computing model. This enables cloud providers and consumers to better maintain their security management processes on cloud platforms and cloud hosted services.

Our new framework is based on improving collaboration between cloud providers, service providers and service consumers in managing the security of the cloud platform and the hosted services. It is built on top of a number of security standards that assist in automating the security management process. We have developed a proof of concept of our framework using .NET and deployed it on a testbed cloud platform. We have evaluated the framework by managing the security of a multi-tenant SaaS application exemplar discussed in Chapter 1.

This chapter is organized as follows. In Section 1 we highlight the existing trials to adopt security management standards to fit with the cloud model. We also highlight the key requirements and challenges that need to be satisfied by any proposed cloud security management platform. Section 2 discusses our refined security management model. Section 3 explains how we aligned NIST-FISMA standard to fit with the cloud model. Section 4 summarizes the key security automation standards we adopted in our prototype. Section 5 outlines our prototype framework we developed based on aligned NIST-FISMA model. Section 6 introduces a usage example of the developed framework.

5.1 Introduction

Although much research into cloud services security engineering has been undertaken [4, 21, 61, 150, 155, 157, 222, 223], most of these efforts focus on the cloud-based services offered as

web services. Such efforts have investigated capturing security requirements and generating corresponding WS-Security configurations. However, they pay no attention to the underlying platform security or the other cloud service delivery models such as SaaS [21]. They also do not address the impact of the multi-tenancy feature introduced by the cloud model on the security of the cloud delivered services even in the case of web services.

From our analysis of the cloud security problem we have identifieid a set of key challenges including: Each stakeholder has their own security management process (SMP) that they want to maintain/extend to the cloud hosted assets; No stakeholder can individually maintain the whole security process of the cloud services because none of them has the full information required to manage security and each one has a different perspective; Multi-tenancy requires maintaining different security profiles for each tenant on the same service instance; No Security SLA is available that can be used to maintain agreements related to cloud assets security; The existing standards such as ISO27000 and FISMA do not map well to the cloud model because these standards consider the SMP from the platform/asset owner not from a Service Provider perspective.

We have also highlighted a set of Key requirements that need to be satisfied by an information security management system targeting the cloud computing model. This includes: Enable cloud consumers to specify their security requirements on the cloud hosted assets and the underlying cloud platform; Enable cloud consumers to monitor their assets security status and the underlying platform security status as well; Support multi-tenancy where different tenants can maintain their SMP with strong isolation of data; Aligned with on one of the existing security management standards that are already adhered by the cloud consumers and cloud providers.

Two new community projects are trying to tackle the cloud consumers trust problem by introducing a list of best practices and checklists that could help cloud providers or cloud consumers such as CSA - GRC project [222], or by aligning existing security standards to the cloud model such as NIST FedRAMP [224]. The focus of both projects is to obtain cloud consumers trust by assessing and authorizing the cloud platforms. In the FedRAMP project, a cloud provider claims supported security level. A certifying authority, certified by the FedRAMP providers - NIST, audits the cloud provider claimed security level. Each cloud consumer specifies their expected security level. The certifying authority matches cloud consumers' requirements and providers' capabilities and assures it. However, this proposed solution by FedRAMP project lacks customizability of the platform-provided security from the cloud consumer perspective – i.e. it does assume that the cloud consumers will use the security provided by the cloud platform provider as it is. Moreover, adaptation of the provided security

is not possible. This also limits the Return of Investment (ROI) of the cloud providers as they become limited to certain security level assessed by the certifying authority. Finally, the proposed security model by this project assumes that the cloud provider is the service provider (like in Amazon AWS or Salesforce.com). However, this is not always the case in cloud computing platforms.

In the Security Registry project introduced by Cloud Security Alliance (CSA), a list of security controls to be operated by a cloud provider is introduced, and a checklist to guide consumers assessing a cloud platform security before adopting the platform. However, such assessment and awareness do not mean to have a real operating security. Neither loss-of-control nor lack-of-trust problems have been mitigated. These projects lack the consumers' involvement in specifying their security requirements and managing their SMP. The NIST project fits better with cloud providers who deliver their own services only. This is because they need to have a deep understanding of the cloud hosted services to be secured.

To address these shortcomings we introduce a novel approach that tackles both the loss-of-control and lack-of-trust problems by enabling cloud consumers to extend their security management process (SMP) to cover cloud hosted assets. Our approach introduces a new cloud security management framework based on aligning the NIST-FISMA standard [225], as one of the main security management standards, to fit with the cloud architectural model. The information required to put the NIST standard into effect is not possessed by one party. Thus we improve collaboration among the key cloud stakeholders to share such required information. Getting cloud consumers involved in every step of the SMP of their assets mitigates claims of losing trust and control. Our approach also mitigates the loss of control claimed by the cloud providers for the hosted services that are developed by other parties. Being based on a security management standard our approach enables both parties to get or maintain their security certifications. Moreover, this helps in assuring that we can cover the majority of the activities done during the security management process. Our approach helps stakeholders to work together to address the following issues:

- What are the security requirements needed to protect a cloud hosted service given that the service is used by different tenants at the same time?
- What are the appropriate security controls that mitigate the service adoption risks and who has the authority to select such controls?
- Are the selected controls available on the cloud platform or we will/can use third party controls?
- What are the security metrics required to measure the security status of our cloud-hosted services?

To validate our proposed alignment, we developed a prototype of our collaboration-based cloud security management approach and deployed it on a cloud platform hosting a SaaS application (Galactic ERP service). We evaluated the approach by securing the ERP service assuming that the cloud platform has multiple tenants sharing the same cloud application. Each tenant has their own security requirements and security management process.

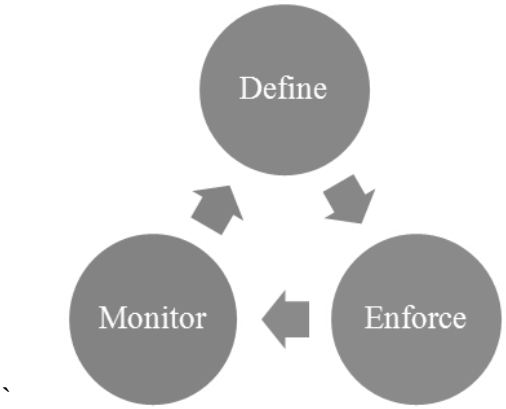


Figure 5-1. Information security management system phases

5.2 Rethinking In Security Management

Information security management systems (ISMS) are defined in ISO27000 as [5] "systems that provide a model for establishing, implementing, operating, monitoring, reviewing, maintaining and improving the protection of information assets.". From analyzing both ISO27000 and NIST-FISMA standards, we define a security management system to have three key phases: defining security, enforcing security, and monitoring and improving security as shown in Figure 5-1. *First*, Defining Security Requirements: this phase covers tasks/efforts required to: identify security goals/objectives that the ISMS should satisfy and deliver, conducting risk analysis and assessment to identify existing risks within the system scope, and detailing objectives/risks into detailed security requirements and security policies. *Second*, Enforcing Security Requirements: this phase covers efforts required to: identify security controls to be used, and implementing and configuring such controls based on the specified security requirements. *Third*, Monitoring and Improving Security: this phase includes: monitoring the current security status of the implemented security controls, analyzing the measured security status to identify existing security issues, and maintaining and improving the current security controls. In this research project we addressed most of the tasks in these three phases with approaches that help facilitating and automating as much as possible and needed. Our holistic approach is based on our refined model of the security management process (define, enforce, monitor and improve) shown in the above figure.

Table 5-1. Alignment of NIST-FISMA standard with the cloud computing model

Phase	Task	CP	SP	CC	Input	Output
Security categorization	Categorize security impact (SC)	Informed	Informed	Responsible	Business objectives	Security Impact Level
Security controls selection	Register security controls	Responsible	Responsible	Responsible	Control Datasheet	Security controls registry
	Generate security controls baseline	Responsible (Automated by the framework)			Service SC + Controls registry	Controls baseline + matching status
	Assess service risks	Responsible (automated in chapter 8)			Service + platform arch. +CVE + CWE	Service Vulns + Threats + Risks
	Tailor security baseline	Responsible (revised in chapter 6)			Baseline + Risk assessment	Security mgmt plan (SLA)
Controls implementation	Implement security controls	Responsible (planned to be automated)			Security mgmt plan	Updated Security plan

Security assessment	Define security metrics	Responsible			Security objective	Security assessment plan
	Assess security status	Rsponsible (Automated by the framework)			Security assessment plan	assessment report
Service authorization	Authorize service	Informed	Informed	Responsible	Security plan + assessment report	Service authorization document
Security monitoring	Monitor security status	Responsible (Automated by the framework and revised in chapter 9)			Security assessment plan	Security status report

5.3 Aligning NIST-FISMA with Cloud Computing

The Federal Information Security Management Act **(**FISMA) standard [1] defines a framework for managing the security of information and information systems that support the operations of the agencies. The framework has six main phases including: service security categorization, security controls selection, security controls implementation, security controls assessment, service authorization, and security monitoring. In order to align this standard with the cloud computing model, we have studied each phase, activity, and task to understand the main inputs, processing, and outcomes. Then we studied the cloud computing responsibility matrix – i.e. who can or is allowed to do what. Based on these two inputs we restructured the NIST-FISMA standard responsibility matrix to make sure that the relevant stakeholder (who owns the information required to fulfill a given task) is allocated as the main responsible for such task while getting other stakeholders informed about the activities being done. Table 5-1 and Figure 5-2 summarize for each phase in the security management standard, how we aligned FISMA to fit with the cloud model in terms of reorganizing the responsibility matrix among cloud stakeholders based on who knows what.

5.3.1 Service Security Categorization

Each service (S_j) on the cloud platform could be used by different tenants. Each service tenant (T_i) owns their information only in the shared service (S_J). The tenant is the only stakeholder who can decide/change the impact of a possible loss of confidentiality, integrity and availability on their business objectives. Each tenant may assign different impact levels (Low, Medium, or High) to possible security breaches on their information. In FedRAMP [4], the cloud provider (CP) specifies the security categorization of services delivered on their cloud platform. However, this is not sufficient as the CP does not have sufficient knowledge about the impact of information security breaches on their tenants' business objectives. Our approach enables cloud consumers (CCs) to be involved in specifying the security categorization of their information. Moreover, our approach enables both scenarios where we can consider the security categorization (SC) per tenant (tenant-oriented security -as in Equation 1) or per service (service-oriented security - as in Equation 2).

In the service-oriented security model, a cloud service can reflect one set of security requirements/controls per time, the security categorization of the service is calculated as the maximum of all tenants' categorizations. On the other hand, the tenant-oriented security model gets services to reflect each tenant security requirements as if no one else is using the service.

$$SC(T_i) = [(\text{Confidentiality, impact}), (\text{Integrity, impact}), (\text{Availability, impact})],$$

$$\text{Impact} \in [\text{Low, Medium, High}] \quad \text{Eq. (1)}$$

$$SC(S_j) = [(\text{Confidentiality, } \mathbf{Max}\ (\forall T_i\ (\text{impact})), (\text{Integrity, } \mathbf{Max}\ (\forall T_i\ (\text{impact})),$$

$$(\text{Availability, } \mathbf{Max}\ (\forall T_i\ (\text{impact}))] \quad \text{Eq. (2)}$$

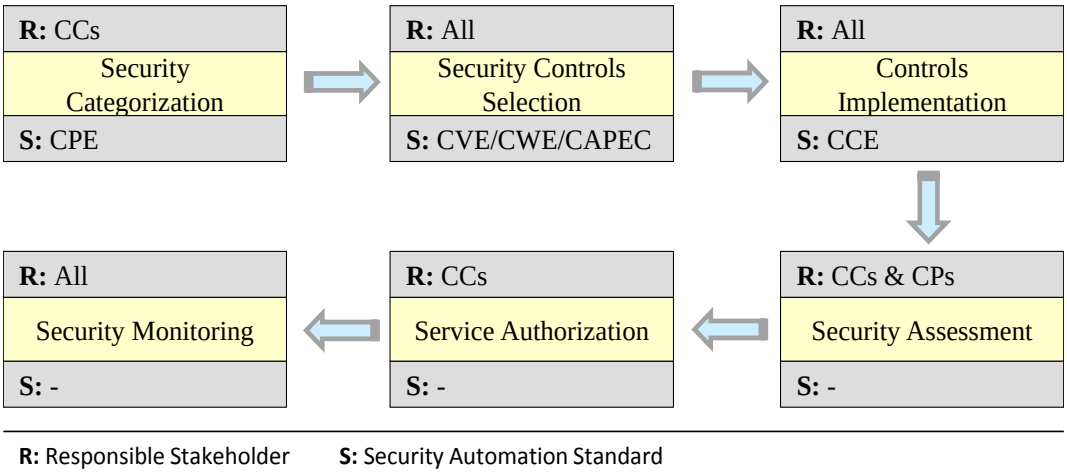


Figure 5-2. Alignment of NIST-FISMA standard with the cloud model

5.3.2 Security Control Selection

The selection of security controls to be implemented in protecting tenants' assets has two steps: *First*, baseline security controls selection. The FISMA standard provides a catalogue of security control templates categorized into three baselines (low, medium and high). Based on the security categorization of the service, specified by service tenants in the first step, the platform should automatically select the initial baseline of controls that are expected to provide the required level of security specified by tenants. *Second*, tailoring of the security controls baseline. Stakeholders should tailor the security controls baseline identified in the first step to cover the service possible vulnerabilities, threats, risks and the other environmental factors as discussed below.

5.3.2.1 *Service Security Risk Assessment*

In this step, stakeholders should conduct security risk assessment to identify service vulnerabilities, threats, attacks, and risks that may require special security handling – i.e. customization of the security controls' baseline that have been selected in step (a) according to service security categorization. This includes:

- *Vulnerabilities Identification*: This step requires being aware of the service and the operational environment architecture. We consider the involvement of the service provider (SP) who knows the internal structure of the provided service and the CP who knows the cloud platform architecture in order to fulfill this task. The main outcome of this step is a list of security vulnerabilities that should be patched.
- *Threats Identification*: The possible threats, threat sources and capabilities on a given service can be identified by collaboration among the SPs, CPs, and CCs. CCs are involved as they have the knowledge about their assets' value and could know who may be a source of security breaches.

At the end of this phase, the cloud service stakeholders will have a list of threats, attacks, and vulnerabilities that they should try to mitigate to prevent such possible security breaches. These tasks will be automated in our platform as discussed in Chapter 8.

5.3.2.2 *Security Controls Baseline Tailoring Process*

Based on the risk assessment process, the selected security controls baseline can be tailored to mitigate new risks and fit with the new environment conditions, as follows:

- *Scoping of the Security Controls*: In this step all stakeholders should be involved in selecting security controls to be operated. This includes: (i) Identification of the common security controls; the cloud stakeholders decide which security controls in the baseline they plan to replace with a common security control (either provided by the CPs or by the CCs). A common security control is a control that is shared among multiple services; (ii) Identification of the critical and non-critical system components; the SPs and CCs should define which components are critical to enforce security on it and which are non-critical (may be because they are already in a trusted zone) so no possible security breaches; and (iii) Identification of the technology and environment related security controls that are used whenever required such as wireless network security controls.
- *Compensating Security Controls*: Whenever the stakeholders find that one or more of the security controls in the tailored baseline do not fit with their environmental conditions or are not available (may be cost wise), they may decide to replace such controls with another compensating security control.
- *Set Security Controls Parameters*: The last step in the baseline tailoring process is the security controls' parameters configuration, such as minimum password length, maximum number of unsuccessful logins, etc. This is done by collaboration between the CPs and CCs. All these details are captured by cloud stakeholders in a model-based approach, as we discuss in Chapter 6. The outcome of this phase is a security management plan that

documents service security categorization, risks, vulnerabilities, and the tailored security controls baseline with the specified security configurations.

5.3.3 Security Controls Implementation

This phase focuses on implementation of the security controls that have been tailored in the previous step. In the original NIST-FISMA standard, this is the sole responsibility of the service owner. Thus this need to be aligned with the new responsibilities we have got in the cloud model. The security plan for each tenant describes the security controls to be implemented by each involved stakeholder based on the security control category (common for all services or service-specific control). The common security controls implementation is the responsibility of the common control provider who is most probably be the CPs. Tenant specific security controls are the responsibility of the service tenants. The service-specific security controls implementation is the responsibility of the SPs. Each stakeholder must document the security controls implementation and configuration details in the security management plan.

5.3.4 Security Controls Assessment

Security controls assessment is required to make sure that the security controls implemented are functioning properly and meet the security objectives specified. This step includes developing a security assessment plan that defines security controls to be assessed, assessment methods to be used, and security metrics to be used with each security control. The results of the assessment process are documented in a security assessment report. This step may result in going back to the previous steps in case of deficiency in the controls implemented or continuing with the next steps. The security controls assessment is a shared responsibility of all cloud stakeholders. Each one should develop the metrics they would like to use in assessing the security status of their cloud assets. The framework tries to automate the assessment process by analysing the log files of the security controls operated.

5.3.5 Service Authorization

This step represents the formal acceptance of the stakeholders on the identified risks involved in the adoption of the service and the agreed on mitigations. We consider the security plan and security assessment plan to be used as the security SLA among the involved parties. These plans reflect mostly all the information required to assess the security properties of a given cloud service and responsibility of each involved stakeholder towards other stakeholders.

5.3.6 Monitoring Security Controls Effectiveness

The CPs should provide security monitoring tools to help the CCs in monitoring the security status of their assets. The monitoring tools should have the capability to capture the required security metrics and report the collected measures in a security status report either event-based or periodic-based. The results of the monitoring process may require re-entering the SMP to handle new unanticipated changes. For now we consider our log-based monitoring component as a tool to help addressing this task. Later in chapter 9, we are going to discuss our refined and automated security monitoring approach.

5.4 Security Automation

After aligning the FISMA standard with the cloud model we adopted a set of existing security standards to help improving the framework automation and its integration with the existing security capabilities, as shown in Figure 5-3 and Table 5-2. These security standards include:

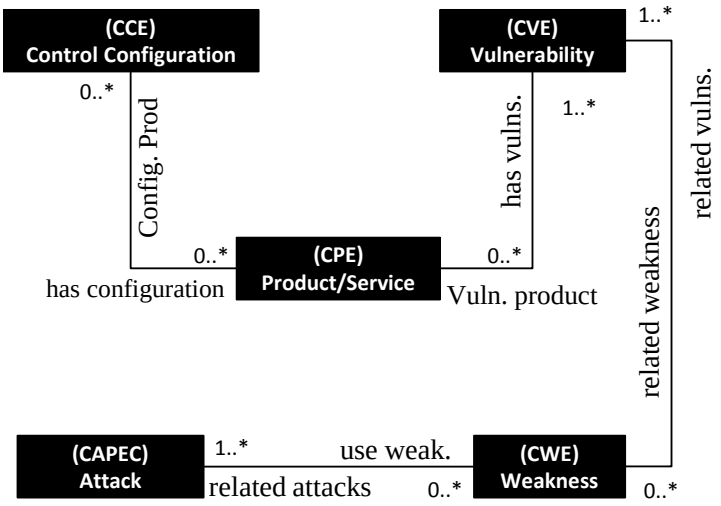


Figure 5-3. Adopted security automation standards and relationships

Table 5-2. Formats and examples of the adopted security standards

Standard	Format	Example
CPE	cpe:/ [part] : [vendor] : [product] : [version] : [update] : [edition] : [language]	cpe:/a:SWINSOFT: Galactic:1.0: update1:pro:en-us
CVE	CVE-Year-SerialNumber	CVE-2010-0249
CWE	CWE-SerialNumber	CWE-441
CAPEC	CAPEC-SerialNumber	CAPEC-113
CCE	CCE-softwareID-SerialNumber	CCE-17743-6

- *Common Platform Enumeration (CPE)* [226]: The CPE provides a structured naming schema for IT systems including hardware, operating systems and applications. We use the CPE as the naming convention of the cloud platform components and services. This helps in sharing the same service name with other cloud platforms and with the existing vulnerabilities databases – e.g. The National Vulnerability Database - NVD [227]. The format of the CPE consists of constant "CPE", part which may be (application, OS, network), software vendor, product name, used version, service pack, edition, and language.
- *Common Weakness Enumeration (CWE) and Common Attack Pattern Enumeration and Classification (CAPEC)* [226]: The CWE provides a catalogue of the community recognized software weaknesses. The CAPEC provides a catalogue of the common attack patterns. Each attack pattern provides a description of the attack scenario, likelihood, knowledge required and possible mitigations. We use the CWE and CAPEC as a reference for the cloud stakeholders during the vulnerabilities identification phase.
- *Common Vulnerability and Exposure (CVE)* [226]: The CVE provides a dictionary of the common vulnerabilities with a reference to the set of the vulnerable products (encoded in the CPE). It also offers vulnerability scoring that reflects the severity of the vulnerability. We use the CVE to retrieve the know vulnerabilities discovered in the service or the platform under investigation. Thus, in this version of our implementation we depend on security experts to identify and report any possible vulnerability in the National Vulnerability Database (NVD) using CVE format. In the next chapters we will introduce our new online security analysis approach that completely automates this task. This will also help in case of new vulnerabilities that are not reported in the NVD yet or in case of using cloud services that do not have CPE ID to be used in retrieving relevant vulnerabilities.
- *Common Configuration Enumeration (CCE)* [226]: The CCE provides a structured and unique naming to systems' configuration statements so that systems can communicate and understand such configurations. We use the CCE in the security controls implementation phase. Instead of configuring security controls manually, the administrators can assign values to security control templates' parameters. Our framework uses these configurations in managing the selected security controls. This point is out of scope for this project as we discussed previously. We are not concerned with how to automate the security controls' configuration because many platforms and frameworks do exist that help in this.

Figure 5-3 shows the relationships between these security automation standards. This helps in understanding why we selected such standards and where they actually fit. At the center of the model we have the CPE. This CPE is referenced in retrieving vulnerabilities from the CVE and controls' configurations in CCE. The CVE is linked to the common weaknesses in the

CWE. The attacks recorded in the CAPEC repository is based on exploiting known weakness recorded in CWE repository.

5.5 Cloud Security Framework Architecture

Our initial framework architecture consists of three main layers: a management layer, an enforcement layer, and a feedback layer. These layers, shown in Figure 5-4, represent the realization of the ISMS phases we described in previous sections.

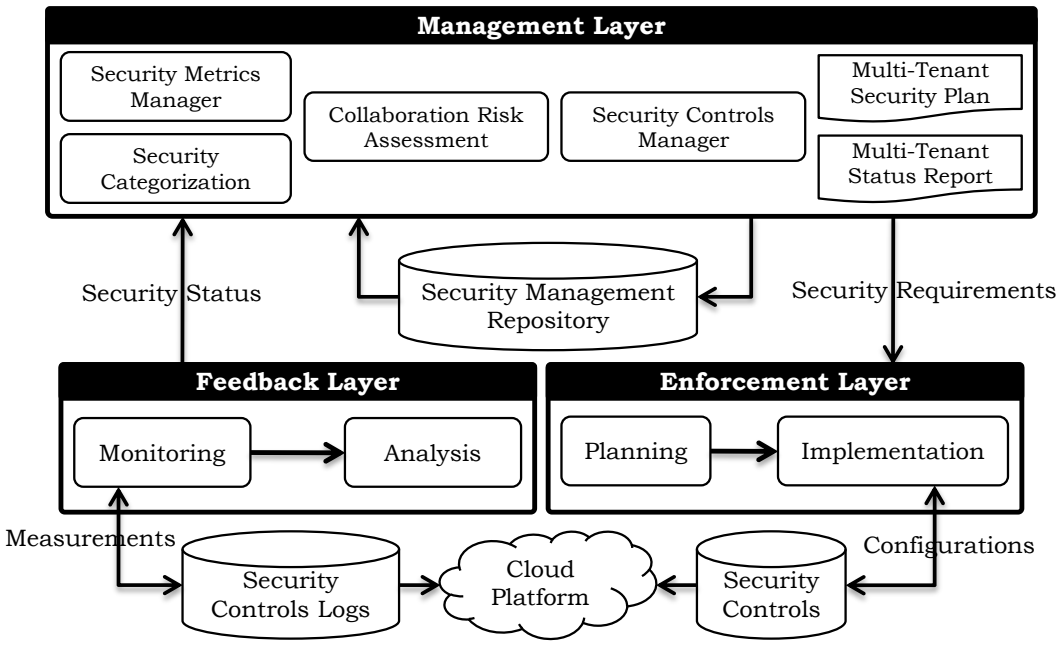


Figure 5-4. Our collaboration-based cloud security management architecture

- *Management Layer*: This layer is responsible for capturing security specifications of the CPs, SPs, and CCs. It consists of: (a) The security categorization service used by the hosted services' tenants to specify security categorization of their information maintained by the cloud services; (b) The collaborative risk assessment service where all the cloud platform stakeholders participate in the risk assessment process with the knowledge they possess; (c) The security controls manager service is used to register security controls, their mappings to the FISMA security controls' templates, and their log files structure and locations; (d) The security metrics manager service is used by the cloud stakeholders to register security metrics they need to measure about the platform security; (e) The multi-tenant security plan (SLA) viewer service is used to reflect the tenant security agreement. This shows the tenant-service security categorization, vulnerabilities, threats, risks, the selected mitigation controls and the required metrics; (f) The multi-tenant security status viewer which reflects the current values of the security metrics and their trends.

- *Enforcement Layer*: This layer is responsible for security planning and security controls selection based on the identified risks. The selected security controls are documented in the security management plan. The implementation service then uses this plan for maintaining security control configuration parameters and the mapping of such parameters to the corresponding security controls. This service does not address the integration of security controls with the target cloud services. Later in Chapter 6, we will introduce our security integration approach.
- *Feedback Layer*: This layer has two key services: the monitoring service which is responsible for collecting measures defined in the security metrics manager and storing it in the security management repository to be used by the analysis service and by the multi-tenant security status reporting service. The analysis service analyses the collected measures to make sure that the system is operating within the defined boundaries for each metric. If there is a deviation from the predefined limits, the analysis service will give alerts to update the current configurations. This service only supports log-based metrics. Moreover, there is no support for possible mitigation actions. The reported measurements can only visualized for the stakeholders in regular security status reports.

5.6 Usage Example

To demonstrate the capabilities of our cloud computing security framework and our prototype tool implementing this framework we revisit the motivating example from Chapter 1, a cloud based ERP system "Galactic" used by Swinburne and Auckland (CCs), developed by SwinSoft (SP), and deployed on the GreenCloud (CP). The two tenants using the Galactic ERP services, Swinburne and Auckland, are still concerned about their assets' security on the cloud. Both have their own SMP and their own security requirements to be enforced on their cloud assets.

First, the service provider registers the service on the cloud computing platform service registry. This enables tenants to search and register to use the service. Then, each registered tenant will get permission to access the security management portal. Each tenant will be required to define the security categorization of the service from their perspective. *Next*, cloud stakeholders should start registering their security controls that they would like to use. This requires mapping such controls to the NIST-FISMA standard template. After this, cloud stakeholders should collaborate to identify the possible threats and existing security vulnerabilities. This should guide the security controls' tailoring process. The platform helps stakeholders to find out which security controls are missing – i.e. exist in the standard as must have, and do not have realization security control specified by any of the service stakeholders. *Finally*, service tenants define the security metrics they would like to monitor or follow up. The

platform keeps track of these metrics and analyzes the security controls' log files on regular basis to extract the specified information usually in terms of aggregation functions on monitored or logged data. Below we show how the cloud computing-aligned security management process works supported with snapshots from our security management platform.

5.6.1 Registering Cloud Services

The first step in our example is to register Galactic ERP service in the cloud platform service repository so that it can be discovered/used by the CCs. This step could be done either by SwinSoft or by the GreenCloud. In this step we use the CPE standard name as the service ID, as shown in Figure 5-5. To register a service, first we search by service name or service CPE ID in the set of registered services. If found, just select it from the found matches to register the service. Otherwise, insert service details as a new record to the service repository. Once the service was registered, cloud consumers can register to use it. A new tenant, Auckland, can register their interest in using the Galactic service. Then Auckland will be granted a permission to manage the security of his information maintained by Galactic service. The same is done by Swinburne, as shown in Figure 5-6. Now Auckland and Swinburne can use our platform to manage the security of their assets.

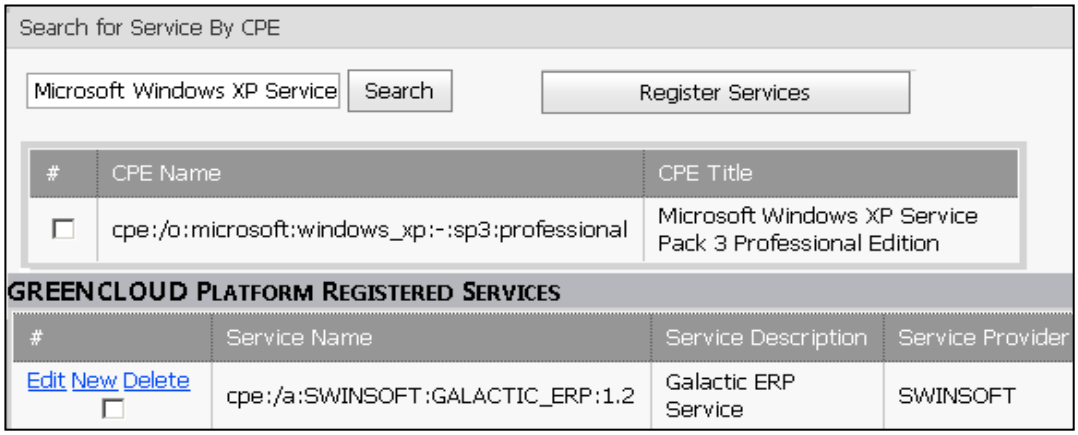


Figure 5-5. SwinSoft is registering their Galactic ERP service with GreenCloud

#	Service Name	Registration Date	Period	Confidentiality Impact	Availability Impact	Integrity
Edit Delete	cpe:/a:SWINSOFT:GALACTIC Galactic ERP Service	1/01/2011	36	Medium	Medium	High

#	Service Name	Registration Date	Period	Confidentiality Impact	Availability Impact	Integrity
Edit Delete	cpe:/a:SWINSOFT:GALACTIC Galactic ERP Service	1/01/2011	24	Low	Medium	Low

Figure 5-6. Registering a service by Swinburne (top) and Auckland (bottom)

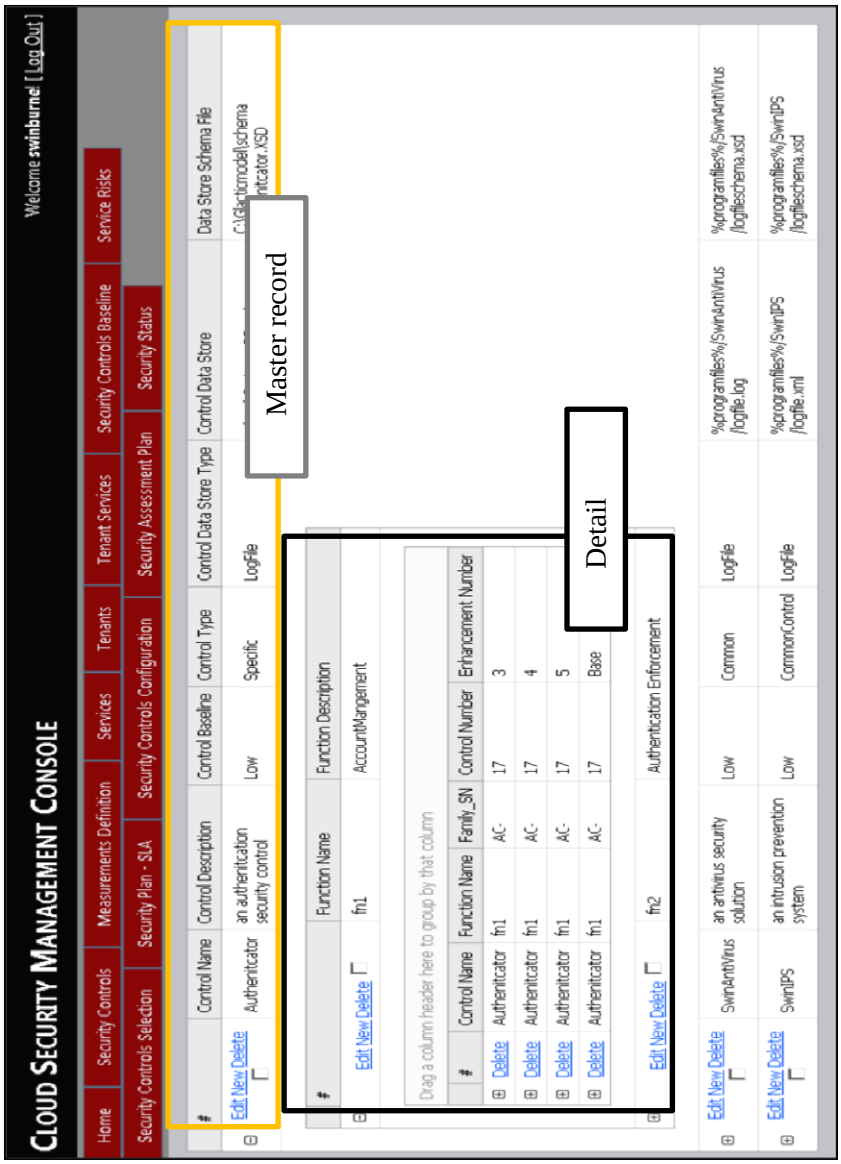


Figure 5-7. Security controls registration

#	Ctl Family	Ctl No.	Enhancement	Ctl Name	Control Status
Edit Delete	AC-	14	1		Missing
Edit Delete	AC-	17	1	Authenitcator	Available
Edit Delete	AC-	17	1	SwinAntiVirus	Duplicate
Edit Delete	AC-	17	2	Authenitcator	Available
Edit Delete	AC-	17	2	SwinAntiVirus	Duplicate

Figure 5-8. Security controls baseline with controls' status

5.6.2 Service Security Categorization

The Swinburne security administrator specifies the impact level of losing the confidentiality, integrity, and availability of their data maintained by the Galactic ERP service, as shown in Figure 5-6(top). The same should be done by Auckland security administrator, as shown in Figure 5-6(bottom). Whenever a new tenant registers their interest in a service and defines their security categorization of data processed by the service (or any of the existing tenants update his security categorization), the platform updates the overall service security categorization with the maximum value as per equation1, discussed in the process alignment section.

5.6.3 Security Controls Selection

GreenCloud as a cloud provider already publishes their security controls database. Swinburne and Auckland can register their own security controls using the security controls manager service. Based on the security categorization step, our framework generates the security controls' templates baseline. Then stakeholders should start registering their security controls and their features and link such features to security controls' baseline as shown in Figure 5-7. The registration of a security control should specify master data including control name, category, control family, location and schema of the log file. Moreover, each registration should map security control features to the NIST-FISMA standard security control template (as in the detail section of Figure 5-7). Our prototype helps in identifying security controls' templates that are: satisfied (matches one of the registered security controls), missing (does not match registered security controls), or duplicate (more than one matched control), as shown in Figure 5-8. This figure shows that in the access control family, the control number (14) which is "*Permitted Actions without Identification or Authentication*", enhancement number (1) which is "*Permitted Actions Should Be Limited to The Limit That Service Business Needs*" is missing. So that stakeholders can highlight this problem and work on it or simply accept this problem. The same with the security control (17) which is "*Remote Access*" has got duplicated security controls defined that satisfy the same template from the baseline which by analysis turned out to be a mistake in the registration of security control done by a stakeholder. This helps stakeholders in revising the status of the security controls to be operated on their services.

5.6.3.1 *Service Risk Assessment*

Galactic vulnerabilities are identified for the first time by SwinSoft with the help of GreenCloud who knows the architecture of the service and the hosting cloud platform. Both SwinSoft and GreenCloud have the responsibility to maintain the service vulnerabilities list up to date. The framework enables to synchronize the service vulnerabilities with the community vulnerabilities

database – NVD, as shown in Figure 5-9. This figure shows the list of found vulnerabilities. Users can click on "Use known vulnerabilities in NVD" to synchronize the list with the least recently reported vulnerabilities. Stakeholders can link on CVE-ID to navigate to the full detailed version of the vulnerability on the NVD website. Each cloud consumer – Swinburne and Auckland – should review the defined threats and risks on Galactic and append any missing threats. The framework integrates with the CWE and CAPEC databases to help stakeholders in identifying possible vulnerabilities whenever the service does not have vulnerabilities recorded in the NVD.

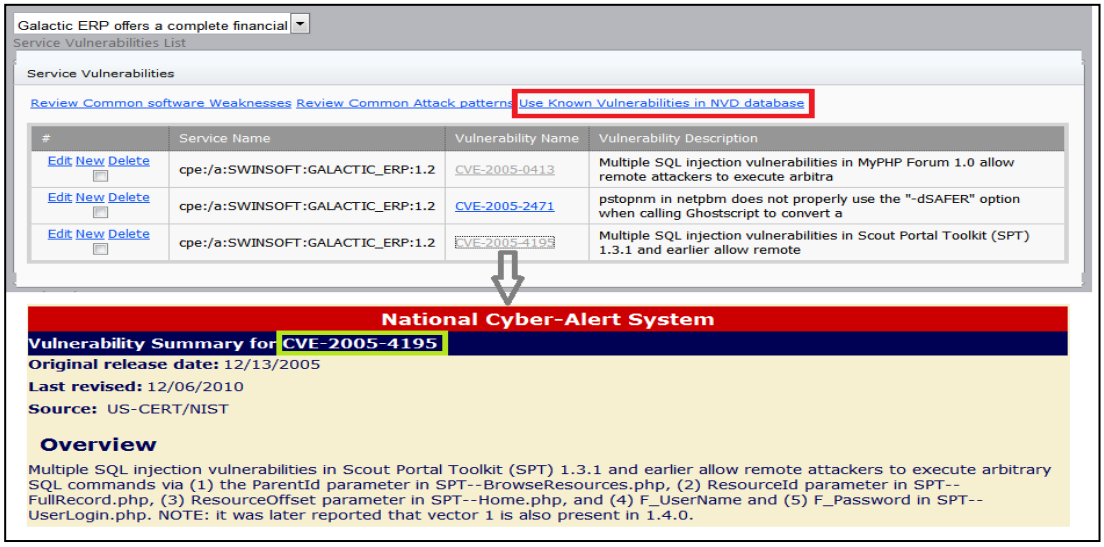
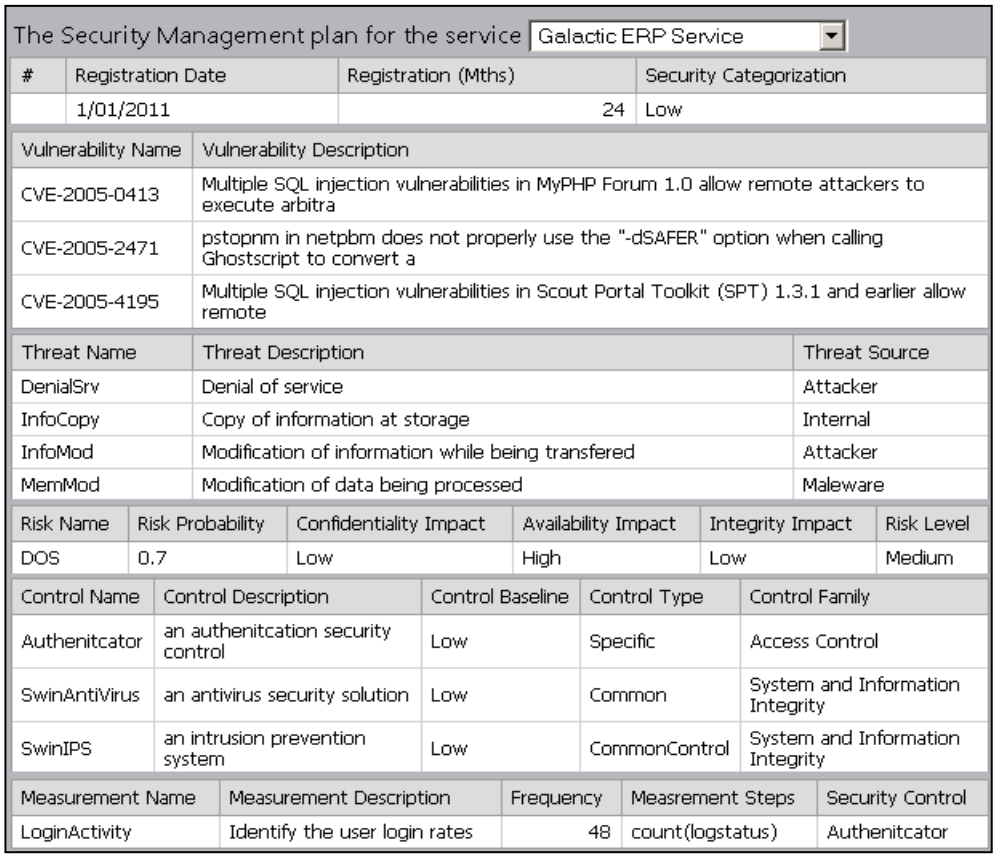


Figure 5-9. Service reported vulnerabilities - integrated with NVD

5.6.3.2 *Security Controls Baseline Tailoring*

The service tenants decide which security controls in the baseline they plan to replace with common security controls provided by the cloud provider or the service tenants, as shown in Figure 5-8. Stakeholders can *edit* the registered security control mapping to another control or they can delete any mapping all together. SwinSoft, Auckland, and Swinburne should also select the critical service components that must be secured. Swinburne and Auckland define their security controls' parameter configurations. The security controls provided by the cloud platform can only be reviewed.

The final outcome of this step is a security management plan that documents the service security categorization (either from the tenant perspective or from the service perspective), found vulnerabilities, expected threats, risks, and the tailored security controls to mitigate the identified possible security breaches, as shown in Figure 5-10.



The Security Management plan for the service: Galactic ERP Service

#	Registration Date	Registration (Mths)	Security Categorization
	1/01/2011	24	Low

Vulnerability Name	Vulnerability Description
CVE-2005-0413	Multiple SQL injection vulnerabilities in MyPHP Forum 1.0 allow remote attackers to execute arbitra
CVE-2005-2471	pstopnm in netpbm does not properly use the "-dSAFER" option when calling Ghostscript to convert a
CVE-2005-4195	Multiple SQL injection vulnerabilities in Scout Portal Toolkit (SPT) 1.3.1 and earlier allow remote

Threat Name	Threat Description	Threat Source
DenialSrv	Denial of service	Attacker
InfoCopy	Copy of information at storage	Internal
InfoMod	Modification of information while being transfered	Attacker
MemMod	Modification of data being processed	Maleware

Risk Name	Risk Probability	Confidentiality Impact	Availability Impact	Integrity Impact	Risk Level
DOS	0.7	Low	High	Low	Medium

Control Name	Control Description	Control Baseline	Control Type	Control Family
Authenitcator	an authenitcation security control	Low	Specific	Access Control
SwinAntiVirus	an antivirus security solution	Low	Common	System and Information Integrity
SwinIPS	an intrusion prevention system	Low	CommonControl	System and Information Integrity

Measurement Name	Measurement Description	Frequency	Measrement Steps	Security Control
LoginActivity	Identify the user login rates	48	count(logstatus)	Authenitcator

Figure 5-10. Examples of Auckland security management plan

5.6.4 Security Controls Implementation and Assessment

Each stakeholder implements the security controls under their responsibility as stated in the security management plan and the security controls configurations as specified in the previous step. In case of Galactic ERP, Swinburne should implement and configure their Swin-Authenticator, Swin-Antivirus, and Swin-IPS security controls. The same should be done by Auckland using their security controls. The controls to be assessed and the objectives of the assessment are defined by GreenCloud, Auckland and Swinburne and documented in the tenant security assessment plan. The execution of such plan, the assessment process, should be conducted by a third party. Our framework helps in assessing security controls status when using security controls that integrate with our framework (the framework can understand and read their log files/database structure). The outcome of the assessment phase is a security assessment report. An example of the metrics to be used in assessing service security is shown in Figure 5-10 – e.g. in the last section "login activity" metric.

5.6.5 Service Authorization

Swinburne and Auckland give their formal acceptance of the security plan, assessment plan, and the assessment reports. This acceptance represents the authorization decision to use Galactic by the cloud consumers.

Measurement Name	Measurement Date	Measurement Value
LoginActivity	12/01/2011	8
LoginActivity	13/01/2011	10
LoginActivity	14/01/2011	14
UnsuccessfulLogins	10/01/2011	2
UnsuccessfulLogins	11/01/2011	4
UnsuccessfulLogins	12/01/2011	6
UnsuccessfulLogins	13/01/2011	8

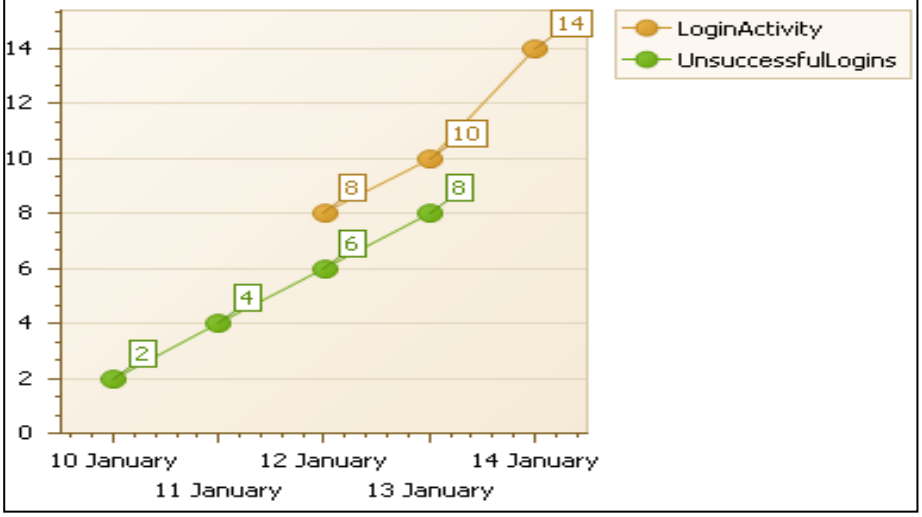


Figure 5-11. Sample of Swinburne security status report

5.6.6 Monitoring Security Controls Effectiveness

The framework collects the defined security metrics as per the assessment plan of each tenant and generates regular security status reports to the intended cloud stakeholders. A report shows the metrics status and trends, as shown in Figure 5-11. This report shows that the number of login activities is increasing which may be a reason for normal workload or malicious attacker trying to break the authentication service. The unsuccessful logins metric helps in deciding which scenario may be most likely to happen. In this case the unsuccessful logins metric is increasing as well which means that someone is trying to login to the system and does not have a correct password. The procedure we went through in the example above should be applied not only on cloud services but also on the cloud platform itself. In this case the cloud provider uses our framework to manage the platform security from a consumer perspective.

5.7 Discussion

Our approach provides a security management process; a set of security automation standards to help in automating the security management process; integration with known threats, vulnerabilities, and weakness databases; and a log-based security metrics monitoring and analysis tool. Our approach is based on joint-collaboration between all stakeholders, allowing different stakeholders to develop a mutually-satisfying security model. It addresses the multi-tenancy nature of shared cloud-hosted services when tenants have different security requirements and different SMPs. This is achieved by maintaining and managing multiple security profiles with multiple security controls on the same service. Such controls are delivered by different security vendors. This enables managing traceability between controls, the identified risks and identifies what are the risks still not mitigated.

Based on our proposed security management model, each cloud service has two possible scenarios: Either to let each tenant to go through the whole SMP as if she is the only user of the service (tenant-based SMP) or to accumulate all tenants' security requirements on a given service and maintain the security management process on the service level (service-based). The later scenario is more straight forward because cloud stakeholders collaborate together to secure the cloud platform and their services with one set of security requirements. The former scenario gives the service tenants more control in securing their cloud hosted asset but it has the following problems: (i) the current multi-tenancy feature delivered by the cloud services enables tenants to customize service functionality but it does not enable tenants to customize service security capabilities; (ii) the underlying cloud platform infrastructure, such as OS, does not support for multi-tenancy, so we cannot install multiple anti-viruses or anti-malware systems on the same OS while being able to configure each one to monitor specific memory process for a certain user. One solution may be to use a VM for each tenant as in [21]. This work around may not be applicable if the service is not designed for individual instances usage or if the cloud platform does not support VM technology.

Whenever the service tenants are not interested in following the security standards or require a light-weight version of our approach, they can just specify their service security categorization level. Based on this, the rest of the other activities will be completed using the default settings. Another variation of our framework is to enable cloud providers to deliver predefined security profiles to be applied on cloud services – i.e. a cloud service X is available with three different security profiles (low, medium, high). Thus, service tenants can select the suitable profile based on their security needs.

The key limitations of this version of the platform are: (i) lack of automated integration capability of security controls specified with the target cloud services (currently need to be done

manually). This issue is addressed in chapter (6) by our model-driven security engineering at runtime approach; (ii) although the platform do support service-level and tenant-level security, the current implementation of cloud applications (SaaS applications) only supports service-level security. This issue is addressed in chapter (6) as well; (iii) the service security analysis is currently done manually or using different existing tools. We introduce an automated, online, signature-based security analysis approach that can cover wide-range of attacks and extensible enough to address new attacks without a need for patches or customizations. This approach is introduced in chapter (8); (iv) The provided monitoring capabilities is based on security controls' log files. This leads to lagging metrics that need to wait until the situation occurs. We address this problem with a unified monitoring platform that is easy to extend to capture different types of security metrics. This issue is address in chapter (9).

5.8 Chapter Summary

In this chapter we introduced a novel alignment of the well-known NIST-FISMA security management standard to fit with the cloud computing model. Based on our alignment, we developed a collaboration-based security management framework for the cloud computing model. We utilize the existing security automation efforts such as CPE, CWE, CVE and CAPEC to facilitate the cloud services security management process (SMP). We have validated our framework by using it to model and secure a multi-tenant SaaS application with two different tenants. The framework can be used by cloud providers to manage their cloud platforms security, by cloud consumers to manage their cloud-hosted assets security, and as a security-as-a-service tool to help cloud consumers in outsourcing their internal SMP for hosting on cloud platforms. In the next chapters, we address the limitations (discussed above) of the solution we introduced in this chapter taking into consideration the multi-tenancy, automation, and extensibility of the task as much as possible.

Chapter 6
Cloud Applications Security Engineering

In the last chapter we introduced our proposed alignment, along with the prototype platform, of the NIST-FISMA standard with the cloud computing model. In this chapter, we address and mitigate two of the key limitations of this approach which are the lack of automated security controls integration, and lack of multi-tenancy support – i.e. getting cloud services to reflect different sets of security requirements for different tenants at runtime. We introduce our new security engineering approach to help in automating the integration of tenants' security needs with cloud services at runtime without getting software developers involved in realizing suh customizations. Our approach is based on modeling service description details (by the service provider) and security specification details (by service tenants). These models are then used to integrate and manage service security from the different tenants' perspective. This chapter is organised as follows. In Section 1 we give an overview of the problem and research questions we are trying to address along with a summary of the existing efforts. In Section 2 we summarize the key challenges and requirements that must be satisfied by a multi-tenant security engineering approach. Section 3 provides details of our model-driven security engineering at runtime approach (MDSE@R). Section 4 describes a usage example of our MDSE@R framework and toolset. Section 5 describes our platform architecture and implementation details. Section 6 presents evaluation results of MDSE@R. Section 7 discusses the key strengths and weaknesses of MDSE@R.

6.1 Introduction

Supporting multi-tenancy places more requirements on service providers. They now have to develop or reengineer their systems to support multi-tenancy and to ensure tenants' data isolation. Multi-tenancy also increases service tenants' concerns about the security of their outsourced, cloud-hosted assets that are now shared with other tenants – who may be either competitors or malicious users. In addition, the range of actual SaaS tenants usually becomes known only after applications have been delivered and thus the range of service tenants is highly dynamic. Tenants may register and unregister from the service at runtime. Service tenants often have different security requirements that evolve at runtime based on their current business objectives and security risks. Existing application security models poorly fit with this dynamic, run-time evolving model as they focus mainly on design time security engineering.

Service providers are in bad need of a new security engineering approach that addresses these challenges.

Existing traditional security engineering approaches, such as KAoS [16, 228], Secure i* [126], and Secure TROPOS [128, 130] focus on identifying, capturing, and modelling security objectives and requirements at requirements elicitation time. Others including UMLsec [14, 134], secureUML [15] focus on mapping these security requirements onto application design entities (classes, methods, interactions) at design time. These security engineering approaches typically result in: applications with fixed security as it is based on one set of predefined security requirements; built-in security as it is usually integrated with system design which means that security related code will be mixed with system code; limited integration with third party security controls because they most of the time are not considered at design time; and very limited flexibility in terms of adaptation and integration with the security management systems operating in the software target operational environment because such environments are usually not known at design time. Moreover, most of such approaches do not support changing application security at runtime to address new unanticipated security risks or new tenant security needs. From the cloud computing and multi-tenancy perspective, these approaches could help in solving the tenants' data isolation problem (i.e. how to prevent tenants from accessing other tenants' data). However, such efforts are not extensible to support different tenants' security engineering – i.e. how to capture and enforce different tenants' security requirements at runtime.

Adaptive security engineering has been investigated in [19, 146, 229]. However most focus on low-level details or limited to specific security properties – e.g. adaptive architecture-level access control mechanism [20]. These efforts require preparing applications at design time to support runtime adaptation. Thus, these efforts cannot be readily adapted to deliver multi-tenant SaaS applications' security engineering. In addition, their actual run-time re-configuration capabilities are still limited.

New research efforts in securing multi-tenant SaaS applications have focused on: (re)engineering multi-tenant SaaS applications to extend their security capabilities – e.g. authentication, authorization, and encryption [22, 153, 230, 231]; maintaining isolation between different tenants' data [155, 223, 232]; and developing security controls and architectures that deliver SaaS application security (e.g. access control) taking into account multi-tenancy [26, 233-235]. Most of those efforts depend on or still lead to built-in, or predefined, security architectures for SaaS applications. Thus, tackling the loss of control concerns raised by cloud consumers - i.e. capturing and enforcing tenants' security requirements

and integration of SaaS applications with tenants' security infrastructure – have not been addressed before.

Two key research gaps in the multi-tenant applications' security engineering area are lack of adaptable security support and lack of multi-tenant security support – i.e. to support capturing and enforcing different tenants' security requirements at runtime without a need to conduct application or service maintenance. We capture these gaps in the following research questions that we address by our new MDSE@R approach explained in this chapter:

- How can we effectively capture important details about different services at different levels of abstraction? And how to make it available for tenants to add their security requirements?
- How can we capture different tenants' security requirements for different service entities at different levels of abstraction?
- How can we enforce these different sets of security requirements for different tenants' on any arbitrary application or service entity at runtime?
- How can we verify that critical entities correctly enforce specified security needs?
- How can all of these tasks be achieved dynamically and at runtime without a need for frequent service code customization?

In this chapter, we introduce our novel approach called MDSE@R (Model-Driven Security Engineering at Runtime) for multi-tenant cloud-based applications. MDSE@R supports capturing, enforcing, and verifying different tenants' and service providers' security requirements at runtime without a need to modify or customize the underlying application or service – i.e. it works with both existing and new SaaS applications. Our approach is based on enabling cloud application security engineering to be conducted at runtime instead of at design time. This is facilitated by externalizing security from the target applications and services. Thus both application and security can evolve at runtime. On the other hand, we automate the integration of security requirements and controls within any service entity that is marked as security critical. The list of critical service entities emerges at runtime based on tenants' current security risks and security requirements.

When using MDSE@R, service providers have to deliver a service description model (SDM) as a part of each application or service delivery package. The SDM is a mega-model (a model that contains a set of models and a set of relations between these models [236]) that contains details of the application or service features, architecture, classes, etc. Furthermore, they deliver a security specification model (SSM). The SSM is a mega-model that contains details of the security they already deliver and enforce on application entities (features, components, etc.). Security controls are not built into the developed application. They rather are implemented and deployed externally and weaved with the secured application and service entities at runtime.

Thus such controls can be modified, updated, or disabled at runtime without modifying the target application. Moreover, different sets of these security controls can be enforced at runtime by different tenants and on different services. For applications with built-in security we have introduced a quick security retrofitting approach discussed in Chapter 7.

During the provisioning of a new tenant, the service provider either creates an instance of the cloud application or configures a shared instance to disable or enable certain features for the new tenant. They also have to create a copy of the service description and service security models for the new tenant. Tenant service description model (TSDM) is a copy of the SDM updated with tenant procured features. Tenants can specify their security details using their copy of the SSM. This copy is called the tenant security specification model (TSSM). Tenants can add new security controls or disable/replace/modify the existing security controls (these modifications are also modelled at runtime). These updates are automatically reflected on the target application or service using MDSE@R. The service provider can specify certain security controls as mandatory. This means that such controls cannot be disabled or modified by the application or service tenants. This is very important in enforcing, for example, security isolation controls. Getting tenants involved in managing their assets' security helps in reducing the lack-of-trust and mitigating the loss-of-control problem. We have validated our approach on a set of significant open source benchmark applications. We have conducted a security adaption evaluation, performance evaluation and user evaluation of our approach and prototype platform. These are described later in this chapter.

6.2 Key Requirements and Challenges

The analysis of the motivating scenario in Chapter 1 and details of the existing efforts discussed above identifies the following challenges: (i) Security requirements differ from one tenant to another; Each tenant's security requirements may change over time based on current operational environment security and business objectives; (ii) Overall application security should support integration with each tenant's security controls in order to achieve coherent security solutions; and (iii) New security vulnerabilities may be discovered in a SaaS application at any point in time. These vulnerabilities need to be patched as soon as possible to prevent attacks that can exploit such vulnerabilities.

Using traditional security engineering techniques would require the application provider to conduct a lot of application maintenance to deliver application patches that block vulnerabilities and adapt the application to every new customer's needs. Multiple versions of the application, one for each tenant and with substantial differing security enforcement embedded in the application, would have to be maintained.

A new security engineering approach that addresses these challenges is needed. Such a security engineering approach should: (i) Enable each tenant to specify and enforce their own security requirements based on their current security needs; (ii) Security should be applied to any arbitrary application or service entity. No predefined application or service security interception points should be specified at design time. This means that it should support interception of calls to any service method once declared as critical; (iii) Security specification should be supported at different levels of abstraction based on the customers' experience, scale and engineers' capabilities; and (iv) Integration of security with application or service entities should be supported at different levels of granularity, from the application as one unit to a specific application method. Integration should be supported with third-party security controls. This should support the application or service and security specifications to be reconfigured at both design time and runtime.

6.3 MDSE@R

MDSE@R approach enables service tenants to be involved in securing their cloud hosted assets. This helps in mitigating the loss-of-control problem arises from the adoption of cloud services. As a consequence of getting tenants involved, a single service instance must support capturing and enforcing different sets of security requirements for different tenants as they become known and as they evolve at runtime. We name this model "tenant-oriented security", compared to the traditional model of "service-oriented security" where a service instance reflects only one set of security controls captured by the service provider at design time. Tenant-oriented security may require integrating cloud services with security controls deployed on or out of the cloud platform. MDSE@R is based on two key concepts: externalizing security management and enforcement tasks from the application or service to be secured while being able to wrap the application or service and intercept calls to any arbitrary critical application or service entity at runtime using dynamic weaving AOP; and Model-Driven Engineering (MDE), using Domain-Specific Visual Language (DSVL) models to capture application or service security properties at different levels of abstraction. Moreover, we automate the generation of security controls' integration code rather than hand-coding of bespoke solutions.

Figure 6-1 shows the basic flow of MDSE@R to support multi-tenant security engineering. Service providers develop a detailed service description model (SDM). Then, they develop a security specification model (SSM) capturing all security details that they deliver in their cloud services. Once a service tenant registers to use the service, they will get a copy of the service SDM and SSM. Tenants can then use these models to manage their instances and develop their

security needs. At the same time, service providers can use service SDM and SSM models to update and manage service security.

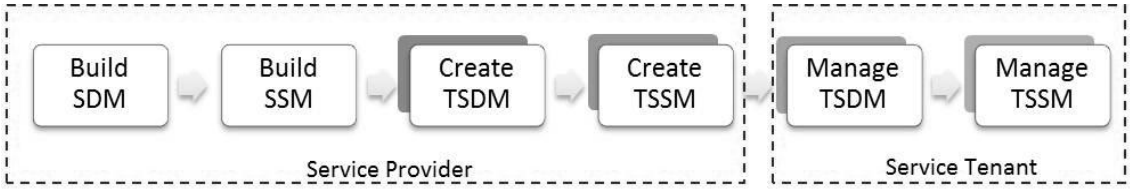


Figure 6-1. Process flow of MDSE@R

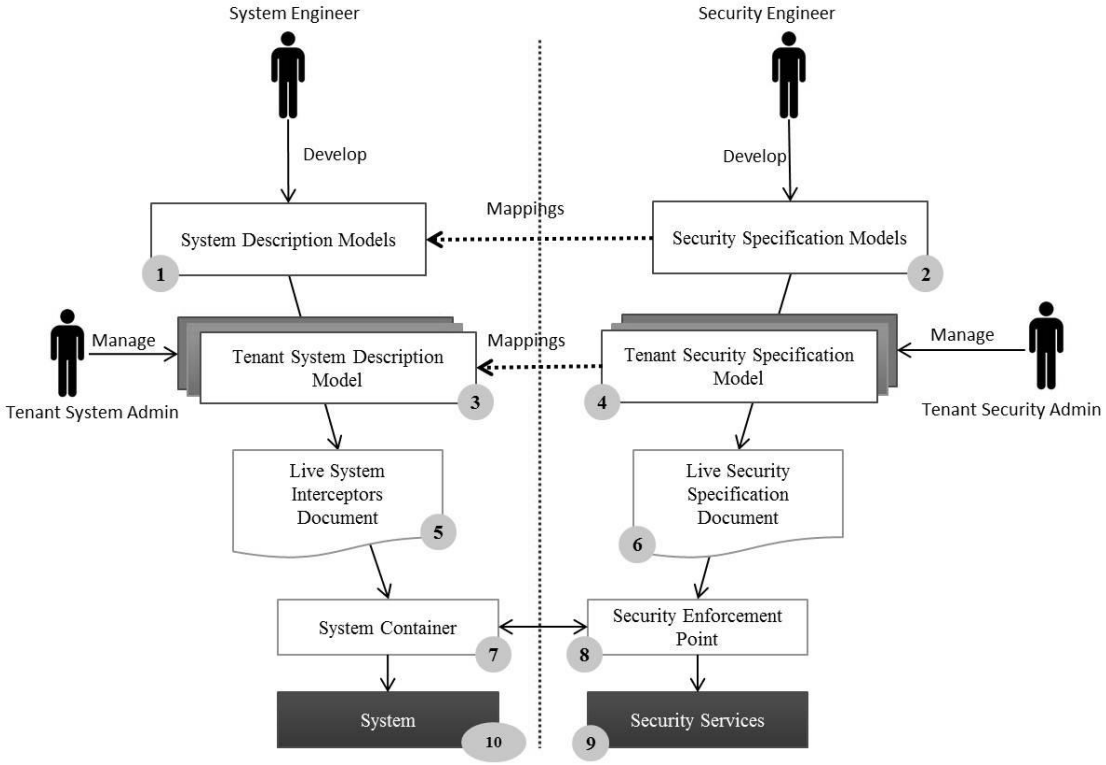


Figure 6-2. Overview of MDSE@R approach

Figure 6-2 gives an overview of the MDSE@R approach to support multi-tenant security engineering and tenants' security management at runtime. After capturing application and security models (steps 1 and 2), tenants application instances and their security details (steps 3 and 4) and mapping security details on system details, the MDSE@R platform realizes such modelled changes using interceptors and dynamic aspect-oriented programming approach (steps 5, 6, 7, and 8) that injects security handlers into the target application entities (components, classes, and methods) to be secured using tenants' specified security controls as we discuss below.

6.3.1 Modeling Service and Security Details

In this phase, stakeholders from both the service providers and tenants develop different models capturing details of the service, tenant instance, service security, and tenants' security.

6.3.1.1 Service Description Model (SDM)

A detailed service description model (SDM) is delivered by the service provider (a detailed example is introduced in the usage example section) as a part of the service delivery package which also contains service binaries and any other deployment packages. The SDM captures various details of the target application or service including system features (we use a simplified version of the UML use case diagram to capture system features), system architecture (using UML component diagrams), system classes (using UML class diagrams), system behaviour (using UML sequence diagrams), and system deployment (using UML deployment diagrams). These models cover most of the perspectives that may be required in securing a given system. These models are usually developed during system development stage. Not all these models are mandatory. Cloud stakeholders may need to specify security on system entities (using system components and/or classes models), on system status (using system behaviour model), on hosting nodes (using system deployment model), or on external system interactions (using system context model). Moreover, they may specify their security requirements on a coarse-grained level (using system features and components models), or on a fine-grain (using system class diagrams). Maintaining service SDM synchronized and up to date with the running service instance may introduce overhead and headache on service providers. However, recent efforts in models@runtime synchronization techniques [236, 237] help in maintaining SDM consistent with service instance. Some of the application or service description details, specifically the system class diagrams, can be reverse-engineered if not available from the target application or service binaries or even from the service source code. We developed a new UML profile to extend UML models used in the SDM with necessary attributes that help in: Capturing relations between different system entities in different models – e.g. a feature entity in the service features model with its related components in the service component model, and a service component entity with its related classes in the class diagram. This part of the profile helps in propagating security modelled and mapped a at coarse-grain level to system and security lower entities; and Capturing security concepts/attributes (security objectives, requirements, controls, etc.) mapped to the SDM entities – e.g. what security requirements specified on a given service feature or service component. This helps in security enforcement and models weaving as we discuss later.

6.3.1.2 Service Security Specification Model (SSM)

A second part of the service delivery package is the service security specification model. The SSM is a set of models developed and managed by the service provider security engineers to specify the security requirements or controls that the service providers enforce and operate on their services (a detailed example is introduced in the usage example section). It provides the details required during the security engineering process including: security goals and objectives; security risks and threats; security requirements; security architecture for the operational environment; and security controls to be enforced. These models capture different levels of abstractions. The key mandatory model in the security specification models set is the security controls model. It is required in generating the security integration code.

6.3.1.3 Tenant Service Description Model (TSDM)

The TSDM model describes system features, architecture and classes available for a tenant T. It is usually different from one tenant to another. It depends on the multi-tenancy model adopted by the service provider in customizing tenant instance or configuring a single shared service instance. At tenant provisioning time, an initial TSDM is copied from the system SDM. Then the TSDM is updated to reflect the current tenant's service instance details. The tenant system administrator can use this model later to turn features on/off at runtime. The TSDM helps in two scenarios: To customize or configure the system based on tenant requirements – e.g. tenant T is permitted to use certain features that she registered for. The service provider uses the tenant initial TSDM and delete other system features that are not required. The same approach can be used in both cases either the tenant has a separate instance or share the same instance with other tenants. Still the model@runtime synchronization techniques can be used to keep the TSDM synchronized with the running tenant instance; and to capture tenants' security requirements on their instance scope – i.e. security to be applied on instance features, components, methods, etc.

6.3.1.4 Tenant Security Specification Model (TSSM)

The TSSM model is the tenant copy of the service SSM, an example is shown in Figure 6-10 (details are explained in the usage example). It describes security objectives, requirements, architecture, design, and controls that the service tenants have and want to enforce on their cloud-hosted assets. This may include authentication, authorization controls, auditing, encryption, etc. that tenants use in their internal sites or even from other security vendors. Tenants may decide to continue using the same security provided by the service provider or rather prefer to use their security controls. However, tenants will not be able to disable security controls that the service provider has marked as mandatory in the service SSM. This helps to avoid disabling critical security controls such as tenants' data isolation control provided by the

service provider. This model can be used by tenants to manage security of multiple cloud-hosted applications – i.e. to provide a single security model to manage all enterprise outsourced services.

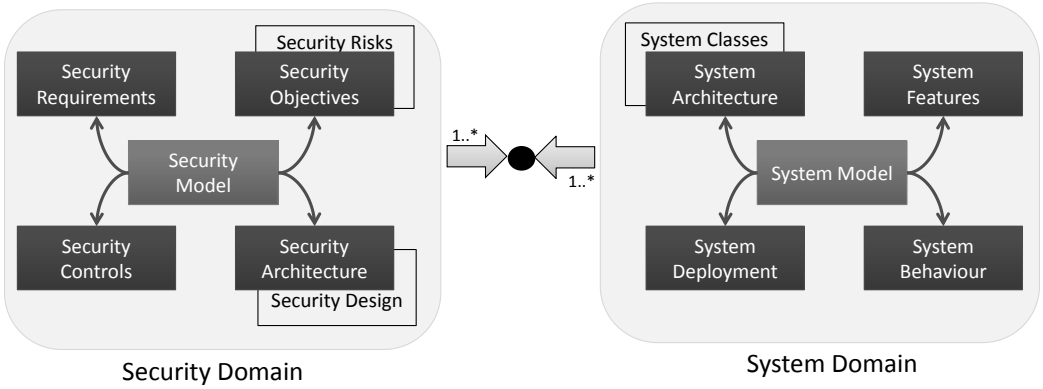


Figure 6-3. Possible service-security models weaving

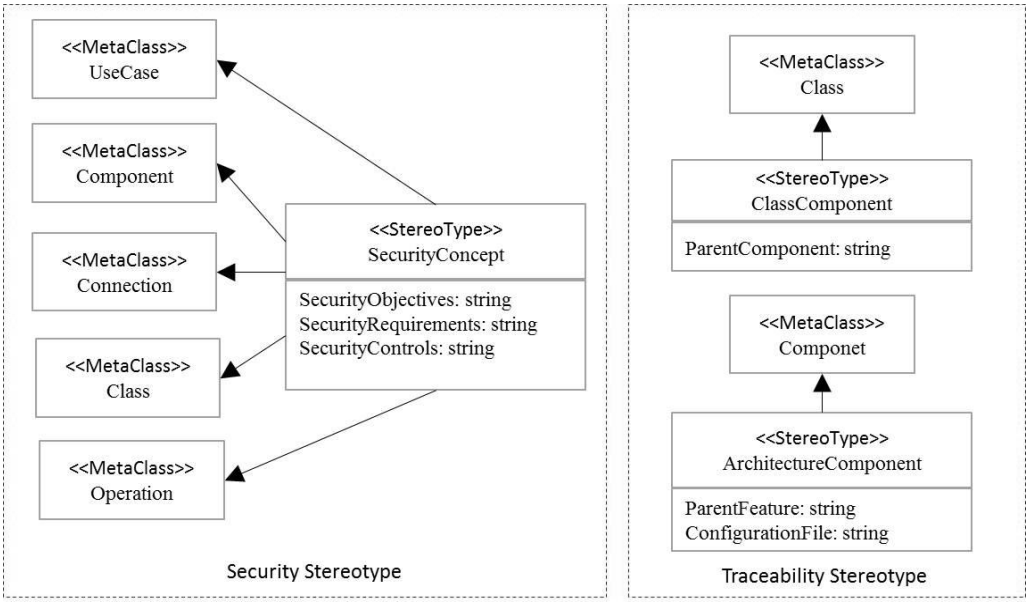


Figure 6-4. Our new UML profile

6.3.2 Weaving Service and Security Models

MDSE@R has two mapping levels: Mapping service SSM model entities to service SDM model entities; and Mapping service TSSM model entities to service TSDM model entities. The first type of mapping is developed and managed by the service provider at design time, deployment time, or even at runtime to reflect new needs. Whenever the service provider discovers a security problem – such as a new vulnerability, or has a new security requirement – they can update or mitigate it on the service security specification model and then map these new updates on the service description model. Such mapping is directly reflected on the tenants'

models. The second mapping type is developed and managed by the service tenant at runtime. Both mappings can be modified at runtime to reflect new security needs or business objectives.

MDSE@R supports many-to-many mapping between the (tenant) service description model entities and (tenant) security specification model (SSM) entities, as shown in Figure 6-3. This is supported by our UML profile which extends every service description concept – i.e. feature, component, class, method, host, connection, etc. with a set of security attributes – i.e. security objectives, requirements, services and controls (see Figure 6-4 for UML profile diagram, details are available in the implementation section). Using drag-and-drop between the SSM and SDM entities, SSM entity will be added as an attribute value, based on the dragged SSM entity, to the selected SDM entity – i.e. if the tenant drag an authentication security control and drop it on a system class, this means that all the methods in this class must use this authentication security control. One or more security entities (security objective, requirement and/or control) can be mapped to one or more service model entity (feature, component, class or method). Mapping a security concept on an abstract service entity – e.g. a system feature – implies a delegation of the same security concept to the concrete entities e.g. the feature realization classes and methods. This is facilitated using our UML profile which helps in managing traceability between application and service entities. Moreover, mapping an abstract security concept – e.g. a security objective to a service entity - e.g. a class - implies mapping all security requirements, services, and controls that realize this security objective to that class and its methods. Any application or service entity that has a security mapping is called a critical service entity.

6.3.3 Enforcing Specified Security on Target Application Entities

In the previous steps, both security details and critical application or service entities emerge at runtime. MDSE@R automates the realization task of the specified security requirements on critical application or service entities without the involvement of security or application engineers. This helps both parties to easily update their application and security capabilities to meet their needs. Moreover, this helps avoiding inconsistency problem that arise from updating application security realizations without reflecting updates on application and security models. Whenever the service provider or service tenant develops a new mapping or updates an existing mapping between an SSM entity and an SDM entity, the underlying MDSE@R platform propagates these changes as discussed below.

6.3.3.1 Update Live Service Interceptors' Document

This document maintains a list of the application security critical entities (CP - an application or service entity that has security attributes mapped on it) where security controls should be

weaved or integrated. Equation 1 states that the critical service entities - CP(s) - are the union of all tenants' critical points - CP (T_i) – where T_0 is the service provider.

$$CP(s) = \bigcup_{i=0}^{n} CP(Ti) \qquad \text{Equation 1}$$

6.3.3.2 Update Live Security Specification Document

This document maintains a list of security controls to be applied at every critical system entity. This may be defined by the service provider or by the service tenant. The service provider can mark security controls as mandatory. This means that these security controls cannot be weaved or replaced by other stakeholders. Service tenants can see such controls and where they are applies – as a part of our solution of the "lack of trust" problem. These security controls must be applied first before other stakeholders' security controls.

6.3.3.3 Update Tenant Accessible Resources Document

This document maintains a list of system resources that should not be accessible for each tenant. For example, in our Galactic scenario if Swinburne did not buy the Customer Management module then they should not be able to access webpages or functionalities provided in this module. Equation 2 is used in specifying tenant T_i inaccessible resources. The prohibited resources list for tenant T_i is the difference between the service SDM resources and the tenant T_i TSDM resources.

$$PR(Ti) = R(SDM) - TSDM(Ti) \qquad \text{Equation 2}$$

This list of tenant's prohibited resources is used by the MDSE@R to deny access to any of such resources by a request submitted by one of the tenant's users. The application or service is now ready to enforce security specified by tenants and service providers based on the woven secure-service model. This update is conducted in parallel with the application or service operation. Thus it does not incur any further performance overhead – i.e. we do not need to take the application offline in order to update system security.

6.3.3.4 Update the System Container

The system container is responsible for intercepting system calls to critical system entities at runtime and delegating such requests to a default request handler "Security Enforcement Point". The system container is updated with critical entities (CPs) from the live service interceptors' document. It is also updated with entities in the prohibited resources list. For the later one, it simply denies requests to such service resources.

```
1  public interface SecurityStandardInterfaceAuthentication
2  {
3      //Authentication
4      public string[] AuthenitcateUser();
5      public bool IsAuthenitcated(object subject);
6  }
7  public interface SecurityStandardInterfaceAuthorization
8  {
9      //Authorization
10     public string[] AuthorizeUser(object subject);
11     public bool IsAuthorized(object subject, object action,
12             object resource, string context);
13 }
14
15 public interface SecurityStandardInterfaceCryptography
16 {
17     //Cryptography
18     public string Hash(string plaintext);
19     public string Encrypt(string plaintext);
20     public string Decrypt(string ciphertext);
21     public string DigitalSign(string data);
22     public bool VerifySignature(string signature, string data);
23 }
24 public interface SecurityStandardInterfaceEncoding
25 {
26     //Encoding
27     public string Encode(string input);
28     public void AddCSRFToken();
29
30 public interface SecurityStandardInterfaceLogging
31 {
32     //Logging
33     public void Log(int type, string message);
34 }
35 public interface SecurityStandardInterfaceInputValidation
36 {
37     //Input Validation
38     public bool IsValid(string ruleName, string input)
39 }
```

Figure 6-5. Our proposed common security interface

```
[Test]
public void AuthorizeGetCustomersTesting()  {
   CustomerBLL  obj = new CustomerBLL();
   GenericPrincipal testIdentity =
                    new GenericPrincipal(new GenericIdentity("TestIdentity"),
                                         new string[] { "TestRole" });
   try {
          obj.GetCustomers();
       }
   catch(Exception ex) {
          Assert.Fail("Firing of AuthorizeGetCustomersTesting test case failed");
   }
   Assert.AreNotEqual(testIdentity, System.Threading.Thread.CurrentPrincipal,
                 " LDAP Authorization Control is not correctly plugged-in", null);
}
```

Figure 6-6. Example of the generated security integration test cases

6.3.3.5 Security Enforcement Point – SEP

A key objective of MDSE@R is to avoid being tightly coupled with specific security controls, specific security vendor, and specific security platform (Java security manager, spring acegi framework, Microsoft Windows Identity Foundations, etc.). It also aims to keep developers and administrators from being too deeply involved in integrating security controls with a target system that often results in inconsistent security being enforced on different systems. We have developed a common security interface for every security attribute (authentication, authorization, auditing, encryption, etc). This interface, shown in Figure 6-5, specifies interface functions and signatures that each security control expects/requires in order to perform their tasks – e.g. AuthenitcateUser function should authenticate the user and return the set of claims including user identity, credentials, roles, and permissions. A security or service vendor must implement this interface in their connector or adapter to support integration with MDSE@R. The sequence of calling/executing these methods is controlled by the SEP and depends on security attributes mapped on the critical point being intercepted. This helps security vendors develop one connector that - using MDSE@R - can be integrated with all target applications/services.

So far we have prepared the system to intercept requests to critical methods via the system container and have prepared security controls to be communicated using the common security interface. The SEP works as a bridge between the system container and the deployed security controls. SEP queries the security specification document for controls to enforce at every intercepted request. It then initiates calls (using the security interface) to the designated security controls' clients or connectors. Moreover, the SEP assigns results returned by such controls to the system context e.g. an authentication control returns userID of the requesting user after being authenticated. The SEP creates an Identity object from this userID and assigns it to the current thread' user identity attribute. Thus a secured application can work normally as if it has authenticated the user by itself. An application may use such information in its operations e.g. to insert a record in the database, it uses the user identity to set the "enteredBy" database field.

6.3.4 Testing the Service-Security Integration

Before allowing the developed specifications and mappings to be applied to live cloud services, MDSE@R conducts security testing to verify that the target service is correctly enforcing the tenants and service providers' specified security needs. We assume that the reused security controls are already tested by the security vendors. Thus, our testing task focuses on verifying that the security controls are now being correctly integrated within specified critical system entities as required. To automate this step, we use the live interceptors' document and the

security specification document to generate a set of test cases (scripts) for each critical entity – i.e. each critical entity will have a set of test cases according to the security specified on it (from the security specification document). Each test case verifies that a security control **C** is correctly integrated within the critical entity **E**. An example is shown in Figure 6-6. As this figure shows, we have GetCustomers method of the CustomerBLL class is marked as a critical point. This critical point has a set of security controls mapped on it including authorize users before executing this method. Thus, the security testing service generates a test case that calls this method and check the resultant system security context (after calls - actual results) against the expected results. In the backend, the SEP is converted in debug mode which let the SEP to raise exceptions if a security control call failed. The testing framework (we use the nUnit framework, discussed in the implementation section) fires these test cases and generates a log of the test cases' firing results to the tenant/service provider security engineers showing the failed test cases, the critical entities, and the failed to integrate security controls.

Figure 6-6 shows a sequence diagram describing a user requesting resource X, from a service operated by MDSE@R. In this scenario we have several interacting entities including user, webserver, MDSE@R system container, SEP, security services and the application resource. Once the web server receives a request (1) submitted by a user to access resource X, it delegates the request to the system container (2) along with the user's tenantID T. The system container queries the live service interceptors' document (3) to decide if the resource requested is marked as "critical" or not either by the tenant or by the service provider. If the resource is critical (4), the system container delegates the request to the security enforcement point (5). The SEP queries the security specification document (6) for the required security controls to be enforced on the requested resource by the user's tenant or by the service provider. This is an ordered list of security controls to be activated by the SEP. The SEP loops through the retrieved security controls list. Using the standard security interface, the SEP generates requests to the security controls required according to their type (7). After each security control call, the SEP updates the current threat security context (8). This includes update the execution context with current user identity, set of claims and roles. Finally, the SEP returns to the system container a recommendation to either proceed with the request or to deny it. If appropriate, the system container then forwards the request to the target resource (9) or else returns an appropriate security exception to the caller. If the tenant defined security properties or controls to be applied on system responses – e.g. to encrypt the response body, the system container intercepts such responses, applies security controls (through the SEP), and then forward the updated response back to the client.

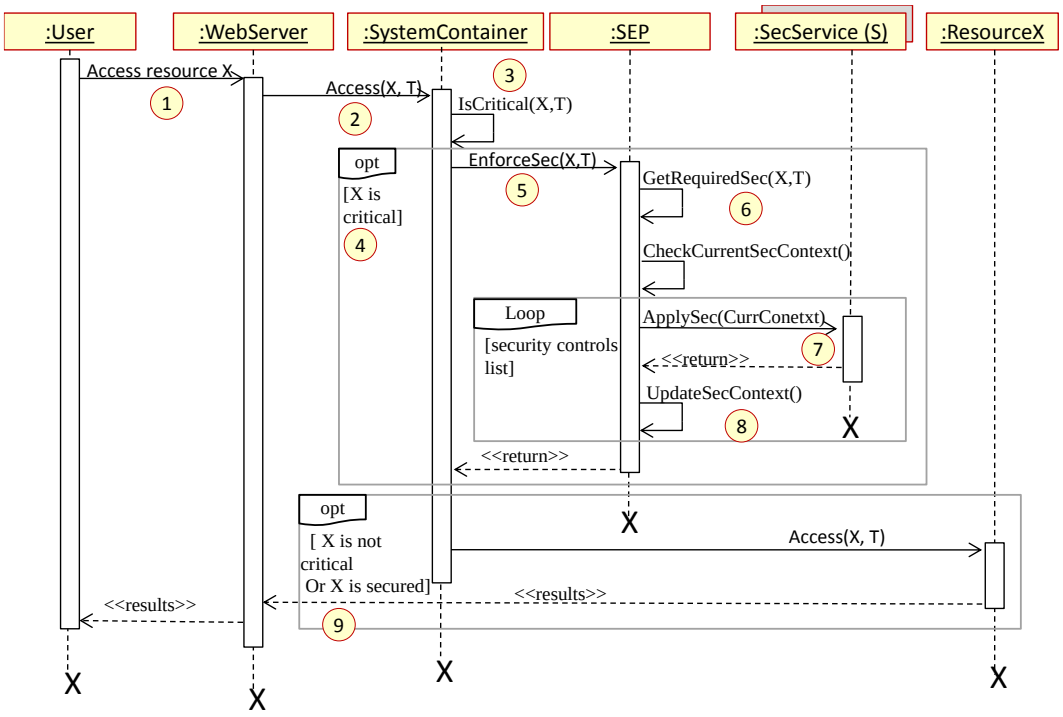


Figure 6-7. Sequence diagram of a user request to critical service entity

6.4 Usage Example

We introduce a usage example to show how the service provider and tenants can collaborate together using MDSE@R and its provided platform toolsets to manage security of their services at runtime. Moreover, we highlight the key stakeholders involved in the security engineering process along with their responsibilities and expected outcomes of every step. We use our motivating example discussed in details in chapter 1, the Galactic application developed by SwinSoft and procured by Swinburne and Auckland. SwinSoft wants to adapt its application security at runtime to block security holes and vulnerabilities that have been discovered at runtime. Moreover, two tenants (Swinburne and Auckland) using Galactic are worried about the security of their assets and have their own, different security requirements to be enforced on their Galactic ERP application instance(s). We illustrate our usage example using toolset screen dumps.

6.4.1 Model Galactic System Description

This task is done during or after the system is developed. SwinSoft, the service provider, decides the level of application details to provide to their tenants in Galactic SDM. Figure 6-8(a) shows that SwinSoft SDM captures the description of system features including customer, employee and order management features (Figure 6-8(a)), system architecture details

including presentation, business and data access layers (Figure 6-8(b)), system classes including CustomerBLL, OrderBLL, EmployeeBLL (Figure 6-8(c)), and system deployment including web server, application server, and database server (Figure 6-8(d)). SwinSoft uses our UML profile (Figure 6-4) to capture dependences and relationships between system features and components, and system components/classes. This model will be used as a reference by SwinSoft system and security engineers. No tenant is allowed to have write access to the Galactic SDM or its details.

6.4.2 Model SwinSoft Security

This task is conducted by SwinSoft (the service provider) security engineers at the system deployment phase. This model is usually updated during their recurring security management process to reflect new risks. In this scenario, SwinSoft security engineers document SwinSoft security objectives that must be satisfied by Galactic system (Figure 6-9(A)). It includes system availability, data integrity, accountability objectives. This model is revised frequently to incorporate emerging changes in SwinSoft security objectives. Security engineers then use this model as a reference in developing system security requirements. They refine these security objectives in terms of security requirements that must be implemented by Galactic system, developing a security requirements model.

Figure 6-9(B) shows a part of the security requirements model focusing on AuthenticateUser as a security requirement identified as a refinement of the data confidentiality and integrity security objectives. The security requirements model keeps track of the security requirements and their links back to the high level security objectives. SwinSoft security engineers next develop a detailed security architecture including services and security mechanisms to be used in securing Galactic.

Figure 6-9(C) shows the main security zones (represent as big boxes - containers) that cover Galactic deployment environment including security management zone, web servers' zone, and enterprise network zone. A network zone means that there is a firewall with an intrusion prevention system deployed. It also shows the allocation of IT systems, including Galactic in these zones. The security architecture also shows the security services, security mechanisms and standards that should be deployed. SwinSoft security engineers finally specify the security controls (i.e. the real implementations) for the security services modelled in the security architecture model.

Figure 6-9(D) shows the key security controls selected by security engineers as a realization of their security requirements. This includes SwinValidator as an input validation control, ESAPI.AccessController as an authorization control, and SecurityIsolator as a multi-tenancy

isolation and access controller security control. Each security control entity defined in the security controls model specifies its family including authentication, authorization, audit, cryptography, and audit. This helps in deciding the suitable API interface to be called in order to use this control. It also helps in sequencing (ordering) the requests to be issued by the SEP to secure a given system critical point. Each security control should define the deployment URL of its connector. This is also required by the SEP when issuing requests to such controls. Each security specification model maintains traceability information to parent model entities.

Figure 6-9(E) shows mappings specified between security entities and system entities. In this example we specify that SecurityIsolator realizes the "TenantsDataIsolation" requirement. Whenever MDSE@R finds a system entity with a mapped security requirement TenantsDataIsolation it adds SecurityIsolator as its realization control – i.e. an SecurityIsolator check will run before the entity is accessed e.g. before a method is called or a module is loaded. SwinSoft security engineers have to mark mandatory security controls that their tenants cannot modify or disable.

6.4.3 Weave Galactic SDM and Security SSM

After SwinSoft system and security engineers have completed the development of Galactic SDM and security SSM, SwinSoft security engineers should specify/map security attributes (in terms of objectives, requirements and controls) on Galactic system specification details (in terms of features, components, classes). This is achieved by drag and drop of security attributes on system entities. Thus, system features, structure, and behaviour can dynamically and at runtime reflect different levels of security based on the currently mapped security attributes on it. Figure 6-9(E) shows a part of Galactic component diagram where PresentationLayer, a UML component entity, is extended with security objectives, requirements and controls compartments. In this example the security engineers have specified TenantsDataIsolation as one of the security requirement to be enforced on the PresentationLayer component (1). Such a requirement is achieved indirectly using SecurityIsolator control (2). MDSE@R uses the security attributes mapped to system entities to generate the full set of methods' call interceptors, as in Figure 6-11(1) (system interceptors document), and application or service entities' required security controls, as in Figure 6-11(2) (security specification document).

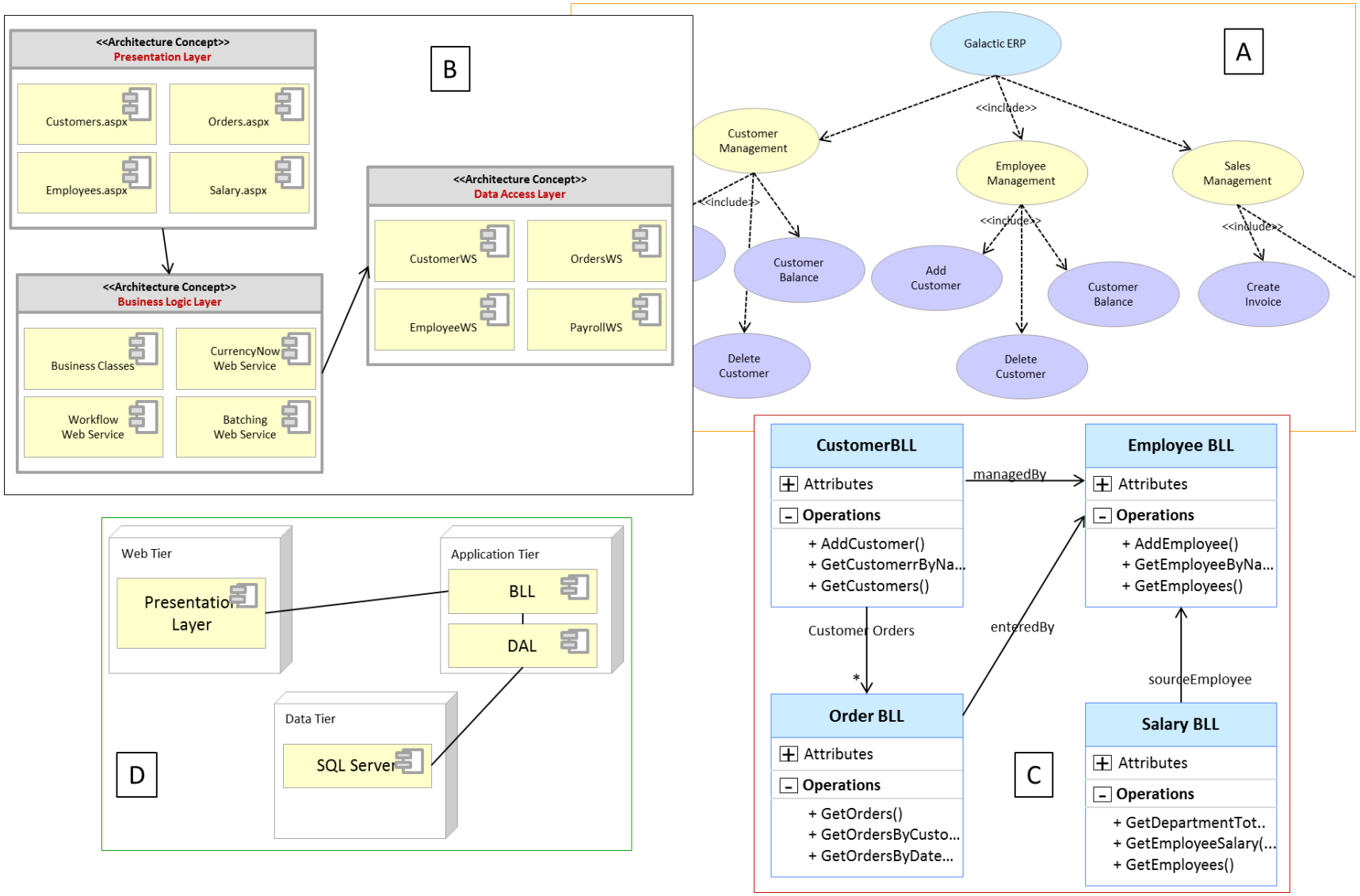


Figure 6-8. Galactic service description model (SDM)

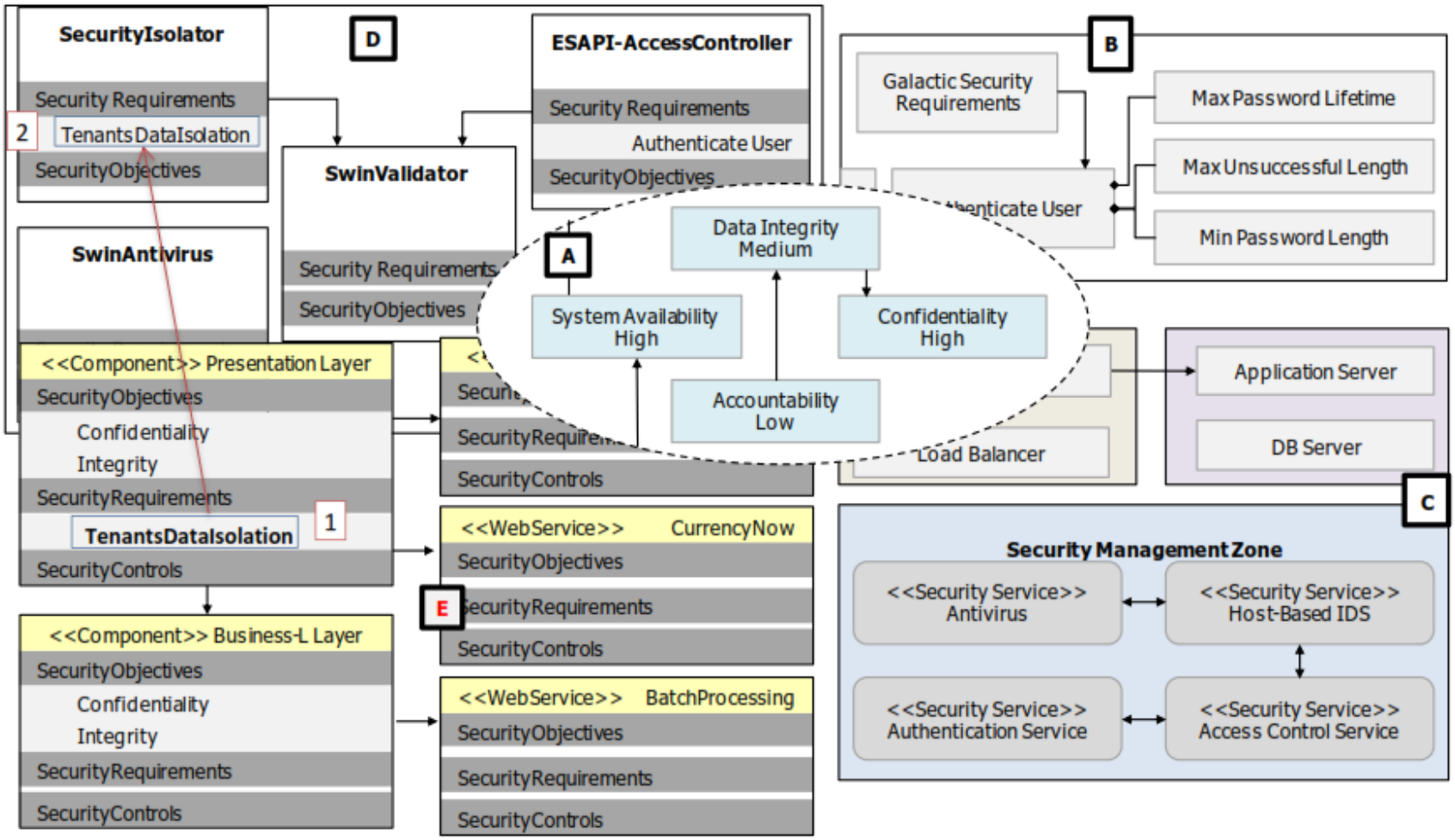


Figure 6-9. Galactic service security specification model (SSM)

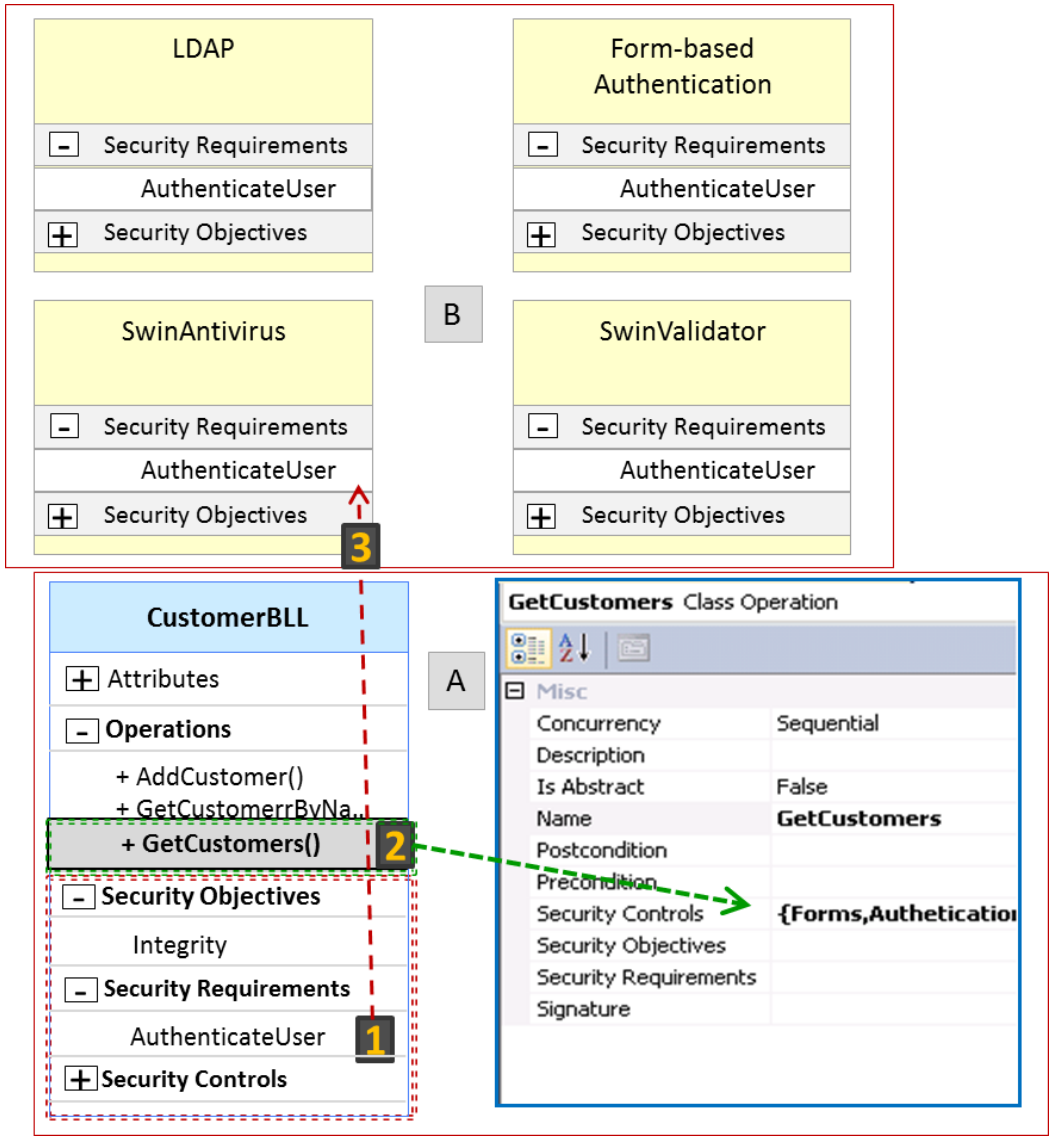


Figure 6-10. Swinburne security specification model

A

```
. . .
<extension type="Interception" />
 <register type="PresentationLayer.CustomerBLL, PresentationLayer ">
  . . .
  <interception>
   <policy name="PolicyCustomersBLL">
    <matchingRule name="MatchingRuleCustomersBLL“ Type="MemberNameMatchingRule">
     <constructor>
     <param name="nameToMatch" value="GetCustomers" />
     <param name="nameToMatch" value="GetCustomerByName" />
     <callHandler name="callhandlerCustBLL“ type="SecurityCallHandler, SecurityKernel">
. . .
```

B

```
<systemlevel>
<componentlevel>
. . .
<classlevel>

  <objectname>
  . . .
<methodlevel>
 . . .
< ObjectName> GetCustomers </ObjectName>
  <Authentication_Method>Forms</Authentication_Method>
  <Authorization_Method>RBAC_Impersonate</Authorization_Method>
 . . .
```

Figure 6-11. Examples of the interceptors and security specification files

```
public IMethodReturn Invoke( IMethodInvocation input, GetNextHandlerDelegate getNext)   {
       EntitySecurity entity = LoadMethodSecurityAttributes(input.MethodName);
       if (entity == null || entity.HasSecurityRequirements() == false) {
              return getNext().Invoke(input, getNext);
       }
      //Check for logging
      if (entity.GetLoggingMethod() != LoggingMethod.None) {
            SecurityInterfaceLogging obj = new Type.GetType(entity. entity.GetInputValidationMethod());
             obj.Log(Datetime.Now, input.Method.MethodName);
      }
      //Check for Input Validation
       if ( entity.GetInputValidationMethod() != InputValidationMethod.None )  {
            SecurityInterfaceInputValidation obj = new Type.GetType(entity.GetInputValidationMethod());
       }
      //Check for Authentication
       if (entity.GetAuthenticationMethod() != AuthenticationMethod.None) {
         if(CurrentThread.CurrentPrincipal == null) {
              SecurityInterfaceInputValidation obj = new Type.GetType(entity.GetAuthenticationMethod());
              obj.AuthenitcateUser();
          }
       }
       //Check for Authorization
       if ( entity.GetAuthorizationMethod() != AuthorizationMethod.None )  {
            . . .
       }
}
```

Figure 6-12. Code snippet from MDSE@R security enforcement point

Once security has been specified and interceptors and configurations generated, MDSE@R verifies that the system is correctly enforcing security as specified. MDSE@R generates and fires a set of required security integration test cases. Our test case generator uses the system interceptors and security specification documents to generate a set of test cases for each method listed in the interception document. An example of a generated test case is shown in Figure 6-6. This contains a set of security assertions (one for each security attribute specified on a given system entity). During the firing phase, the security enforcement point is instrumented with logging transactions to reflect the calling method, called security control, and the returned values. Security engineers should check the security test cases firing log, an example is shown in Figure 6-13, to verify that no errors introduced during the security controls integration with Galactic entities. After SwinSoft security engineers have checked the MDSE@R Security testing service log files and make sure that no integration errors have been introduced, they can publish their updated Galactic security model for their tenants.

Figure 6-13. A snapshot of MDSE@R security test cases firing log

6.4.4 On-boarding Swinburne and Auckland Tenants

During the tenants on-boarding process (preparing the service to be used by a new tenant), SwinSoft system engineers/admins start to customize/configure Galactic instance for tenant based on their requirements and purchased modules. Depending on the adopted multi-tenancy model, they may register new features or components as well. The final Swinburne or Auckland TSDM is similar to Galactic SDM in Figure 6-8. Swinburne and Auckland system administrators can update their own tenants' TSDMs to reflect any further system customization, such as enabling or disabling sub-features such as calculate overtime, nightshifts, and vacations in the Employee Management module. This TSDM is used by Swinburne security engineers to define and map required security on it. Moreover, any updates done by SwinSoft or Swinburne on their TSDMs are reflected on the prohibited resources list (Eq. 2)

6.4.5 Managing Swinburne and Auckland Security

Swinburne and Auckland security engineers go through the same process as SwinSoft did when specifying their security requirements and controls. Each tenant can customize their TSSM as far as they want and as frequent as required. For example, in Figure 6-10 Swinburne engineers have specified that LDAP "realizes" the AuthenticateUser requirement. Whenever MDSE@R finds a system entity with a mapped security requirement AuthenticateUser it adds LDAP as its realization control i.e. an LDAP authentication check will run before the entity is accessed - e.g. before a method is called or a module loaded. This applies to the CustomerBLL class methods, Figure 6-10 (1). However, Swinburne security engineers have a different requirement for the GetCustomers method - the requester should be authenticated using Forms-based authentication instead, Figure 6-10(2). Auckland can specify their specific requirements, context, and security controls based on their specific needs. This results in quite different generated security enforcement controls. Both Swinburne and Auckland security engineers can modify the security specifications while their Galactic application is in use. MDSE@R platform updates interceptors in the target systems and enforces changes to the security specification for each system as required. For example, the Swinburne Galactic security model can be updated with a single sign-on security authentication component and these updates are directly applied on the running Galactic instance.

6.5 MDSE@R Architecture and Implementation

The architecture of MDSE@R platform is shown in Figure 6-14. This is designed as a cloud Platform-as-a-Service (PaaS) that can manage multiple SaaS applications hosted on the same platform. MDSE@R consists of system and security specification modellers, models and security controls specifications repositories, system container to intercept request, testing services and security enforcement point.

6.5.1 MDSE@R Platform Architecture Details

System Description Modeller (1) is developed as an extension of Microsoft Visual Studio 2010 modeller with an UML profile (Figure 6-4) to enable system engineers modelling their systems' details with different perspectives including system features, components, deployment, and classes. The UML profile, as shown in Figure 6-4, defines stereotypes and attributes to maintain the track back and forward relations between entities from different models. This includes related features stereotype extending system components' entities; system components stereotype extending system classes' entities. Moreover, a set of security attributes to maintain the security concepts including objectives, requirements and controls mapped to every system

entity. The minimum level of details expected from the system provider is the system deployment model. MDSE@R can use this model to reverse engineer system classes and methods using .NET Reflections in case of system binaries only available. We use .NET parsers to extract classes and methods from system source code by analysing the generated AST files.

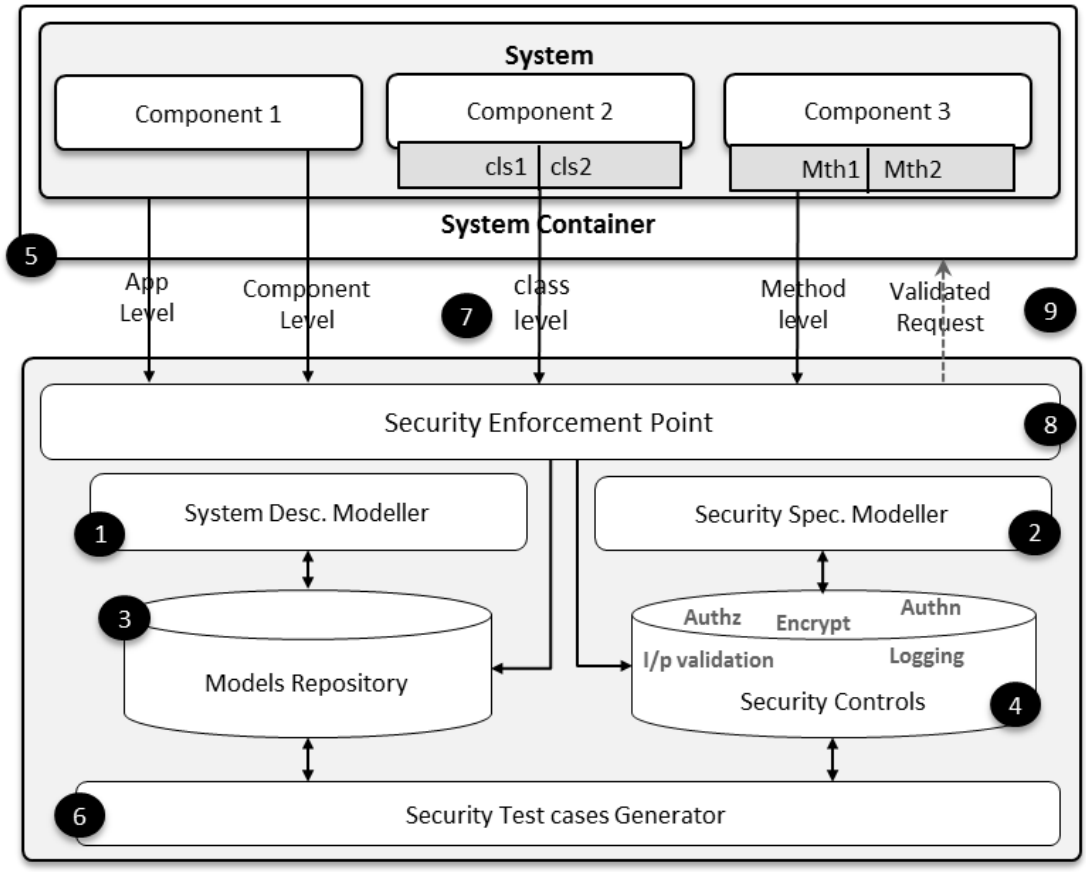


Figure 6-14. MDSE@R architecture

Security Specification Modeller – SecDSVL (2) is also developed as a Microsoft Visual Studio 2010 plug-in. It enables service providers and tenants, represented by their security engineers, to specify the security attributes and capabilities that must be enforced on the service and/or its operational environment. Figure 6-15 shows the meta-model of the MDSE@R SecDSVL which captures security details developed during the security management process. We will discuss SecDSVL details in the next Section.

Models Repository (3) is a shared repository to maintain models developed either by the system engineers or the security engineers. This repository also maintains the live system interceptors' document and security specification document. An example of these documents is shown in Figure 6-11. This example shows a sample of the Galactic interceptors' document generated from the specified security-system mapping. It informs the system container to

intercept GetCstomerByName and GetCustomers methods (1); a sample of Swinburne security specification file defining the security controls to be enforced on every intercepted point (2).

Security Controls Database (4) is a database of the available and registered security patterns and controls. It can be extended by the service providers or by a third party security provider. A security control must implement certain APIs defined by the security enforcement point in order to be able to integrate with the target system security standard interface. Having a single enforcement point with a predefined security interface for each security controls family enables security providers to integrate with systems without having to redevelop adopters for every system. We adopted OWASP Enterprise Security API (ESAPI) library [238] as our security controls database. It provides a set of authentication, authorization, encryption, etc. controls that we used in testing our approach.

System Container (5) used to support run-time security enforcement. MDSE@R uses a combined dependency injection and dynamic-weaving AOP approach. Whenever a client or application component sends a request to any critical system component method, this request is intercepted by the system container. The system container supports wrapping of both new developments and existing systems. For new development, SwinSoft system engineers should use the Unity application block delivered by Microsoft PnP team to support intercepting any arbitrary class entity. Unity supports dynamic runtime injection of interceptors on methods, attributes and class constructors. For existing systems we adopted Yiihaw AOP, where we can modify application binaries (dll and exe files) and add security aspects at any arbitrary system method (we add a call to our security enforcement point). For component level interception, we can use httpModules to add interceptors on the component level.

Security Test Case Generator (6) uses the NUnit testing framework to partially automate security controls and system integration testing. We developed a test case generator library, using test cases template, to generate a set of security test cases for authentication, authorization, input validation, and cryptography for every enforcement point defined in the interceptors' document. MDSE@R uses nUnit library to fire the generated test cases and notify security engineers via test case execution result logs.

At runtime, whenever a request for a system resource is received (7), the system container checks for the requested method in the live interceptors' document. If a matching found, the system container delegates this request with the given parameters to the security enforcement point (8). Figure 6-12 shows a sample of the security enforcement point API that injects the necessary security control calls before and after application code is run for different security attributes. Security Enforcement Point (9) is a class library that is developed to act as the default interception handler and the mediator between the system and the security controls. Whenever a

request for a target application operation is received, it checks the system security specification document to enforce the particular system security controls required. It then invokes such security controls through APIs published in the security control database (4). The security enforcement point validates a request via the appropriate security control(s) specified, e.g. imposes authentication, authorization, encryption or decryption of message contents. The validated request is then propagated to the target system method for execution (10).

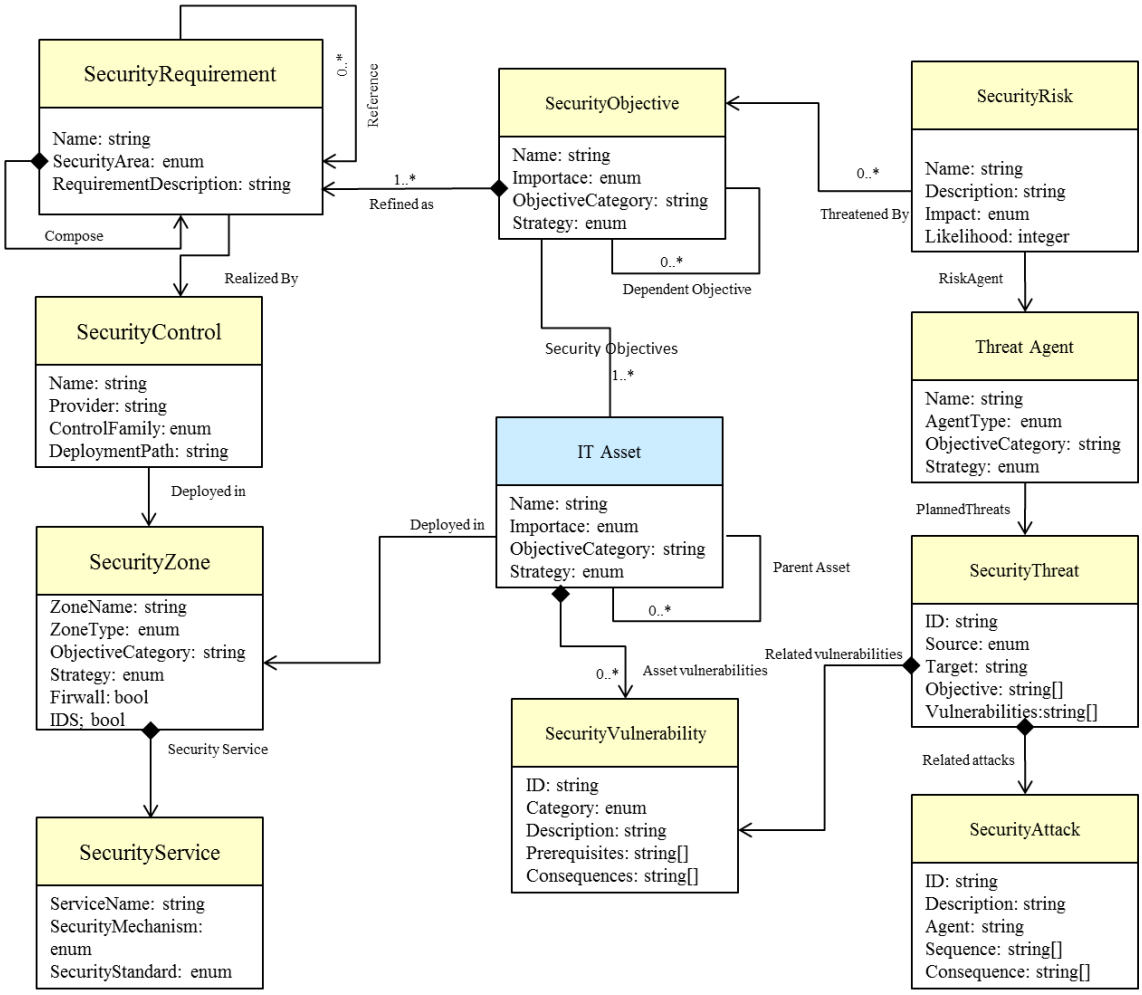


Figure 6-15. SecDSVL meta-model

6.5.2 SecDSVL: Security Domain Specific Visual Language

SecDSVL provides a mega-model using visual notations to be used by security engineers in managing IT systems' security. To develop SecDSVL, we studied the existing security management standards (including NIST, ISO27000) details and come up with a comprehensive security meta-model that captures all relevant details, as summarized in SecDSVL meta-model Figure 6-15 and discussed below:

6.5.2.1 Enterprise Assets

The first step in the security management process is the identification of existing IT assets that need to be secured. We capture enterprise assets in an asset model. This model captures all enterprise assets along with their categories i.e. information systems, physical assets or business value - and interrelationships. We use UML models to capture assets' detailed descriptions as discussed in the system description model. Stakeholders need to assign security categorization for every modelled asset. This categorization depends on the asset assigned criticality level.

6.5.2.2 Security Objectives

Enterprise top management defines key security goals, objectives, and losses of breaching assets' security. These objectives are captured in a security objectives model. Objectives may be specified per asset– i.e. objectives are mapped to the corresponding asset, or enterprise-wide thus a given security objective could be mapped to many assets. Possible relationships between objectives include: composition – a security objective is made up of sub-objectives; dependency – a security objective depends on other security objectives in order to be satisfied/achieved. Availability, integrity, confidentiality, and accountability are the key security objective categories [239]. Each security objective is assigned an importance level. This indicates the impact of the failure to meet such objective as a result of security breach – e.g. impact of breaching asset confidentiality may be high, moderate, or low. A security objective may be assigned realization security strategy including preventive, detective, and recovery strategies.

6.5.2.3 Risk, Threats, Attacks, and Vulnerabilities

Security engineers conduct risk analysis on critical enterprise assets to identify possible threats on a given asset, and likelihood and impact of such threats. This also may include performing vulnerability analysis to identify inherent flaws that may be exploited by threat agents while attack the system. These security details are captured in a security risk model. This may be developed per asset – i.e. for each enterprise asset we develop risk model capturing risks, threats and attacks, or enterprise-wide risk model capturing all possible risks, threats and attacks and map such items onto different assets. Threats should be linked with the source threat agents and to the exploited vulnerabilities. Vulnerabilities should be mapped to the vulnerable assets. Security risks map identified threats to the breached security objectives – i.e. a risk is a violation of a security objective through a possible threat. For each risk, we should specify the probability that a given threat can be exploited and the impact of exploiting such a threat by a threat agent.

6.5.2.4 Security Requirements

Security requirements are the treatments to be taken by security engineers in order to mitigate or avoid the identified threats. Security requirements are captured in a security requirements model. For each specified security objective and identified security risk, we may define a set of security requirements e.g. "the system should not grant access to a resource X unless the user is authorized by the user name and password". NIST [240] has 18 Security requirements family including audit, communication, cryptography, data protection, identification and authentication, privacy, etc.

6.5.2.5 Security Architecture

Security architects use the given security requirements model to develop a security architecture model. This model captures planned behaviour and structure of enterprise security. It shows how and where security controls and enterprise assets are positioned. Moreover, it captures how these security controls are integrated with other enterprise assets. A security architecture model includes identifying security zones (domain) in the enterprise operational environment including uncontrolled, controlled, restricted, and managed zones. Security architects define the security services that will be deployed or used in every zone. These services include authentication, authorization, cryptography, audit, etc. these services may also specify the mechanism or standard that should be provided by every security service e.g. cryptography should use AES instead of DES, authorization should use LDAP and SSO instead of forms-based authentication or Microsoft membership security.

6.5.2.6 Security Controls

Security administrators specify security controls that realize security services specified in the security architecture model. These security controls are captured in a security controls model. This model includes for every security control, the configurations to be applied on it. Moreover, each security control entity should specify the security control family. Thus, we can load configurations from the Common Configuration Enumeration (CCE) database [241].

6.6 Evaluation

In this section we summarize some of the experiments we have performed to assess the soundness and scalability of our MDSE@R approach in:

– Capturing descriptions of different real systems and different security details for both service providers and tenants;

- Propagating security attributes on different system entities (features, components, classes, and methods);
- Enforcing unanticipated security requirements that emerge at runtime including authentication, authorization, auditing, etc. at runtime with an acceptable performance overhead;
- Validating that security controls are correctly integrated with the target entities.
- Usability of our SecDSVL language?

We divided the benchmark set (the set of applications discussed in Chapter 4) into two groups: Group-1 has two applications including Galactic ERP and PetShop. Both applications have been modified to adopt the Unity application block as the system container. Group-2 has the other five open source web applications including Splendid, KOOBOO CMS, NopCommerce, BlogEngine, BugTracer, and TinyERP. For this group we use Yiihaw framework as the system container to inject interceptors into system binaries. Except for Galactic, we do not have any previous experience with these applications.

6.6.1 Experimental Evaluation Setup

Using MDSE@R, we developed three security specification models (SSM) with security objectives, requirements, and controls as described in Figure 6-9 and Figure 6-10. One model for service provider and two other models were copied from it and modified to reflect two security requirements sets. We specified security requirements and controls for authentication, authorization, input validation, logging and cryptography as shown in Table 6-1.

We used MDSE@R to model the system description (SDMs) for applications in Group-1, as we know the details of these systems – i.e. we can develop a complete SDM including system features, components, classes, etc. For Group-2, we used system deployment diagram for these applications and used reverse engineering to extract systems' class diagrams from their binaries. Thus for applications in Group-1 we should be able to map security to system features, components, classes, methods. However, in Group-2 we should be able to specify security on component, class, and method levels only because these are the only available models (features cannot reverse engineered from system source code or binaries so far).

6.6.2 Evaluation Results

Table 6-2 shows security attributes that MDSE@R succeeds in capturing and enforcing at runtime, including authentication, authorization, input sanitization, auditing and cryptography. This represents most common security attributes. Table 6-2 also shows that MSDE@R succeeded in mapping and enforcing these security attributes on systems in both Group-1 and

Group-2 with different levels of system abstractions (F: feature, C: component, S: class, and M: method). Note that for Group-2 applications we do not have a system feature model to map and enforce security on this level. The enforcement of cryptography has a limitation with Group-2 applications especially when securing methods. This is because it requires that the caller and callee expect parameters of type String. To address this problem, we used format-preserving encryption (FPE) techniques [62]. The output of these techniques is in the same format (type) of the input - i.e. if the input to encrypt is of type integer then the output is of the same type.

Table 6-1. Security controls used by service provider, Swinburne, Auckland

Sec. Attribute	SwinSoft Ctls	Swinburne Ctls	Auckland Ctls
Authentication	ESAPI	Forms-based	LDAP
Authorization	ESAPI	Forms-based	LDAP
I/P santization	ESAPI	SwinFirewall	–
Audit	ESAPI	PrivateAuditor	PrivateAuditor
Cryptography	ESAPI	DES	AES
Sec. Isolation	ESAPI	–	–

Table 6-2. Validating MDSE@R against Group-1 and Group-2 applications

Benchmark Applications		Security Attributes				
		Authn	Authz.	I/P Valid.	Audit	Crypto.
Group-1	Galactic	F, C, S, M				
	PetShop	F, C, S, M				
Group-2	SplendidCRM	C, S, M			(C, S, M)*	
	KOOBOO CMS	C, S, M			(C, S, M)*	
	NopCommerce	C, S, M			(C, S, M)*	
	BlogEngine	C, S, M			(C, S, M)*	
	BugTracer	C, S, M			(C, S, M)*	
	TinyERP	C, S, M			(C, S, M)*	

6.6.3 SecDSVL Evaluation

We have evaluated SecDSVL capabilities in capturing different kinds of enterprise security details with different levels of abstractions in comparison with the existing security management, risk management, and security engineering approaches. Table 6-3 shows SecDSVL compared to a range of other existing security modeling techniques based on their documented capabilities in Chapter 3 (related work). Table 6-3 shows that none of the existing approaches provides a comprehensive security model that covers every aspect in the security management process. Security management approaches (ISO27000, NIST-FISMA) focus on assets, risks, threats, and mitigation controls. Risk management approaches (OCTAVE, CORAS) focus on similar areas except for security controls. Early stage security engineering efforts (KAOS, i*, Tropos) focus on security objectives and requirements. Later-stage security engineering efforts (UMLsec, SecureUML) focus on security requirements, mapping and integration with target systems.

Table 6-3. Comparison between SecDSVL and existing efforts

Approach	1	2	3	4	5	6	7	8	9	10
Misuse case	X	X	√	√	√	X	X	X	X	X
UMLSec	X	X	X	X	●	X	●	X	X	●
SecureUML	X	X	X	X	●	X	●	X	X	●
KAOS	X	√	●	√	√	X	X	X	X	X
i*	X	√	●	√	√	X	X	X	X	X
Tropos	X	√	●	√	√	X	X	X	X	X
CORAS	√	●	√	√	X	X	X	X	●	●
OCTAVE	√	●	√	√	X	X	X	X	●	X
FISMA	√	√	√	√	X	X	X	√	√	X
ISO27000	√	√	√	√	X	X	X	√	√	X
SecDSVL	√	√	√	√	√	√	√	√	√	√

[1] Assets Model, [2] Security Objective, [3] Security Threats and Vulnerabilities, [4] Security Risks, [5] Security Requirements, [6] Security Architecture, [7] Design, [8] Security Controls, [9] Traceability, [10] Mapping between systems and security models

√: Fully Supported ● : Partially supported **X** : Not supported

6.6.4 User Evaluation

We carried out a preliminary user evaluation of our tools and platform to assess MDSE@R approach and platform usability. We had seven post-graduate researchers, not involved in the development of our MDSE@R approach, to use our developed tools and platform after receiving an hour training session on the tool and platform features. We asked them to explore several MDSE@R system and security DSVL specifications of the PetShop and Galactic applications. Then we asked them to perform updates on these models and to modify the security specification models at run-time. We conducted a basic usability survey to gain their feedback on our DSVL, modelling tools, and the security enforcement platform. The results show that they successfully understood and updated security models for the target systems. They gave positive feedback about the overall approach and the tool usability, and the capabilities in managing system security, as shown in Figure 6-16 (1: Strongly disagree to 5: Strongly agree). A key recommendation was to use more expressive icons in the security DSVL rather than just boxes.

6.6.5 Performance evaluation

In this section, we discuss the performance evaluation of MDSE@R platform in two key areas: runtime performance overhead of the MDSE@R platform on the secured system; and the offline system security adaptation overhead.

6.6.5.1 Runtime Performance Overhead

The runtime performance overhead of MDSE@R equals time taken to intercept requests, plus time spent by the security enforcement module in querying the security requirements repository to be enforced on the intercepted point, plus time spent in calling the security controls specified. The time spent by security controls themselves we do not factor in, as this needs to be spent whether using our approach or as hard-coded security solutions. Arguably, traditional approaches may incur some of these other time penalties as well e.g. checking authenticated user access controls or generating audit checkpoint information to log.

Figure 6-17 shows the time required (in msec) by MDSE@R to process a request for systems with different numbers of concurrent users and different number of system entities that have been marked as critical. Experiments were conducted on a Core2Duo desktop PC with 4GB Memory. The maximum performance overhead we got for a system with 10000 CPs defined and having 100 users concurrently sending requests equals 140msec. This performance considers efficient memory utilization as interceptors and security specification documents are loaded as needed. Significantly better performance could probably be achieved by caching these

MDSE@R models in memory and using a hash table data structure to enable faster search. Moreover, using replicas of the MDSE@R platform on different servers and for different applications will result in further improvement of the approach performance overhead.

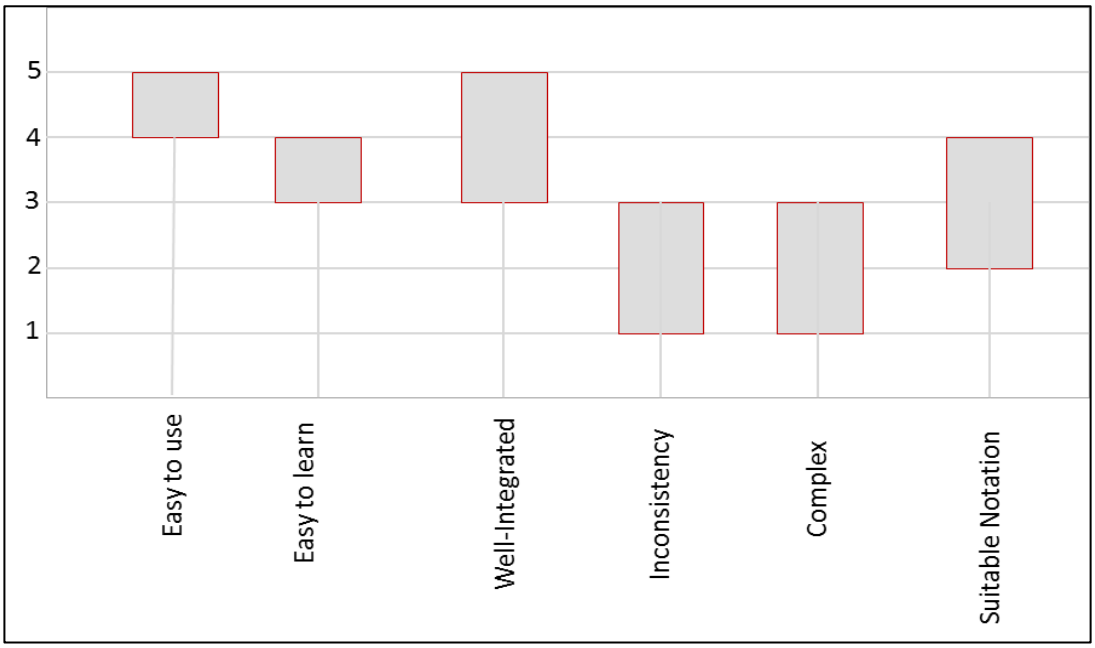


Figure 6-16. SecDSVL usability level of agreement

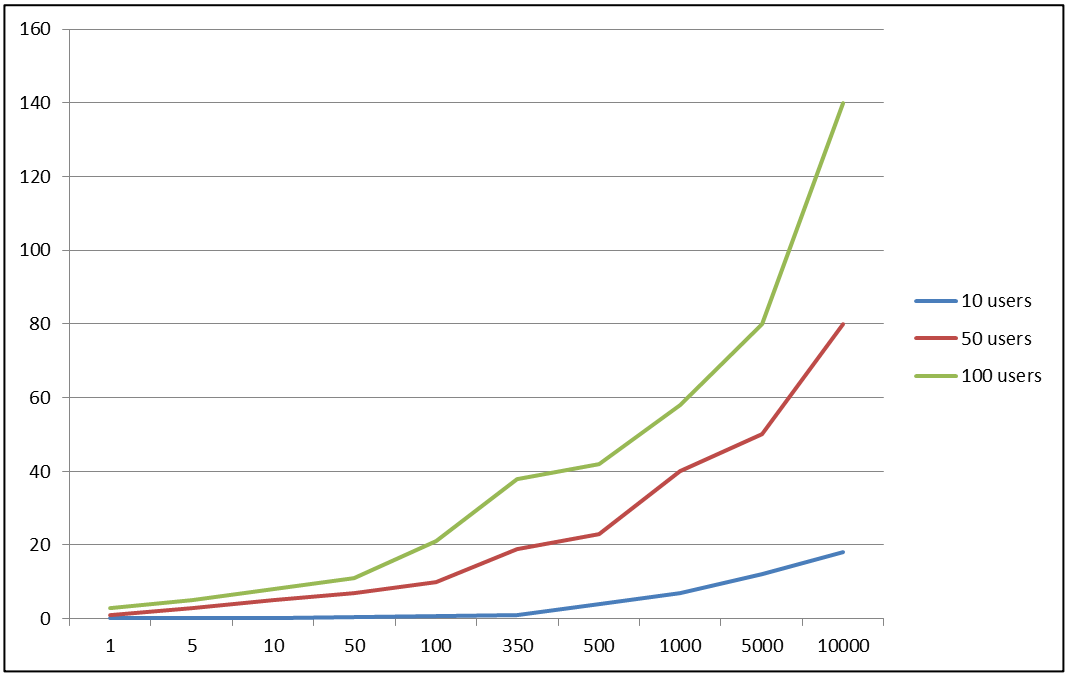


Figure 6-17. MDSE@R platform average performance overhead

6.6.5.2 Security Adaptation Overhead

We have measured the adaptation delay incurred by MDSE@R in order to realize a single simple mapping between a security entity and a system entity – e.g. system methods. This overhead equals on average 3 seconds. This represents the time taken to update the security interceptors and security specification documents and time to generate and fire the required integration test case(s). This is an offline task and so does not impact the performance of the running system instance.

6.7 Discussion

MDSE@R approach promotes multi-tenancy security engineering from design time to runtime. This is based on externalizing security engineering activities including capturing objectives, requirements controls, and realization from the target system implementation. This permits both security (to be enforced) and critical system entities (to be secured) to evolve at runtime (supporting adaptive security at runtime). Moreover, it enables enforcing different security requirements' sets for different tenants who are not known at design time. We name this as "tenant-oriented security" compared to the traditional service-oriented security where a service can reflect only one set of security requirements usually captured by service provider at design time. One may argue that our approach may lead to a more open and vulnerable system as we did not consider security engineering during design time. Our argument is that at design time security engineering is often done by security non-experts and this is a leading reason why we still discover a lot of vulnerabilities in systems. Moreover, service providers can still perform security engineering during design time using MDSE@R. The service provider delivers both the SDM and SSM to their tenants for further customization. This also helps small tenants or tenants who are satisfied with the delivered security.

A key benefit reaped from MDSE@R approach is supporting model-based security management. Tenant security requirements, architecture and controls are maintained and enforced through a set of centralized TSSMs instead of low level scattered configurations and code that lack consistency and are difficult to modify. A tenant can have a single TSSM for all of their IT systems that captures all of their security specifications and can be updated anytime to reflect his new configurations. Thus any update to their TSSM will be reflected on all IT systems that use MDSE@R platform. We developed one security model and used it with different systems. Each system enforces the security mapped to its entities. Moreover, any update to the security model results in updating all systems linked to it. This is a key issue in environments where multiple applications must enforce the same security requirements. Having one place to manage security reduces the probability of errors, delays, and inconsistencies.

Moreover, automating the propagation of security changes to underlying systems simplifies the enterprise security management process.

The selection of the level of details to apply security on depends on the criticality of the system. In some situations, we may intercept calls to the presentation layer only (webserver) while considering the other layers secured by default (not publicly accessible). In other cases, such as integration with a certain web service or using third party component, we may need to have security enforced at the method level (for certain methods only).

Security and performance trade-off is another dilemma to consider. The more security validations and checks the more resources required. This impacts application performance. This should be included as a part of the Service Level Agreement (SLA) with the tenants. We plan to extend our generated test cases to include performance tests, allowing MDSE@R provider to assess the overhead of new security configurations in terms of cost and to help both providers and tenants to optimize the security level enforced. MDSE@R helps in engineering security into systems at runtime, while the security controls' configuration and administration should be managed by security administrators. Moreover, MDSE@R does not support defining business rules at runtime – e.g. employee should not be able to retrieve customers' records of type VIP. The target system should have this rule while MDSE@R will provide the current user roles/permissions as returned by the tenant security access control.

Security isolation between different tenants' data is a very critical requirement in engineering security of a multi-tenant SaaS application. Although multi-tenancy security isolation is out of the project scope, the MDSE@R can help in addressing the security isolation problem. Security isolation controls, that simply perform authorization of the tenants supplied inputs, are added to the service SSM as a mandatory security control to be applied before proceeding with any given request. Thus no tenant can access other tenants' data by providing malicious inputs. However, the service providers have to perform the data filtration when loading/storing data from/to the application database.

Currently the communication (request/ response) between the MDSE@R and tenants' security controls is not encrypted. Thus, the key management itself does not fall directly under the responsibility of MDSE@R. However, MDSE@R is responsible for issuing requests for cryptography security controls to encrypt or decrypt tenants' data as specified in their security specification model. Such security controls have to know where to get the cryptography keys for example. If the encryption of these communication messages is also a requirement, we can use a PKI as an extension of the MDSE@R to manage cryptography keys used for secure communication, as shown in Figure 6-18. This would be used by MDSE@R to get tenants' public keys to be used in encrypting communications with tenant's controls.

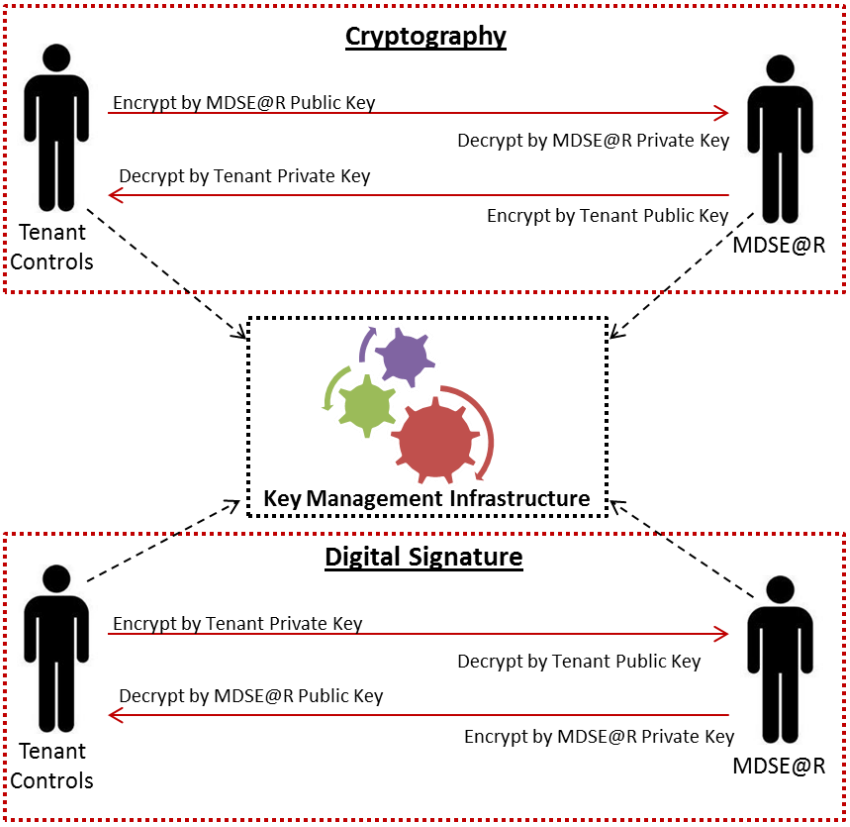


Figure 6-18. Cryptography scenario between MDSE@R and tenants' security controls

The multi-tenant security engineering of existing services (extending system security capabilities) has three possible scenarios: Systems that already have their SDMs, we can use MDSE@R directly to specify and enforce multi-tenant security at runtime; Systems without SDMs, we reverse engineer parts of system models (specifically the class diagram) using MDSE@R. Then we can use MDSE@R to engineer required system security; and Systems with built-in security, in this case we can use MDSE@R to add new security capabilities only. MDSE@R cannot itself help modifying or disabling existing security. In chapter 7, we introduce our approach (reengineering aspects – re-aspects) to support disabling of existing security methods and partial code using modified AOP techniques.

In cloud computing model, most of the services are publicly accessible to end users who may be malicious users. Those users may try to exploit services' vulnerabilities to breach data security. Thus, it is very important to operate a security service that can easily mitigate such vulnerabilities at runtime without any delays to develop security patches. MDSE@R could be used in automating such vulnerability mitigation process. Reported vulnerabilities will be used to extract the critical points that need to be secured. A set of mitigation actions that should be applied to mitigate the reported vulnerability will be used to integrate required security controls within the vulnerable points at runtime. We will discuss this case in more details in the case studies chapter (chapter 10).

6.8 Chapter Summary

MDSE@R is a new model-driven approach to dynamically engineering security for multi-tenant SaaS applications at runtime. Our approach is based on using a set of multi-level service description models (SDM), developed by service providers, to describe different perspectives of their applications or services; a set of security specification models (SSM), developed by the service provider, to capture security objectives, requirements and environment security controls using Domain-Specific Visual Languages. Then, tenants can customize their copies of the SDM and SSM to reflect their application or service and security configurations. MDSE@R then bridges the gap between these two specifications through merging of the service and security models for both service provider and service tenants into a joint service security model. MDSE@R uses dynamic injection of security enforcement interceptors and code into the target application or service to enforce the security specified. Security specifications are thus externalized and loosely coupled with application specifications, enabling both the application and security specification to evolve.

It also allows sharing of security specification models among different applications "model-based security management". Security controls can be integrated with MDSE@R (which was implicitly integrated with the tenant service) by implementing a standard security interface we introduced. We have developed a set of modelling tools and a prototype of MDSE@R. We have successfully validated our approach by applying it to a set of benchmark applications, most of them open source, successfully modelling and enforcing a range of security needs on these applications. We performed a user evaluation of our toolset that demonstrates that it is readily usable by a technical audience but with little security engineering background. We assessed the performance overheads of using our current prototype of MDSE@R. It has a performance overhead ranging from 0.13msec up to 140msec per request for each critical application or service entity. MDSE@R has adaptation delay of 3 seconds for each simple mapping between SSM and SDM. This represents time to update interceptors and security specification documents as well as generating and firing security test cases.

Chapter 7
Cloud Applications Security Reengineering

In the last chapter we introduced our multi-tenant security engineering at runtime approach, MDSE@R, to enable cloud services to reflect different sets of security requirements for different tenants that emerge at runtime. However, MDSE@R does not help in case of cloud services that have been originally developed with built-in security capabilities (functions). MDSE@R helps in adding new security capabilities. Such new capabilities may conflict with existing service security capabilities. In this chapter we introduce a new security reengineering (retrofitting) approach that is used as a preprocessing step to help in disabling services' built-in security as well as mitigating system security vulnerabilities found in such services that may be reported by a security analysis service (we introduce our approach in chapter 8). Our approach is based on Reengineering-Aspects "Re-aspects" as a new concept we introduce to address and capture the complex details involved in fulfilling such security reengineering tasks. This chapter is organised as follows. Section 1 introduces an overview of software reengineering and key limitation of the existing efforts. Section 2 introduces some motivating examples that we may face during the security reengineering process. Section 3 provides an overview of the normal change request management process that should be followed when conducting system maintenance task. Section 4 provides an overview of our re-aspects concept. Section 5 describes how re-aspects concept helps automating the change impact analysis task. Section 6 describes how re-aspects concept helps automating change propagation task. Section 7 discusses, SMART, our reengineering tool based on the re-aspects concepts along with the key implementation details. Section 8 discusses a usage example that shows how SMART tool works. Section 9 describes evaluation experiments of our approach. Section 10 discusses strengths and weaknesses and areas for further research.

7.1 Introduction

Software systems are usually exposed to extensive changes and evolution after deployment. This might be to address quality problems (e.g. fixing bugs), performance problems (e.g. too slow), make use of new APIs or integrate with new systems (e.g. change system to use company-wide LDAP authentication for single sign-on from a custom ID/password system), or to fix security problems (e.g. found to be vulnerable to SQL Injection attack).

These maintenance activities represent up to 80% of the total system cost and effort [242]. System re-engineering is concerned with system understanding, organization, and migration [165]. System maintenance [166] is concerned with post-delivery modifications to an existing system in order to address new issues. These can be small spot-patches to major revision of system architecture and codebase. Dynamic runtime adaptation is more a limited approach and is sometimes used to handle post-delivery "unanticipated" requirements made while the system is running [37, 174, 243]. System reengineering, refactoring and maintenance are concerned with removing, modifying and replacing existing features as well as adding new system features at design time. This requires: (i) capturing new features or modifications of existing features; (ii) locating system entities that must be modified; (iii) locating system entities that is impacted by this modification and should be modified; and (iv) propagating or reflecting the required modification on the whole system.

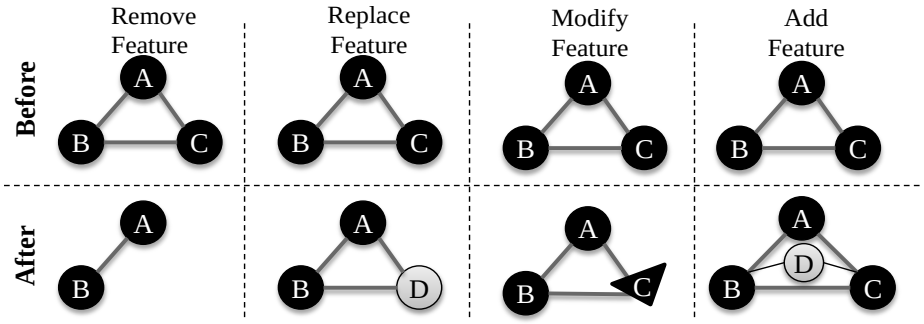


Figure 7-1. Possible system modifications and their impact on system entities

Figure 7-1 illustrates possible system modifications (types of change requests): (i) a feature is removed (e.g. code taken away); (ii) a feature is replaced (e.g. old code replaced by new code); (iii) a feature is modified (some old code replaced by changed code); and (iv) a feature is added (new code is inserted into old code). In these scenarios, other features may be impacted – e.g. the removal of feature C requires updating dependent features (A, B). This figure also highlights a key problem which is that realizing a given system modification on a specific feature (added, removed, modified, or replaced) requires modifying other related system features that integrates (interacts or uses) the modified system feature. Below we discuss some of the relevant efforts related to how we realize system modification/updating.

Existing system reengineering approaches focus on understanding the target system and locating implemented features [177, 178, 181, 244], discovering implemented design patterns [245], aspects mining [182], understanding source code evolution between different system versions [246], applying system restructuring [247]. These efforts are limited in their expressiveness and identification precision, as most of them are targeted to help program

understanding rather than supporting actual program modifications. On the other hand, the existing system refactoring approaches [172, 173, 248] focus on specific refactoring patterns and requires user involvement. Existing system maintenance approaches are limited to change impact analysis [167-169, 249, 250]. Moreover, these approaches help in identifying what are the impacted entities only. Specifying parts required to be updated and how to update them is not addressed at all. Add to that, they focus on modifications on class, method and field level. Thus block-of-code modifications are not addressed. Existing Syntactic pointcuts, such as those delivered by AspectJ, are limited to arguments and attributes of the caller or the callee. Although statement and block level interception do exist [251, 252], they depend on explicit, manual, marking of statements or code blocks to be intercepted. Moreover, these syntactic pointcuts are fragile under system evolution [253]. On the other hand, the semantics-based pointcut specification approaches are more powerful than syntactic pointcuts [253]. Existing semantics-based pointcuts are either informal and not powerful enough [254] [255] or formal but are often very complex to use by software developers [256].

Aspect-oriented software development (ASOD) techniques repetitively applied to support software maintenance [37, 174], re-engineering [182, 247] and refactoring [173, 248] for both object-oriented and aspect-oriented programs [257]. On the other hand, existing AOP languages such as AspectJ [258] and Caesar [259] support two types of crosscutting concerns: static crosscutting concerns that impact the static structure and signature of program entities, and dynamic crosscutting concerns that impact the system behavior by injecting code "advice" to run at well-defined points in the program execution. The static crosscutting constructs supported by AspectJ "inter-type declarations" are limited to adding new declarations and methods rather than modifying existing system entities (classes, methods, attributes, fields). This is a key limitation in adopting existing AOP approaches for software reengineering and maintenance activities. The existing runtime dynamic system adaptation approaches are limited in their capabilities in updating the running system with dynamic aspects (updating methods – removing, modifying and replacing). Thus, static aspects (updating classes, inheritance hierarchy, method signature, etc.) are not supported to be updated at runtime [175].

To address these issues, we introduce the concept of re-engineering aspects – or "re-aspects" - as a novel integrated and systematic solution to the system re-engineering and maintenance problem. A re-aspect can capture signature of system entities to be modified, actions required, and code to apply on the identified entities. Then we analyse the system source code, locate entities that match the specified signatures, conduct detailed impact analysis to identified impacted system entities, and then propagate the changes required on these entities. Re-aspects help in removing, replacing, modifying or adding code at any arbitrary code block. These code

blocks may have a heterogeneous and complicated signature that is more complex than can be expressed using existing AOP approaches. Changes supported to be made on a target system include removing declarations, method calls, sets of lines of code, or whole methods, etc. We introduce two novel signature designators to help capturing formal and flexible semantic signature expressions as well as flexible syntactic signatures.

Using the re-aspect de-weaving and replacement concept, we have developed a supporting model-driven application reengineering tool, SMART. SMART captures a set of required target system changes as re-aspects. These re-aspects are mapped to target system entities as a set of change requests. SMART applies these change requests and updates the source code as appropriate. We have validated SMART on our set of benchmark applications introduced in Chapter 4.

7.2 Motivating Examples

Figure 7-2 shows example code snippets that need to be modified to satisfy different change requests for a security retrofitting task (modifying application security capabilities). These code snippets are excerpted from Galactic – our research project motivating example; a web-based ERP system developed using .NET. These examples also show possible system modifications for these change requests, the code with grey shading - i.e. required re-engineering of the original code to address raised issues.

A

```
bool updateCustomerBalance(string custID, decimal nBalance) {
    if(!AuthenitcateUser( username, password)) return false;
    if(!AuthorzUser(username, "updateCustBalance")) return false;
    LogTrx(username, dateTime.Now, "updateCustomerBalance");
    Customer customer = Customers.getCustomerByID(custID);
    customer.Balance = nBalance;
    Customers.SaveChanges();
    LogTrx(username, dateTime.Now, "updateCustBalance done");
}
```

B

```
if( Request.Cookies["Loggedin"] != true ) {
    if(!AuthenticateUser(Request.Params["username"],
                         Request.Params["password"] ) )
        throw new Exception("Invalid user");
}
DoAdministration();
```

```
bool updateSalary(string userID, strig password, string staffID, decimal nSalary) {
    IDManager idm = IDManager.getIDManager();
    if(idm.CheckAccessOk(userid, password, "updateSalary") {
            Staff staff = Staff.getStaffByID(staffID);
            staff.Salary = nSalary;
            staff.SaveChanges();
    }
     else {
       throw new BadAccessExcption("user is not authorized");
    }
    }
```

C

```
    if( !AuthenticateUser( Request.Params["username"],
                    Request.Params["password"] ) )
                throw new Exception("Invalid user");
    if( !AuthorizeUser( Thread.CurrentPrincipal,
                    (new StakeFrame()).GetMethod().Name,
                    (new StakeFrame()).GetMethod().GetParameters()  )  )
            throw new Exception("User is not auhorized");
    updateCustomerBalance(Request.QueryString["cID"], nBalance);
```

D

```
    Inputsanitizer( (new StakeFrame()).GetMethod().GetParameters() );
    string query = "SELECT *  FROM USERS WHERE UserID = '"
            + EncodeForSQL(username)
            + "' AND password = '"
            + EncodeForSQL(password)  + "'";
```

E

```
    void public onbtnSave_Click(….)  {
            string TenantID = Session[“TenantID”];
            BusinessLayer.UpdateCustomerBalance(TenantID,…);
        …
    }
```

F

Figure 7-2. Examples of code modification snippets

Figure 7-2-A, we have old security function calls throughout the codebase that we want to disable in order to integrate the application with the customer environment security controls. Customer security engineers want to replace this with a declarative security e.g. attribute-based webserver security – through configuration files. We need to update every method that has this shaded code and delete these obsolete lines of code, or replace, modify, insert this shaded code.

In Figure 7-2-B, the code is vulnerable to authentication bypassing attack as it depends on user inputs (stored in a cookie) to check if the user is logged-in or not. If the user is not logged-in, they will be authenticated using "AuthenitcateUser" function. A malicious user can modify the cookie file to bypass the authentication process. One possible mitigation problem is to replace checks on user cookies with a session variable managed by web server.

Figure 7-2-C, we have a more complicated example where we need to modify the method signature (parameters) to remove the userID and password parameters. Moreover, relevant code using these parameters should be removed.

Figure 7-2-D shows code vulnerable to improper authorization attack as user inputs are not authorized before being used. A malicious user can pass invalid data to retrieve information they are not authorized to see. A possible mitigation is to authorize every user input before using within the system. This is done by modifying the old code to do this checking i.e. injecting code to perform request authorization and input data authorization.

In Figure 7-2-E we have code that uses user inputs directly in SQL statements without sanitization. A malicious user may enter data to execute unauthorized commands. A possible mitigation to this problem is to conduct input sanitization before constructing the SQL statement or precede references to user inputs with encoding functions. This requires inserting code, at statement level, to carry out the checking of user inputs used in dynamically SQL statements.

In Figure 7-2-F shows a code snippet from the presentation layer (webpage) that must be modified to inject code that retrieves tenantID session variable. Moreover, we need to modify business functions to pass in tenantID parameter.

7.3 Change Request Management Process

In order to develop a realistic solution to the software systems (security) reengineering, we studied how software vendors realize such system modifications. We figured out that any software house operates a change request management process that defines and manages how software systems could be changed. Developers frequently receive change requests (CR) from customers, marketing and sales teams, and application implementers. These require them to modify, disable or add new features to one of their delivered systems. The change request

management process is initiated once a new CR is received or as planned in the project. This process is conducted to determine and document expected impacts of the CR on system artifacts including requirements, architecture, design, and source code. This helps in estimating cost and effort required to realize the given change request.

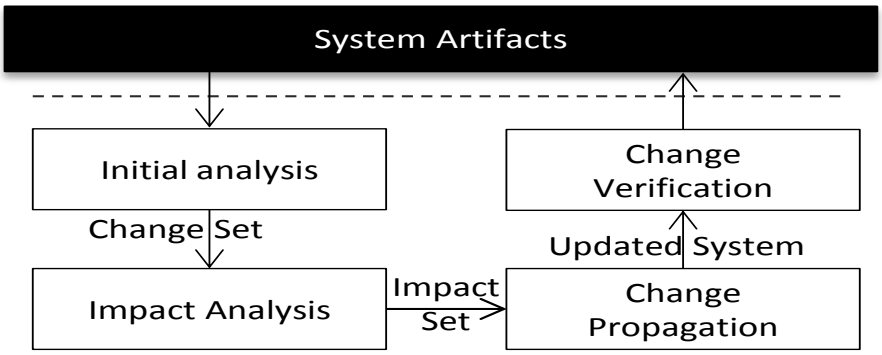


Figure 7-3. Our simplified change request management process

The change request management process, as shown in Figure 7-3, starts with assigning the CR to a development team to conduct an initial impact analysis. The results of the initial impact analysis are maintained in a "**change set**". This task is usually broken down into subtasks that are assigned to different stakeholders (business analyst, software architect, designer, developer, and tester). Each item in the change set may be removed, modified, replaced, or new code, model entity, or test case injected. *Next*, a deeper analysis is then conducted by stakeholders to develop the "**impact set**" which includes items to be impacted by changes to entities in the "change set". Both sets are used to assess the time and cost required to effect the change. *Thirdly*, software stakeholders propagate the specified system modifications on target system entities including system requirements, architecture, design, source code, and test cases. *Finally*, stakeholders have to verify the changes made using appropriate reviews and test suites.

This software maintenance process is challenging as different system entities at different abstraction levels may need modifying; code may be developed with different programming languages; and a change may touch code parts with different syntactical format (variable name, conditions' order, format) that perform the same function. An effective approach that facilitates system maintenance activities requires: capturing complex code signatures ranged from a class name down to a block of code; locating change set for the required modifications; identifying impacted system entities; propagating the required modifications on the target system source code and models; support abstract signatures' definition and analysis. In this chapter we focus on supporting automation of the first three tasks in the change management process. Testing can also be automated using the change and impact sets, checking pre and post conditions that must be satisfied by modified entities (this needs to be specified by re-aspects' developers). However,

we also test that the modifications introduced did not break the validity and integrity of the final system executable file.

7.4 Reengineering Aspects - "Re-Aspects"

The reengineering aspects ("re-aspects") concept is motivated by the change request management process we discussed above. The relevant information required to realize a given change request is consolidated in a re-aspect. Then, using our re-aspects engine, we automate the change impact analysis required and change propagation of system modifications. Re-aspects concept is inspired by traditional AOP, but aimed at supporting system re-engineering and maintenance. In re-engineering, an existing application has code scattered throughout its codebase that we need to remove, replace, modify, or add additional code to, in order to effect the desired changes. In fact, we want to identify such code blocks, sometimes disabling them, sometimes replacing, sometimes selectively modifying, and sometimes inserting new code into them. Such code blocks can be coarse-grain (classes and methods) or fine-grain (lines of code). Moreover, these blocks may have different formats, structures or even programming languages. This leads us to the concept of re-engineering aspects, or "re-aspects". A re-aspect is analogous to the "aspect" in traditional AOP excepting that signatures are more complicated and more actions could be applied on matched source code blocks in the target system.

Re-aspect	::= **s**:[Sign] **a**:[Action] **d**:[Advice] **i**:[Impact]
Sign	::= NULL | **st**:SignType **se**: [Signature Expr] | Sign Sign
SigType	::= code-snippet | OCL-expression
Action	::= **at**:ActionType
Action Type	::= Delete | Modify | Replace | Inject
Impact	::= NULL | Re-aspectDef | Impact

Figure 7-4. Re-aspect Syntax

Each *re-aspect* has signature, action, advice, and impact parts. The syntax of re-aspects is shown in Figure 7-4. A *re-aspect signature(s)* captures invariants that describe footprints of the target system entities that should be deleted/modified/replaced or into which new code is inserted. These may be a line of code, whole method, or a class. A *re-aspect instance* is a specific system entity that matches a given re-aspect signature. A re-aspect instance maintains its specific context information – i.e. location, parent entity, children, etc. The set of re-aspect instances represent the change set. A *re-aspect action* specifies what to do on each matching entity. A *re-aspect impact* represents the re-aspect that handles system entities impacted by a given system modification. This may be entities that are directly impacted by the modification –

i.e. after modifying a method name; all methods that call this method should be updated. Moreover, the re-aspect developer can define signatures of other entities that should be modified as well e.g. methods in the same component, methods that have specific signature, etc. These are called heuristics-based impact analysis. We categorize possible system re-aspects into four types according to specified re-aspect action:

- *Adding re-aspec*t (used in situations similar to Figure 7-2-D)**:** this is a conventional aspect like what traditional AOP can deliver. Code to be injected is specified in a separate advice that is weaved with the target system at a given re-aspect instance. Unlike many existing AOP techniques it has capabilities to add to any static code structure (including new method, field, and lines-of-code) to system entities.
- *Deletion re-aspect*, or "anti-aspect" (used in situations similar to Figure 7-2-A)**:** this is a special case re-aspect that has only signature and no advices. The identified re-aspect instances, e.g. classes, code blocks, are removed from the target system.
- *Replacing re-aspect* (used in situations similar to Figure 7-2-C)**:** this re-aspect is a combination of deletion and adding re-aspects. It includes signature of code to be removed and an advice specifying new code to be added.
- *Modifying re-aspect* (used in situations similar to Figure 7-2-B)**:** this is the most complicated re-aspect. It allows a developer to specify selective deletion, reordering, or addition of new elements into matched code instances. For example, the problem in Figure 7-2-B should be mitigated using a modifying re-aspect. It receives the identified re-aspect instance (an Abstract Syntax Tree - AST node) as input parameter. At weaving time we call the modifying aspect script on each identified instance. The returned, modified AST is used to replace the original sub-tree.

7.5 Change Impact Analysis

The software reengineering and maintenance domain requires expressive and accurate signature specification approach to identify target system structures on which to apply changes. Exiting impact analysis efforts assume that the software developer knows exactly what entities need to be modified in order to satisfy the system modification request. However, in re-aspects, we start one step earlier to help developers build the change set (entities that need to be modified). This is facilitated through the specification of signatures of entities that should be modified in the target system. Using these same signatures we can locate entities that will be impacted by specified modifications. Re-aspects' signatures are specified using a hybrid approach that delivers flexible syntactical code signature specification and semantic Object Constraint

Language (OCL)-based signature specification. Below we introduce our proposed signature specification approaches.

7.5.1 Code Snippet Signature Designator

Re-aspects' developers can specify flexible code snippets as a re-aspect signature i.e. a pattern to match parts of the target system that needs to be modified. Developers can use the code snippet template shown in Figure 7-5. To avoid fragility problems related to using lexical pattern matching [178], or being specific to code written in specific programming language, our code snippet signature matching algorithm works on source code abstract syntax tree (AST). A "Dummy" keyword acts as a '*'-like wild card in regular expressions (we cannot parse or compile code with * in C#). For example, using myClassDummy instead of Dummy for a class name means the developer wants to locate classes that start with 'myClass' in any namespace with any contents. If a developer is assured in which namespace the code match is expected they can modify the Dummy namespace (line 2). The same applies with class name - a class name can be specified or leave it as "Dummy" (line 4), and for method names (line 6). Signatures can be matched with code blocks inside method body. A developer can specify a code block to locate regardless where this block is located. If they do not know details of the code block, they use "Dummy" (line 8). This indicates that all statements in the method body will be ignored until a match between the target method statements and the next statement in the signature is found (A = Dummy). Same applies to control statements (if, while, …).

```
1  //update namespace or class with specific name if any
2  namespace Dummy {
3    class Dummy {
4        // update method modifier, return type or
5       // name for specific method signatures
6      public void Dummy () {
7          // update method body in case of code block re-aspect
8          A = Dummy;
9          if (Dummy) {
10         }
11       }  // end of Dummy Method
12   } // end of Dummy Class
13 }  // end of Dummy Namespace
```

Figure 7-5. Code snippet re-aspect template

7.5.2 Semantic OCL-based Signature Designator

To support semantic re-aspect signatures we use the Object Constraint Language (OCL) as a signature definition language. Below we summarize some of the key features of the OCL and explain how we succeed in using OCL to capture signatures of system entities to be located in different software artifacts.

Syntax	Example
package PackageName **context** TargetEntity **inv** InvariantName: OCL expression **endpackage**	**package** SecurityTesting **context** Class **inv** PublicMethods: self.Methods->select(M | M.IsPublic = 'true') **endpackage**

Figure 7-6. OCL expression format and example

Table 7-1. List of possible operations in OCL

OCL Operation	Description
Exists	check if the given collection of elements contains elements that satisfy a given expression
ForAll	Is used to check if the given collection of elements satisfies (all) a given expression
Select	Returns all elements in a given collection that satisfy a given expression.
Reject	Returns all elements in a given collection that does not satisfy a given expression.
Iterate	Iterate on all elements in a given collection checking for satisfaction of a given expression
Sequence	Returns a sequence of elements that satisfy specific Type T
First, Last	Returns the first/last element in a collection
Intersection	Returns a collection containing all elements of a given collection A contained by B

7.5.2.1 Object Constraint Language (OCL)

OCL is a declarative, formal language that helps in specifying rules with "invariant conditions" that should be satisfied in a given model or in query expressions over objects in such model [179]. OCL was developed to overcome the problem of specifying such constraints using natural languages which lead to ambiguity problems. Thus, OCL was introduced as a formal

language that can capture such signatures in a formal way. Unlike traditional formal languages such as linear temporal logic (LTL)) and computational tree logic (CTL) that heavily depend on mathematics and hard for many software engineers to use in writing invariant expressions; OCL uses a more familiar and easy to use syntax and semantics to capture such signatures. OCL expressions are declarative i.e. they have no side-effects on the target systems. Figure 7-6 shows the basic syntax of an OCL expression. OCL expressions (invariants) are usually consolidated in packages. Each invariant should have a context entity that specifies where this invariant should be applied. Moreover, the context attribute is used to load the entity properties and operations that could be used in the specified signature. OCL is supported with many functions that could be used in defining invariant expressions. Table 7-1 shows some examples of the key functions supported by OCL. OCL is also an extensible language. Thus, we can use common expressions as base expressions (base functions) to create complex expressions to be used in developing more complex invariants.

7.5.2.2 System Description Meta-model

We developed a system description meta-model, shown in Figure 7-7, that captures all entities in any object oriented programming-based system including component, class, instance, method, inputs, input sources, control statements, etc. It also reflects key attributes and relations between these entities. Moreover, it can be extended to capture more system details such as platform APIs, or more abstract system entities and relations such as security APIs and system or security models.

This model is used in validating OCL re-aspect signatures and in generating code to look for matches in target system entities. Table 7-2 shows examples of re-aspect OCL-based signatures at different levels of abstraction: (a) a signature that specifies all public methods that belong to classes derived from ASP.NET Page class; (b) a signature that specifies all methods that call EXEC_SQL function; (c) a signature that specifies all public classes that implement the customer management system feature.

Table 7-2. Samples of Re-aspect signatures as OCL expressions

A	Context Method inv PresentationLayerPublicMethods: self.IsPublic = **true** and self.Class.BaseClass = “Page”
B	Context Method inv MethodsMayContainSQLInjection: self.Body.Contains(stmt:MethodCall | stmt.MethodName = “EXEC_SQL”)
C	Context Class inv MethodsImplementCustMgmtFeature: self.IsPublic = **true** and self.RelatedFeature = “CustomerManagement”

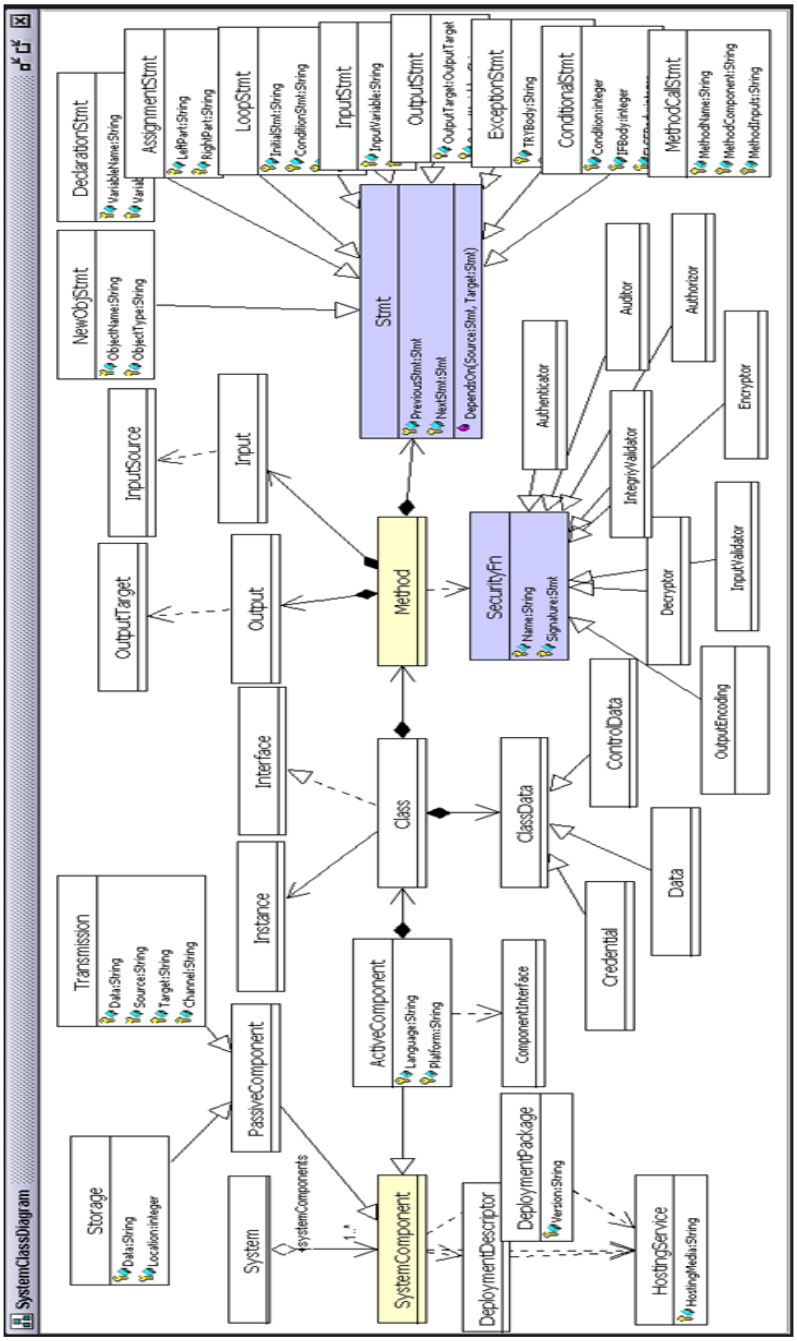


Figure 7-7. System description meta-model

7.5.3 Code Snippet or OCL Semantic Signatures

The selection between using code snippet or OCL when specifying re-aspect signatures depends on the type of entities that we want to retrieve, experience with the software, and re-aspects' developers skills. OCL can support more abstract/semantic signatures such as retrieve list of methods that use methods from other components. Another example for OCL signatures is retrieving all methods that use user inputs in calling critical functions without sanitization (SQL Inject attacks), etc. Capturing these signatures using code snippet is more complicated. On the

other hand, some signatures for code blocks with specific structure can be easily captured using code snippet approach. For example, retrieve all classes that start with a prefix or postfix or call specific methods. This signature is easier in code snippet than OCL.

7.5.4 Generating Change Set

The list of entities to be modified in order to effect a given system modification is generated using re-aspect signatures specified as either a code snippet or as an OCL signature. We have developed two algorithms (discussed in the implementation section) that analyse system source code to retrieve the change set. Algorithm 1 (for code snippet signatures) traverses the AST of the source code and re-aspect signature looking for matching sequences (taking into consideration the dummy nodes). Algorithm 2 generates a system model from the system source code that confirms to our system description meta-model. Then, it generates C# code from this OCL signature. The C# code analyses the generated system model looking for matched entities that satisfy the specified conditions.

7.5.5 Generating Impact Set

In traditional AOP we have code to be injected encapsulated as a self-contained advice, separate from the target joinpoint itself and executed as separate method call before/after/around the joinpoint. Thus no impact analysis is required. However, re-aspects handle more complex scenarios as we modify existing code parts that have similar signature but different structure and format and are located in different places. Thus any system modification requires a detailed impact analysis to identify other system entities that should be updated, other than the identified re-aspect instances, as part of code modification. Many efforts do exist in this area using heuristic rules, use-dependency relations, structural containment relation, or even hybrid techniques [260]. However, a key limitation of these efforts is that they do not deliver high soundness and completeness. Moreover, they do not support customizable user-defined impact analysis techniques that retrieve impacted entities with different relations with entities that belong to the change set. Re-aspects does support defining such customizable variations using OCL to capture signatures (techniques) to be used in retrieving such entities. Examples of supported impact analysis techniques are discussed below.

7.5.5.1 Impact Set Using Dependency Relations

For each re-aspect instance (in the change set) we compute a corresponding *impact set* based on the re-aspect instance type (class, method, property, field, line-of-code). Any given code

modification will have either local impact (on the method level) or global impact (other system entities will be impacted) based on the re-aspect instance as follows:

Table 7-3. Samples of impact analysis signatures using OCL signatures

A	Context Method inv GetImpactedMethodsforMethod: Self.Contains(S:MethodCall| S.MethodName = "ModifiedMethod")
B	Context Method inv GetImpactedMethodsforClass: Self.Contains(S:NewObj | S.ClassType = "ModifiedClass")
C	Context Method inv GetImpactedMethodsContainment: Self.Statements.Contains(S:NewObj | S.ClassType = ModifiedPropert.Class)
D	Context Method inv GetImpactedMethodsContainment: Self.Class = ModifiedMethod.Class

- *Block-of-Code*: if the re-aspect instance is a block-of-code, including declarations, assignments, control statements, then it will have local impact only – i.e. it will impact other code blocks in the same method, but it will not impact other entities, thus the corresponding impact set is empty.
- *Method*: if the re-aspect instance is a method, then it will have a global impact. To compute the impact set, we locate methods and properties that contain method calls to the modified method. Table 7-3(a) shows the signature used to identify method impact set.
- *Class*: if the re-aspect instance is a class, then it has a global impact. The change impact set contains all methods that have identifiers of this class; properties of this type or have identifier of this type; fields of this class type; and classes that have this class as base class. Table 7-3(b) shows a sample signature used to identify class impact set.
- *Property*: if the re-aspect instance is a property, then it has a global impact. To compute the change impact set, we locate all methods that have this property in any expression statement – e.g. assignment, call, if condition, loops. Table 7-3(c) shows a sample signature used to identify property impact set.

7.5.5.2 Containment-based and Heuristic-based Impact Set

Different impact set identification techniques can be supported using our OCL-based signatures. For example, the containment-based approaches focus on retrieving entities that are co-located in the same component with the modified entities. Table 7-3-D shows a simple OCL signature that can retrieve such entities. Heuristic-based approaches focus on capturing patterns of system modifications from history or relations between system entities. To support these approaches, we have to modify our system description meta-model to capture source code versioning information. Then, we can develop OCL signatures that retrieve entities that are usually

modified together. Re-aspect developers will need to write impact analysis signatures once and then use them as templates to retrieve impact set of every system modification.

Table 7-4. Samples of code modification advices

Re-aspect type		Advice
A	Modify Method Signature	Method.Parameters.Add(new Parameter(“TenantID”, “Guid”)
B	Inject code to extract TenantID	string currentTenatID=Session[“TenantID”];
C	Modify Method Invocation	InvocationExpression.Argument.Add(new IdentifierExpression(currentTenatID));
D	Inject code to add TenantID Param	db.AddInParameter(command, "tenantId", DbType.Guid, tenantId);

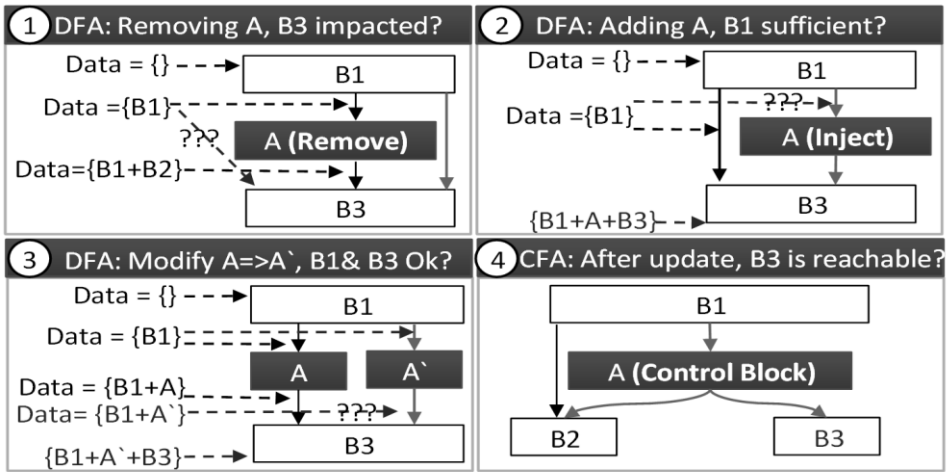


Figure 7-8. Control and Data flow analysis, local impact analysis

7.6 Change Propagation

Automating the change propagation phase in software reengineering and maintenance is very challenging. Refactoring techniques do apply some code modifications. However, these techniques depend on the nature of refactoring problem where predefined templates are used to identify bad smells and fix such code snippets using code modifications [172]. The change propagation of a given system modification depends on the re-aspect type (action) - to insert, delete, replace, or modify code of the located re-aspect instance.

To avoid inconsistency problems that may arise from repetitive updating of system source code and to support different system components that may be developed with different programming languages, we conduct change propagation on system source code ASTs. Then, we generate the final code version from the updated AST. Comments are saved when parsing source code to the AST and re-inserted in the re-generated source code. Entities in the impact

set are updated using the re-aspect impact part. Table 7-4 shows examples of re-aspect advices and their corresponding actions from the multi-tenancy reengineering domain, we are going to discuss in the case studies chapter. In Table 7-4(a) we have a modification advice that adds tenantID parameter of type GUID to a method signature. In Table 7-4(b) we have an inserting advice that has a block-of-code to be injected. In Table 7-4(c) we have modification advice that adds a parameter to the method call. Table 7-4(d) we have an injection advice that injects a new code block to a method at the matched location. It is worth noting that the modifying re-aspect requires that the advice is developed as code to be used in modifying the system entities AST. Moreover, we do not have advices for deletion re-aspects because it only deletes code with no update. Finally, the replacing and injection re-aspects have the same advices except that a replacing re-aspect has a pre-weaving step that deletes matched entities.

Whenever a system modification requires updating a method body, confirming that changes do not cause cascading problems is an extremely hard problem in general and requires a deep understanding of the logic behind the code block. Here we focus on confirming that the added, removed, replaced, or modified code does not break the data flow or the control flow between the blocks before and after the modified block, as shown in Figure 7-8. Data flow analysis (DFA) helps in confirming that the required data for the modified block is available from previous blocks and that the next blocks in the same method still have the required data items (Figure 7-8 - cases 1, 2, 3). In case 1, we removed a block of code (block A). This means that we need to make sure that data required to execute block B3 still available. In case 2, we are interested in adding block A, so it is important to make sure that data required by block A is already available from the previous blocks. The control flow analysis (CFA) helps in confirming that the modification does not lead to unreachable code (case 4).

We can use re-aspects at the model level as well as code level, to support model-driven engineering practices. Identified change set and impact set can be used to highlight (using different format – e.g. color) system UML model entities that must be modified (change set) and entities that should be modified (impact set). Developers can then update the target system models to effect required changes. Using model-driven engineering, they can propagate such changes on system source code level. Developers can continue to use re-aspect's code change propagation component. Updates are applied on code entities in the change and impact sets. Updated source code could be used to update back and synchronize system model entities. This helps in resolving the source code and models inconsistency problem that arise from frequent code updates that are often not reflected on system models.

7.7 SMART: A Re-aspect Engineering Tool

In order to support re-engineering with re-aspects, we have developed SMART (Supporting Model-driven Application Reengineering with Re-Aspects). We outline the key components of SMART as shown in Figure 7-9and its usage in re-aspects-based re-engineering as below:

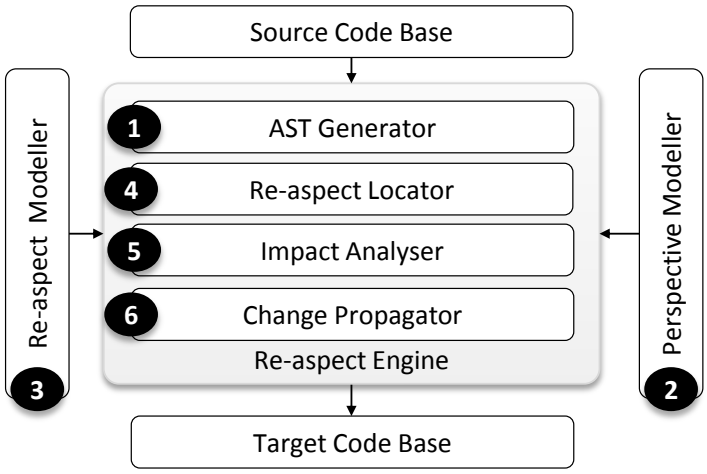


Figure 7-9. SMART tool architecture

Given the system codebase, SMART extracts system abstract representation as shown in Figure 7-9(1). Using a set of different programming languages parsers, we can build an abstract syntax tree (AST) of the input program codebase. We use AST as a program representation because it is a quick, straight forward transformation and still maintains all necessary information about the source code. In the meanwhile, it leaves out unnecessary details related to formatting and grammar details. Moreover, we can easily regenerate the same code from a given AST which is still required in the change propagation phase. SMART generates a system class diagram from the generated AST. This class diagram helps easing the next steps for the re-aspects developers. We use NReFactory, an existing .NET parser, which supports VB.NET and C#. We developed a class library to transform generated AST into a more abstract representation that conforms to our system description model Figure 7-7.

Software engineers develop different perspective models to be used in the change management process, as shown in Figure 7-9(2). This step is optional in our proposed re-engineering process. However, it is crucial for two reasons: *First*, to help specifying re-aspects' signatures that take into consideration different system perspectives – e.g. get all methods that realize a given system feature, included in a given test case or belongs to a certain system component. *Second*, to identify possible system entities that will be impacted as a result of a given change request – e.g. disabling a system function may require updating the system test cases to drop related test cases or even drop a system feature at all. Possible system perspectives

include system description models (SDM, Chapter 6) such as features model, system security model, system test cases, etc. Developing a perspective-aware reengineering and refactoring tools, that avoids inconsistency problems between the updated code and system models, is an open research challenge in the system reengineering field [154]. SMART system perspectives modeler is extensible. Developers can define a perspective meta-model, develop a parser to parse perspective models (or scripts – e.g. test case script or configuration files) and start creating and linking instances of system perspectives with source code entities modeled as system class diagram entities – e.g. marking classes or methods that deliver a certain feature.

System engineers specify system modifications they want to carry out on the target system using re-aspects, as shown in Figure 7-9(3). For each required system modification, system engineers develop a set of re-aspects that delete, replace, modify, or insert code at different places with different signatures. Developers have two options: (i) to use SMART modification guide, set of extensible patterns we developed, based on our analysis, and shown in Table 7-5, to facilitate the re-aspect specification process. This will save time in developing re-aspects and at the same time avoid fragile and incomplete signatures; or (ii) to specify re-aspects manually. In this case, the system engineers first specify where they want to touch the source code using re-aspects' signatures. This may be a code snippet written in one of the supported programming languages (currently C# or VB.NET) or using OCL constraints. Next, they need to define the set of modifications (advices) to be applied on the identified re-aspect' instances. Finally, system engineers specify actions (link advices with signatures) to be applied on each matching entity. This includes replace, modify, inject with suitable conditions – e.g. apply this action on all identified instances that within method X but for method Y apply different actions.

Given the source code, perspectives models, and re-aspects model, SMART starts locating re-aspects' instances as shown in Figure 7-9(4). Given the re-aspect definitions, SMART checks the aspect signature type first. If the signature is a code snippet it traverses the source code AST looking for matches to the given re-aspect signature. Otherwise, OCL-based, it generates a corresponding re-aspect check class (in C#) that implements the OCL specified constraints. This class parses the system description model (extracted from the source code) to identify entities with matching signatures.

Table 7-5. Part of system modification patterns and related Impacts

Level	ID	Modification	Re-aspect Signature	Action	Advice	Impact (By ID)
Class	1	Delete class parent	self.ClassName == "MyClass"	Modify	self.BaseClass == ""	5, 11
	2	Decrease Accessibility or Add Static modifier	self.ClassName == "MyClass"	Modify	self.Modifier.Add("New Modifier") self.Modifier.Remove("Old Modifier")	9
	3	Change Class Name	self.ClassName == "MyClass"	Modify	self.ClassName=="NewClassName"	10
Method	4	Delete a method	self.MethodName=="MyMethod"	Delete	self.Class.Methods.Delete(MyMethod)	11
	5	Change method signature	self.MethodName=="MyMethod"	Modify	self.Modifier.Remove("virtual")	-
	6	Add static	self.MethodName=="MyMethod"	Modify	self.Modifier.Add("static")	12
	7	Change return type	self.MethodName=="MyMethod"	Modify	self.Returntype == "New Type"	13
	8	Add Parameter	self.MethodName=="MyMethod"	Modify	Self.Parameters.Add(new Parameter(…))	
Statement	9	Delete Class Instance	Body.Contains(Createobj("MyClass"))	Delete		Local Impact
	10	Modify Class Instance	Body.Contains(Createobj ("MyClass"))	Replace Modify	new NewClassName(…) self.TypeReference = "NewClassName"	
	11	Delete Method Call	Body.Contains(InvocExpr ("MyMthd"))	Delete	If self.ReturnType = void Then Delete Else Replace with null	
	12	Modify to call static mthd	Body.Contains(InvocExpr ("MyMthd"))	Modify	Self.ReferenceType= "MyClass.MyMethod"	
	13	Modify Called Method Return Type	Body.Contains(InvocExpr("MyMthd"))	Replace	NewReturnType t = MyMethod(…)	

Figure 7-10. A snapshot of the SMRT signature locator

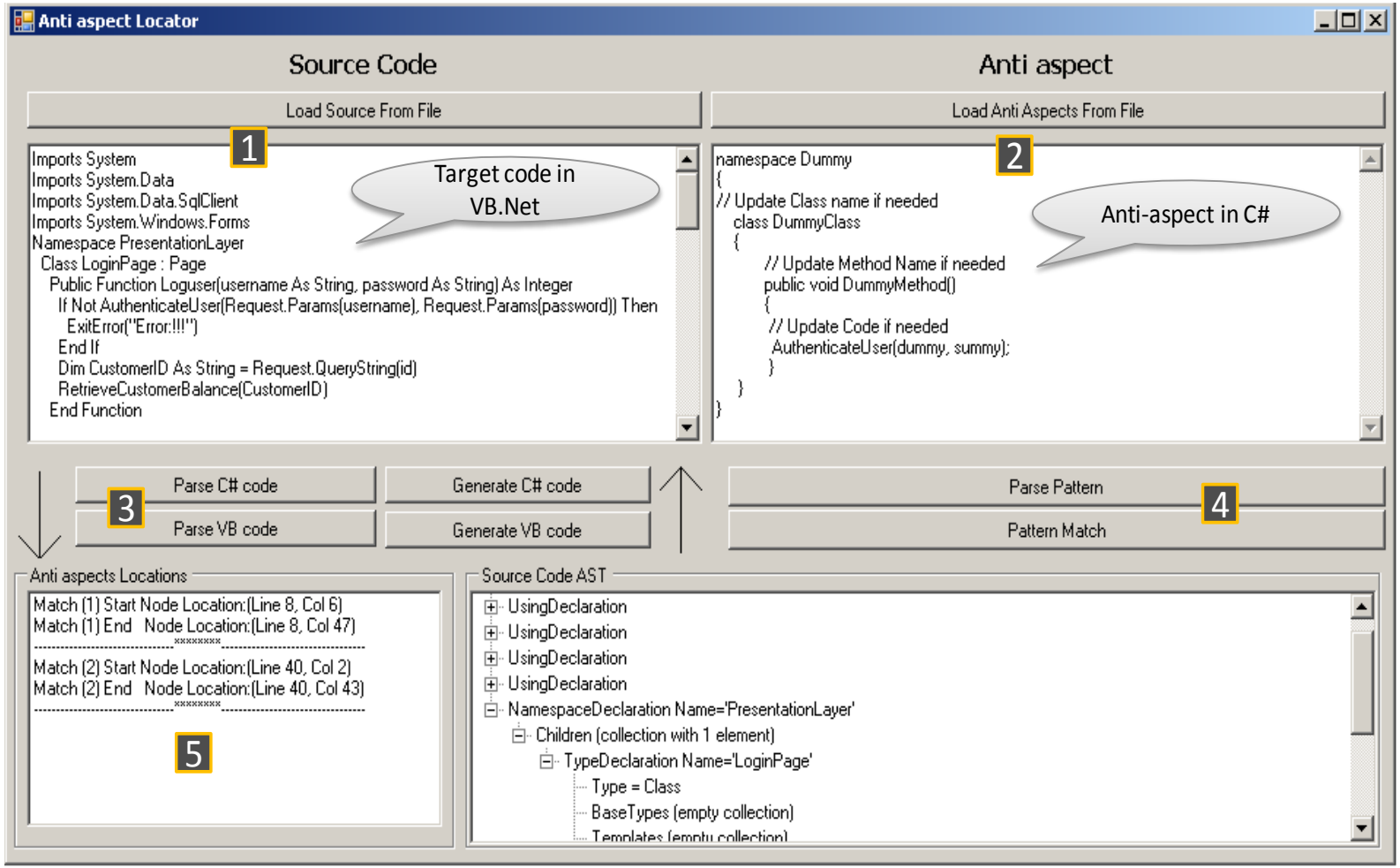


Figure 7-9 shows a snapshot of the re-aspect locator with GUI interface. Given the system source code (1), re-aspects definition (2), the re-aspect locator parses the system source code (3) and generates the corresponding AST. Then the locator parses the supplied re-aspect and generates the corresponding AST as well. Finally the locator traverses system AST searching for matches against re-aspects AST using either code snippet matching algorithm (algorithm 1) or OCL matching algorithm (algorithm 2, after converting the AST into abstract system model) and generates a list of identified re-aspect instances (5). The selection between these matching algorithms depends on re-aspect signature type. If it is code snippet then apply algorithm 1, else apply algorithm 2.

- *Algorithm 1*: The aspect locator, shown in Figure 7-11, traverses the input source code AST and the input re-aspect code snippet AST looking for matches. The matching takes into consideration the node hierarchy in both the signature and the system code. It iterates through the source code AST comparing with the signature AST treating the *dummy* constructs as "do not care" nodes in the AST.
- *Algorithm 2*: Is based on compiling and validating the given OCL signature, shown in Figure 7-12, using an OCL parser against the system meta-model from Figure 7-7. Then we generate C# class from the given re-aspect OCL signature. This class performs checks on system entities to locate entities that match the specified constraints that have been converted into set of conditions in C#.

Given the outcomes of the re-aspect signature locator, the impact analysis component, Figure 7-9(5), traverses the AST looking for nodes that depend or use any of the modified system entities using impact analysis signatures as in Table 7-3, and matching algorithm 2 shown in Figure 7-12. The results of the impact analysis component are system impacted entities as in Table 7-5 - the impact analysis column. The identified modifications are added to the re-aspect impacted entities to be considered in the re-aspect enforcement phase.

Given the identified instances of the current re-aspect, SMART executes the specified actions for the given re-aspects including injecting code (adding re-aspect), removing code (anti-aspect), replacing code (replacing re-aspect), or executing the aspect code (modifying-re-aspect), as shown in Figure 7-9(6). The re-aspect enforcer compiles the resultant code to make sure that no compilation errors have been introduced. The code injected by the enforcer depends on the target system entity language not on the aspect language – e.g. if the aspect defined in C# and one of the system components is written in VB.NET, the generated code will be in C# for all places except for the VB.NET component. Then, SMART updates the system AST, class and perspectives diagrams with the realized modifications including deleting/adding classes,

methods. Steps 3-6 should be repeated for every change request. These steps comprise the same scenario followed by any developer when implementing a given change request.

```
Procedure  CheckNodes
    Set SigAST = Call Generate signature AST
    Set StartNode = codeAST.CurrentNode
    CheckNodes:   //Recursively traverse the source code AST
    IF code-AST.CurrNode = NULL THEN
        Exit
    Dummy = True
    IF SigAST.CurrentNode.Contains("dummy")  ==  True
        DummyStatement = True
    END IF
    IF (codeAST.CurrNode.Type == SigAST.CurrNode.Type)
    OR (Dummy = True  AND codeAST.CurrNode  = SigAST.NextNode) THEN
    BEGIN
       Result = Call CompareNodes(codeAST.CurrNode, SigAST.CurrNode)
       IF Result = True THEN  //Nodes are equal
       BEGIN
          Set codeAST.CurrNode = codeAST.NextNode
          Set SigAST.CurrNode = SigAST.NextNode
        END IF
        ELSE IF Result = False THEN
        BEGIN
            Set StartNode = StartNode.NextNode
            Set codeAST.CurrNode = StartNode.NextNode
            Set sigAST.CurrNode = SigAST.Root
       END IF
       GOTO CheckNodes
    END IF
    ELSE
    BEGIN
       Set codeAST.CurrNode = codeAST.NextNode
       Set StartNode = codeAST.CurrNode
       GOTO CheckNodes
    END IF
```

Figure 7-11. Syntactical code snippet matching algorithm

```
SigAST = Call ParseOCL(OCLSig)
SigClass = Call GenerateC#(SigAST)
SigInstance = Call CreateInstance(SigClass)
SystemModel = Call ExtractSystemModel(codeAST)
Foreach entity in SystemModel DO
IF entity.Type == SigClass.ContextType THEN
BEGIN
  Var Output = SigInstance.InvariantName_Test(entity)
  MatchesList = Output.ToList()
END IF
```

Figure 7-12. Semantic OCL signatures matching algorithm

7.8 Usage Example

To demonstrate re-aspects and SMART capabilities, we apply it on Galactic application, introduced in Chapter 1, and security reengineering examples described in Section 2. SwinSoft engineers were given a set of change requests and security vulnerabilities/bugs to correct in Galactic. The list of change requests required to be realized includes: disabling built-in security controls, and solving the set of reported security bugs/vulnerabilities reported by Auckland, including SQL injection vulnerability and incorrect authorization approach. We illustrate this security reengineering scenario via screen dumps from SMART tool.

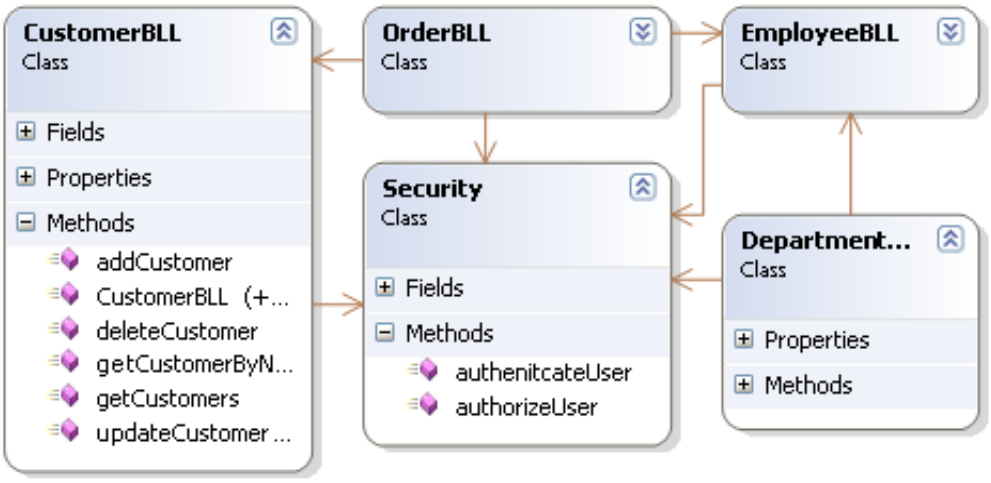


Figure 7-13. A snapshot of Galactic class diagram

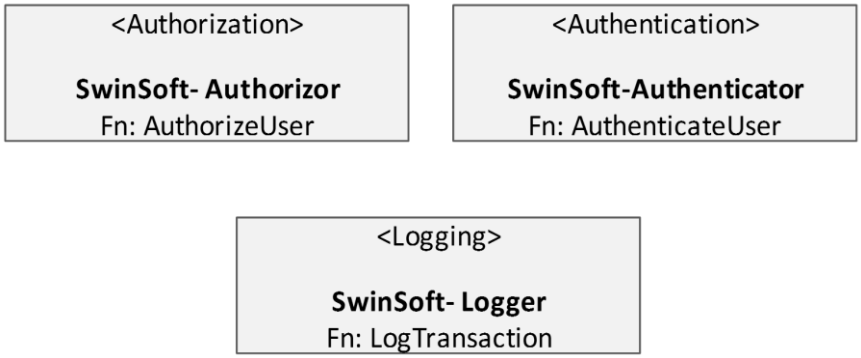


Figure 7-14. A snapshot of the Galactic security model

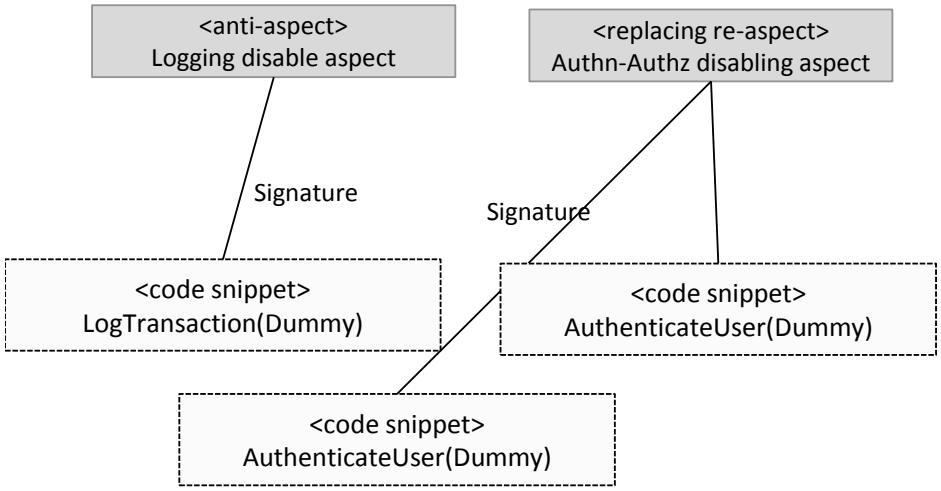


Figure 7-15. Req. 1 – Security disabling – re-aspects model

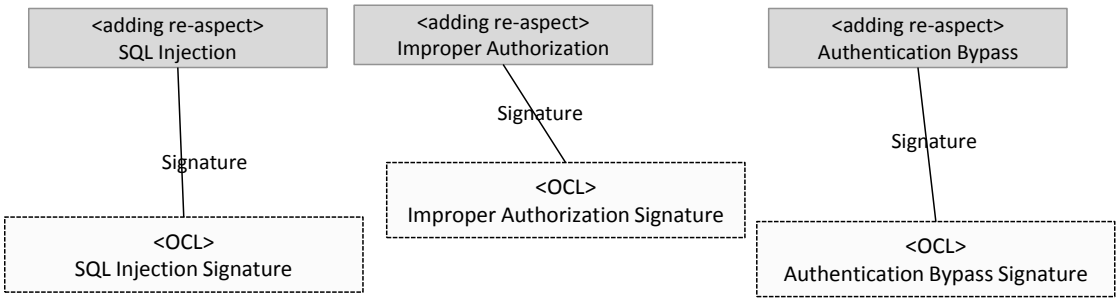


Figure 7-16. Req. 2 – Vulnerable code – re-aspects model

1. *Model System Diagrams*: Given Galactic codebase, SMART loads and parses the source code and generates the corresponding AST. Using this AST, SMART builds a class diagram reflecting all classes, methods, attributes and relationships defined in Galactic – in Figure 7-13.
2. *Model System perspectives*: SwinSoft engineers upload system UML models they are going to use in their change request implementation process or they want to include in the impact analysis phase. Here we model Galactic security APIs in a system security model, as shown

in Figure 7-14. This model is used as a reference in specifying re-aspects' signatures. Each entity in the security model shows the security control name, APIs, and the security control family.

3. Model Re-aspects: SwinSoft system engineers then model changes discussed in section 2 in terms of re-aspects model as shown in Figure 7-15 and Figure 7-16. Here we consider two requirements: disabling a set of built-in security controls; and patching a set of reported vulnerabilities as discussed in section 2. For requirement 1, security engineers determined three security controls (authentication, authorization and logging) need modification. These security controls changes are defined by three re-aspects' signatures. These signatures are defined as code snippets with only one line of code "security_fn_name (dummy-params)" – e.g. AuthenitcateUser(Dummy), developers may use an OCL signature instead. *Next*, security engineers identified two situations to take out the built-in security functions. Security functions used in If-Else statements, the security function call is replaced with "true", and security controls that are used in a simple method invocation (such as logging). In this case we just de-weave. For requirement 2, SwinSoft has been notified with three vulnerabilities in Galactic including improper authorization, authentication bypass, and SQLI shown in Figure 7-2. SwinSoft Security engineers figured out that it is better to describe these vulnerabilities in OCL – as shown in Figure 7-17. The authentication bypass re-aspect signature is defined as "any If-Else statement that contains a user input and the If-Else body has an invocation expression to the authentication API". For this re-aspect we need to modify this vulnerable code as shown in Figure 7-2. The improper authorization is defined as "any statement that uses user input without being checked by the authorization API". Finally SQL injection re-aspect is defined as "any statement that contains SQL keywords and uses user inputs". For the later re-aspects we need to inject input sanitizer and authorization function call at each re-aspect instance.

4. *Locating Re-aspects*: As shown in Figure 7-10, given the system AST and a re-aspect definition, the re-aspect locator parses the supplied re-aspect signature using SMART registered language parsers (C#, VB.NET and OCL parser) and generates the corresponding AST as well. Finally the locator traverses system AST searching for matches against re-aspects AST using either algorithm 1 or algorithm 2 and generates a list of found re-aspects instances (5).

5. Applying System Modifications: At each identified re-aspect instances, SMART checks the modeled actions on each re-aspect signature and their conditions (if any), and then it executes the linked aspects (advices). The resultant code is shown in Figure 7-2 with gray background.

```
Conext Method
inv AuthenticationBypass:
MethodBody.Select( stmt: IfElseStatement | Stmt.Condition.Contains(Method.Inputs)
  AND Stmt.Body.Contains (s : InvocationExpression | s.Method.IsSecurityFunction == true
                                  AND s.Method.SecurityFamily = "Authentication")
```

```
inv ImproperAuthorization:
MethodBody.Select ( stmt : Expression |
 (  (stmt.Contains(Self.Parameters) OR stmt.Contains(UserInputs)) AND NOT
   MethodBody.Exists(s : InvocationExpression | S.Method.IsSecurityFunction == true
                And S.Method.SecurityFamily == "Authorization"
                And S.Params.Contains(UserInputs)
                AND S.Params.Contains(self.Parameters)))
```

```
inv SQLInjection:
    MethodBody.Exists ( stmt:AssignmentStmt |
                        stmt.RightPart.Contains("select")
                And stmt.RightPart.Contains(Method.Inputs))
```

Figure 7-17. Req. 2 re-aspects semantic signatures

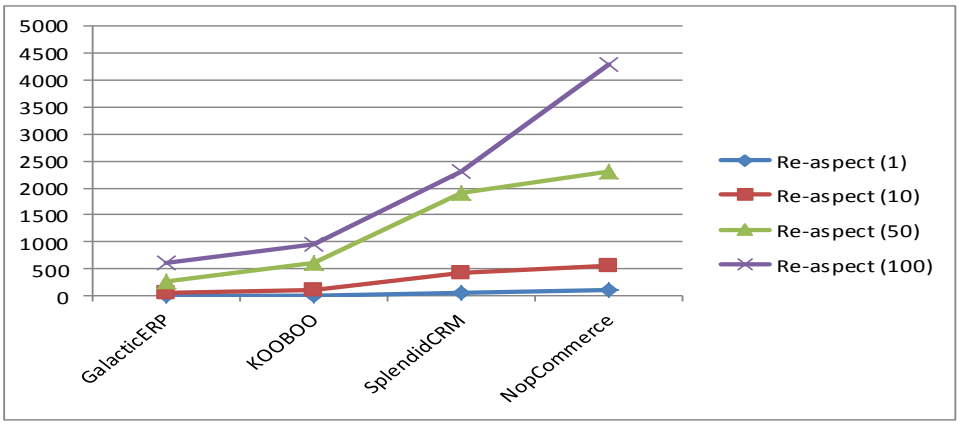


Figure 7-18. Re-aspects approach performance evaluation (in seconds)

7.9 Evaluation

We performed several evaluation experiments to assess the capabilities of our re-aspects toolset for change impact analysis and change propagation tasks. We have selected four applications of our benchmark applications introduced in Chapter 4. These applications include Galactic ERP, SplendidCRM, KOOBOO, and NopCommerce. To evaluate our approach, we developed a set of three re-aspects from the security reengineering domain including: (CR1) legacy security APIs disabling (Figure 7-2-A); (CR2) authentication bypassing mitigation (Figure 7-2-B); and (CR3) improper authorization mitigation (Figure 7-2-D).

To assess the effectiveness of our approach in software reengineering and maintenance using re-aspects, we use a set of metrics to measure the soundness and completeness as discussed in Chapter 4. From our experiments, as shown in Table 7-6, the average precision of the change set using code snippet is (89%) and the recall value is (92%). The OCL-based signatures achieved Precision (96%) and recall (97%). We see that the OCL-based signatures are capable of capturing more semantic signatures than code snippets. However the code snippet is useful with some rigid well-defined signatures such as get methods in specific layer with specific signature. The heuristics-based approach (here we use file containment as a heuristic rule) achieved average precision of (48%) and recall (50%). This was expected as the assumption that modifying a method in a file or component implies that other methods in this file should be modified is not usually valid. From the figures we conclude that OCL signatures outperform other approaches. However, accuracy of retrieved results depends heavily on the soundness of the specified signatures.

The results of the impact set generation, Table 7-7, were fair enough. Our approach achieved precision rate (85%) and recall rate (87%) percentages. Security reengineering change requests that we have selected did not have global impact (only modification in the method body). We used other change requests from the multi-tenancy reengineering domain (discussed in Chapter 10, case study 2). Thus, their impact sets where empty. OCL supports this task as well as it enables querying system source code in the AST to accurately retrieve dependent entities to be impacted by given changes. These results can be further improved by developing more sound OCL-based impact set signatures. The dependency-based approach is extensible as it is built on top of OCL. This means that we can develop more signatures for entities that should be retrieved in impact sets.

The evaluation of change propagation was different. We count how many entities successfully updated from the given entities in the change and impact sets. The results of change propagation were good enough with average success rate (89%). However, it heavily depends on the re-aspect developer to define correct advices that will be applied on the system entities according to the re-aspect action type. The precision and recall of existing efforts such as [261] were (28%) and (74%) respectively. In [168], metrics were around (50%) and (90%) respectively. In [167], metrics of the best reported effort (40%) and (50%), respectively.

Figure 7-18 shows some performance evaluation results. Numbers of re-aspects range from 1 re-aspect to 100 re-aspects. We used a desktop PC with core2Duo and 4GB memory. The time required to locate possible instances of a given re-aspect depends on the system size (KLOC). Re-aspects take on average 0.2 sec. to check 1 KLOC for a given re-aspect. The time required

for re-aspect modification depends on amount of code included in re-aspect advice and what is to be done as a re-aspect action.

7.10 Discussion

Re-aspects were inspired by traditional AOP code injection concept, but provide more possible actions – delete, replace or modify - needed for re-engineering. Re-aspects' signatures are highly flexible and specified on abstract code structures to capture syntactical code snippets, avoiding fragility factors including spaces, comments, new lines, specific variable or parameters names, variable code blocks sizes, and language syntax. Re-aspects' signatures can also capture abstract target system signatures, such as features, architecture, design and testing entities using OCL expressions. OCL-based signatures also allow capturing semantic expressions.

From experiments we found that we need to use a hybrid approach between a heuristics-based and dependency-based approach to develop an impact set. This gives a more comprehensive approach that can capture entities that have a variety of relations with the entities to be changed. A Key issue with re-aspect signatures is how to ensure that developers have written the correct signature definition for the target system entities they want to locate and change. This is, of course, also an issue for conventional AOP aspect specification and debugging too. Currently we provide a re-aspect locator UI to help developers in writing and testing their signatures. Thus, they can review the signature located entities before proceeding with the change propagation step.

Code updating usually suffers from code dependency problems where the existing code depends on code parts that we have been modifying, replacing or deleting. We have identified two key cases for dependency analysis. When changing an entity interface e.g. changing a method name from M1 to M2, we impact other system entities i.e. have a "global impact". Existing efforts identify entities that need to be modified – e.g. methods that call method M1. In our approach we support further analysis by generating signatures of entities to be modified e.g. as we renamed M1 to M2, we generate another re-aspect with signature specifying location of all method invocations to M1. Thus using the re-aspect locator we pinpoint not only the entities to change but also specific lines of code to be updated in every entity. Code required for update may be complex such as adding new method parameter. This requires developers to specify how to obtain the new argument in every updated method call. When changing a method body we use existing techniques of control flow and data flow analysis to make sure that the resultant code is still consistent. Moreover, we compile the resultant code to make sure that no compilation errors have been introduced during the reengineering process. The resultant binary

files are verified by PEVerify. Ultimately, we still depend on testing tools to make sure that the updated application functions as required.

7.11 Chapter Summary

We introduced a novel solution, the re-engineering aspect or "re-aspect", to help with two key tasks: disabling built-in security capabilities of the cloud-services as a preprocessing step before applying MDSE@R for security engineering; and patching of the reported security vulnerabilities in cloud services. Re-aspects are inspired by traditional AOP but capture richer details required for system modifications. They include rich signatures to identify target system entities that need to be modified, actions to apply on located matches, including take away (de-weaving), replace, modify or insert new code, and code to update matched entities. A key strength of re-aspects comes from the signature specification. Re-aspects support flexible signature specification approaches using syntactical code snippet templates and formal OCL-based signatures. We have developed a prototype tool that supports software reengineering including locating code entities to change, conducting impact analysis, and automated code updates. We validated the effectiveness of our approach in locating system entities to be modified and propagating changes using a set of open source .NET benchmark applications.

Table 7-6. Re-aspects change analysis effectiveness

Application		**Galactic**						**SplendidCRM**						**KOOBOO**						**NopCommerce**					
Techniques		C		O		H		C		O		H		C		O		H		C		O		H	
Metrics		P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R	P	R
Change Request	CR1	1	1	1	1	0.7	0.6	1	1	1	1	0.5	0.6	1	1	1	1	0.7	0.5	1	1	1	1	0.4	0.5
	CR2	0.8	0.9	0.9	0.9	0.4	0.5	0.8	0.8	0.8	1	0.5	0.5	0.7	0.8	0.9	0.8	0.3	0.4	0.8	0.8	1	1	0.6	0.4
	CR3	0.7	0.8	0.9	0.8	0	0	0.6	0.8	0.9	0.9	0.1	0.1	0.7	0.7	0.8	0.8	0.2	0.1	0.8	0.7	0.9	0.9	0.2	0.2

Table 7-7. Re-aspects impact analysis and change propagation effectiveness

Impact Set										**Change Propagation**							
Application		Galactic		SplendidCRM		KOOBOO		NopCommerce		Galactic		SplendidCRM		KOOBOO		NopCommerce	
Metrics		P	R	P	R	P	R	P	R	M	S	M	S	M	S	M	S
Change Request	CR1	L	L	L	L	L	L	L	L	3	3	13	9	11	11	10	10
	CR2	L	L	L	L	L	L	L	L	9	6	3	2	13	12	3	3
	CR3	L	L	L	L	L	L	L	L	3	3	5	6	0	0	0	0

P: Precision, R: Recall, C: Code Snippet, O: OCL signatures, and H: Heuristics-based

L: has local impact only, M: Number of entities to be modified, S: number of entities successfully modified

Chapter 8
Cloud Applications Security Analysis

In this chapter, we discuss the key security analysis tasks and challenges when applied to cloud computing applications and how we address these challenges in our new online security analysis approach. This chapter is organised as follows. In Section 1, we give a general introduction of the software systems' security analysis problem and how this becomes more complicated under the cloud computing umbrella. In Section 2, we discuss key security analysis tasks with few examples of each subtask. In Section 3, we introduce our comprehensive, extensible cloud application security analysis approach. In Section 4, we describe implementation details of our approach. In Section 5, we summarize the experimental evaluation results.

8.1 Introduction

Although the adoption of publicly accessible cloud computing platforms to host IT systems helps customers to minimize cost and increase availability and reachability of their applications, it has serious implications on their applications' security. Hackers can easily exploit vulnerabilities in such publically accessible services. Moreover, some hackers may become legitimate tenants of the shared cloud services which enable them to exploit more advanced and complicated vulnerabilities that require higher privileges. In addition, the number of newly identified and reported application vulnerabilities is increasing rapidly. Delays in discovering and mitigating such vulnerabilities increase the probability of successful application attacks and security breach.

Web applications are the prominent application delivery model used in cloud computing to deliver SaaS applications. Web applications do not require client deployment or configuration, and can be centrally updated and managed. However, web application vulnerabilities continue to make up the largest percentage of the total reported vulnerabilities in software applications. Web applications vulnerabilities constitute 63% on average of the total reported vulnerabilities [60]. Of these reported vulnerabilities, well-known vulnerabilities such as Cross-Site Scripting (XSS) represents 28%, while SQL Injection (SQLI) vulnerabilities represent 20%. These figures mean that web applications are the weakest link in the cloud computing model where many security breaches may be exploited.

From our investigation of the cloud computing model, cloud services, their security problems, and existing industrial and academic efforts, we have reached a conclusion that it is

very important to have an online security analysis service. Such a service can help different cloud stakeholders in analyzing and mitigating against existing (known) as well as new (i.e. never seen before) security flaws and vulnerabilities before attackers do. However, security analysis is a very complicated and time consuming task. It usually takes place at different stages of the software lifecycle starting from the development phase, deployment, and at runtime. In each of these stages, we have different artifacts to verify (system models, security models, source code, and software binaries) and different techniques (black-box, white-box, dynamic analysis, static analysis) that are applicable at each stage.

From our analysis we have categorized the security analysis task into three subtasks: *threat analysis***,** which is conducted in the early stage of software development and focuses on identifying the security flaws resulting from the adoption of specific platforms, patterns, or languages*; vulnerability analysis*, which is conducted during software development given the source code is available or after the software delivery using the software binaries; and *attack analysis*, which is conducted using software security and deployment models to identify possible attack vectors that exploit existing vulnerabilities either in the software or its operational environment.

Security flaws, bugs, and attacks reported by different security analysis tasks are usually recorded in commonly available databases, such as vulnerabilities' databases - NVD [262] or CVEdetails.com [263]. Specifications of classes of possible vulnerabilities (known as weaknesses) are already maintained in the Common Weaknesses Enumeration (CWE) database. Possible attack patterns are already maintained in the Common Attack Patterns Enumeration and Classification (CAPEC) database. Both databases are used as a reference framework by application developers, deployment engineers and security engineers to help identifying possible weaknesses and attacks on the software under analysis. A key problem with both CWE and CAPEC is that recorded vulnerabilities and attacks are specified informally. This leads to adoption of manual security analysis done by security experts using some of their helping tools developed by different security vendors. Such tools are usually based on the security vendors' understanding of security vulnerabilities, threats, and attacks. Commercial vulnerability scanners such as IBM AppScan, HP Web inspect, Cenzic, McAfee focus on black-box vulnerability analysis [116] (where few knowledge about the target software is required) to avoid being limited to specific programming languages or platforms. However, none of these scanners cover all known vulnerability types [116]. These tools cover no more than 47% of the known vulnerabilities. To achieve good results and high accuracy in the vulnerability analysis mission, multiple scanners should be applied [116]. On the other hand, most existing research efforts [113, 114, 117, 121, 264] tend to focus on specific vulnerability, threat, or attack types.

Thus, addressing new vulnerabilities or threats is often not possible with these approaches. Most of existing vulnerability analysis efforts, for example, focus on SQLI [107, 109, 115], XSS [113, 115, 265], or input sanitization [118, 119, 121] using static analysis with different variations [108, 109, 112, 113, 264], dynamic analysis [116, 117, 265, 266], or hybrid techniques of static and dynamic analysis [111, 121, 264, 267].

From our analysis of both industrial and academic efforts, we have reached a conclusion that the root cause of the security analysis problem lies in the vulnerability, threat and attack definitions and not in introducing new analysis techniques, as most of the existing approaches use similar techniques in various combinations. Moreover, the various existing vulnerability and attack databases, while useful, cannot be directly utilized by security analysis tools due to their informality.

We determined that different security analysis tasks, including vulnerability analysis, attack analysis and threat analysis, can be facilitated given that a formalized weakness definition exists. In our approach discussed in this chapter focus on the following open research questions:

- What details do we need to capture to fully describe a given security flaw and vulnerability?
- How can we formalize the signatures of such security flaws and vulnerabilities?
- How can we effectively use such formal specifications in automating the security analysis process?
- How can we enable different tenants to specify and analyze their cloud services security?

In the next sections we introduce an analysis of the well-known security issues (attacks and vulnerabilities). Then we introduce our new approach to address the research questions specified above. Finally, we discuss the limitations of our approach and future extensions.

8.2 Security Analysis

In this section we analyze some of the frequently reported security flaws and vulnerabilities in software systems. However, this is neither a comprehensive nor a complete list of all possible attack scenarios or security vulnerabilities. The main objective from this analysis is to show details of such security flaws/bugs and discuss proposed signatures that we can use to locate such flaws/bugs in the software under analysis. The example signatures discussed in this section are not meant to be complete. Security experts might need to develop more detailed signatures to use in analyzing systems using our signature-based security analysis approach.

8.2.1 Architecture Security Threat Analysis

Assessing software architecture security risks is usually conducted either using attack scenarios-based approaches [92, 96, 97, 268] or using architecture assessment metrics [92, 93, 98, 103, 139]. Developing security attack scenarios to be used in assessing software architecture is a key task in scenario-based architecture analysis approaches. However, it requires deep knowledge of the security domain, which is usually not feasible for software engineers. Microsoft introduced STRIDE model [94] (Spoofing, Tampering, Reputation, Integrity, Denial-of-Service, and Elevation-of-Privilege) that defines a framework that gives guidance in identifying such security scenarios. Microsoft has introduced further refinements on this model (EOP Card Game) to simplify the threat identification process [269]. However, this approach still depends heavily on engineers' experience to analyze the architecture of the software under test. Recently, a new community effort, CAPEC, introduces a reference repository that can be used in assessing systems' security. It provides a comprehensive list of possible attack patterns that are frequently used to breach systems' security. However, CAPEC is not yet formalized enough for use in automated architecture security analysis tools. Below we discuss a few of the key patterns that currently exist in these repositories. Then we show how we have succeeded in developing formal signatures of these attacks using our signature specification approach. We note that these attacks may have other signatures and specifications when it comes to source code level analysis (bugs) i.e. for vulnerability analysis.

8.2.1.1 Examples of Security Attack Scenarios

We summarize some of the key attack scenarios that may be used in assessing architecture security of software systems. More attacks can be found in the CAPEC database. Later we will show how we have developed formalized signatures of such attack scenarios.

- *Man-in-the-Middle Attack (MITM):* In this attack, the attacker intercepts communications between two components or two parties. The attacker makes independent connections with the victims and relays messages between them, making them believe that they are talking directly to each other. How to decide that the software under analysis is vulnerable to such attack? A signature of such attack is to check if the system has any unsecure connection between two communicating components, or if the components communicate in an untrusted zone without security authentication applied.
- *Denial of Service Attack (DOS)*: This attack aims to make a system or one of its key resources unavailable for legitimate users. DOS attacks have different formats and different signatures. Some use invalid inputs or big sized inputs. Others overwhelm the system with a tremendous number of requests. Possible signatures of such attack include: (i) a publicly

accessible component that does not use input validation control (or application firewall) to validate incoming requests, or (ii) a public interface that does not implement appropriate authentication control to filter malicious or unauthenticated requests.

- *Data Tampering Attack*: An attacker can tamper with data at rest (storage), in transmission, or during processing if data is manipulated as plaintext. Possible signatures of these attacks include: (i) a system with one or more components that operate in an untrusted host (malicious insider); (ii) data communicated between components or to a client in plaintext, or (iii) absence of appropriate security authorization controls on user accessible components.
- *Injection Attack*: These attacks use the lack of input validation to pass in malicious inputs that can be used to gain higher privileges, modify data, or get the system to crash. There are different types of injection attacks including SQL Injection, OS Command Injection, and XML Injection attacks. The key signature of such attacks is that system components do not apply suitable input filtration on user inputs or on inputs from other untrusted components.

8.2.1.2 Examples of Architecture Security Assessment Metrics

Developing security metrics to be used in assessing security strength of a software system's architecture is also a very complicated task. Different security metrics exist with different scope of applicability. Below we discuss some well-known metrics that are used in assessing system architecture security soundness based on software and security architectural structures.

System Architecture Security Metrics. These metrics help in assessing the security soundness of the software architecture itself. Examples of these metrics include attack surface metric [270], total public classified attributes and methods [101], critical super-classes proportion, least privilege, and least common mechanisms [271]. These metrics can be used to assess the exposure, exploitability, and attack-ability of the software system given its architecture, design, and source code details. New architectural patterns such as multi-tenancy require new security metrics that can assess tenants' data isolation, security elasticity, *etc*. Examples of such metrics are:

– *Attack Surface Metric [270]*: This metric has been frequently used in assessing different system versions from the security perspective. It measures the proportion of the system accessible to public users which an attacker can exploit to attack the system. This can be measured as the number of system methods that receive data from the software environment, number of methods that return data to the software environment, number of communication channels, and number of untrusted data items. The larger the attack surface value, the more potentially insecure the system.

- *Compartmentalization Metric [271]*: Compartmentalization means that a system and its components run in different compartments, isolated from each other. Thus, the compromise of any of these components does not impact the others. This metric can be measured as the number of independent components that the system is based on to deliver its function and do not trust each other - i.e. components authenticate and authorize requests and calls coming from other system components. The higher the compartmentalization value, the more secure the system. However, higher compartmentalisation usually has higher performance overheads and system complexity.
- *Least Privilege Metric [271]*: This metric states that each component or user should be granted the minimal privileges required to complete their tasks. This metric can be assessed from two perspectives: from the security controls perspective we can review users' granted privileges – i.e. security permissions. From the architectural analysis perspective this can be assessed as how a system is broken down to minimal possible actions i.e. the number of components that can access critical data. The smaller the value, the more secure the system.
- *Fail Securely Metric [271]*: The system does not disclose any data that should not be disclosed ordinarily at system failure state. This includes system data as well as data about the system in case of exceptions. This metric can be evaluated from the security control responses – i.e. how the control behaves in case it fails to operate. From the system architecture perspective, we can assess it as the number of critical attributes and methods that can be accessed in a given component. The smaller the metric value, the likely more secure the component in case of failure.

Security Architecture Metrics. These metrics help in assessing the security architecture and mechanisms used in securing a target system. Security mechanisms include: security functions and components, security patterns, and security controls. NIST [271] introduced a set of design principles that should be adopted in developing secure systems. These principles include: layered security; simplicity of the security design; protect information while it is being processed, in transit, and in storage; and never trust external inputs. Examples of metrics that can be used to judge such characteristics include:

- *Defence-in-depth (layered security) Metric*: This metric verifies that security controls are used appropriately at different points in the system chain including network security, host security, and application security. Components that have critical data should employ security controls in the network, host, and component layer. To assess this metric we need to capture system architecture and deployment models as well as the security architecture model. Then we can calculate the ratio of components with critical data that apply the layered security principle compared to the total number of critical components.

– *Isolation Metric*: This assesses the level of security isolation between system components. This means getting privileges to a component does not imply accessibility of other co-located components. This metric can be assessed using system architecture and deployment models. Components marked as confidential should not be co-located with non-confidential (public) components. Methods that are not marked as confidential should not have access to confidential attributes or methods.

```
public bool LogUser(string username, string password)
{
   …
   string query = "SELECT username FROM Users WHERE
         UserID ='" username " ' AND Password = '" +  password + "'";
…
 }
```

Figure 8-1. A code snippet vulnerable to SQL Injection attack

```
if( Request.Cookies["Loggedin"] != true )
{
  if(!AuthenticateUser(Request.Params["username"],  Request.Params["password"] ) )
        throw new Exception("Invalid user");
}
DoAdministrativeTask();
```

Figure 8-2. A code snippet vulnerable to authentication bypass

```
if(!AuthenticateUser(Request.Params["username"],
                     Request.Params["password"] ) )
      throw new Exception("Invalid user");
updateCustomerBalance(Request.QueryString["custID"], nBalance);
```

Figure 8-3. A code snippet vulnerable to improper authorization

8.2.2 Vulnerability Analysis

Security vulnerability analysis is usually conducted on either software binaries or source code. Before we discuss how we formalize software system vulnerability definitions, we give an overview of the OWSAP Top 10 web application vulnerabilities. OWSAP (Open Web Security Application Project) is a community effort to define and share knowledge about web application security approaches. We discuss these Top 10 vulnerabilities and signatures that we deduced from the vulnerabilities recorded in NVD and CWE. These signatures are used by our vulnerability analysis tool; however, they can be further revised by experts to get more accurate results.

- *Injection Flaws*: This type of vulnerability includes several well-known attacks intended to compromise application inputs in order to gain control or modify data, such as SQLI, OS Command Injection, LDAP query injection, and XPath query injection. All arise from input validation problems. "All external inputs are untrusted" is a well-known security principal

[271] that should be realized in securing systems. These vulnerabilities occur whenever the system under analysis trusts inputs from users (first order injection) or from a repository (stored or second order injection) and uses it to build dynamic queries that run Operating System or database commands without sufficient input sanitization or validation. An attacker can use this type of vulnerabilities to execute malicious commands or gain privileged access to the system under attack. Figure 8-1 shows code vulnerable to SQLI. For example, a password argument of the form "' OR (1=1) OR ''='" allows access to any specified username e.g. 'admin' or 'root'. The signature of these vulnerabilities is a dynamic query statement that uses external inputs without proper sanitization.

- *Cross-Site Scripting Flaws:* This is a two-step vulnerability. First, an attacker uses the application to store malicious data. Whenever a victim sends a request to resource X, the web server responds with data containing "malicious code" without being encoded. This malicious code executes on the victim browser causing disclosure of their confidential information to the attacker. This vulnerability type may be from stored data (e.g. from a database) or reflected (from user input). This is a very common attack in applications that use user inputs for search or discussions. The signature of these vulnerabilities is to call output functions using external or stored inputs without sanitization or encoding.
- *Broken Authentication and Session Management Flaws:* This is a common problem with security authentication. It includes attacks such as: authentication bypassing via external inputs (depend on external input to decide whether to conduct authentication or not on the received request); authentication checking not included in critical functions; using hard-coded credentials; using an easy to guess password; or session timeouts not set or checked. This enables unauthenticated users to maliciously access and use system resources. Figure 8-2 shows a code-snippet vulnerable to improper authentication attack, where a user can modify their cookie to bypass the authentication check. The signature of these vulnerabilities is that every publicly accessible function should not trust external inputs to bypass (by conditional statement) triggering the authentication function.
- *Insecure Direct Object Reference Flaws*: Authenticated users can send malicious inputs to access unauthorized data. Figure 8-3 shows an example where an attacker sends custID = XYZ instead of custID = ABC. This enables the attacker to access other customers' data. The signature of these vulnerabilities is that user inputs are not authorized before use in business functions. This is a very critical problem in multi-tenant SaaS applications where different tenants sharing the same service instance should not be able to request data of other tenants.
- *Cross-Site Request Forgery (CSRF) Flaws*: An attacker deceives an authorized user by sending a forged request to the user's application to perform malicious actions. This attack

requires the victim to have a valid session or cookie with the application (already authorized). The signature of these vulnerabilities is that requests' origins are not validated or that responses are usually predictable or have fixed URL format. It is usually difficult to identify CSRF using static analysis because it is usually managed externally by the web server.

- *Security Misconfiguration Flaws:* The system is not securely configured. This includes exposing information through exceptions; a system executing with higher privileges than it requires; system files are accessible to unauthenticated users; or resources have misconfigured permissions. Some of these vulnerabilities can be discovered from the exception handlers whether they expose system details or not. Others need to be examined by application responses for unauthorized actions using dynamic analysis.
- *Invalidated Redirect and Forward Flaws:* The application redirects requests to a target URL that is concatenated from user inputs "Response.Redirect(userInput)". This type of vulnerability is similar to the injection vulnerabilities where web redirect functions use external inputs to build the redirect URL.
- *Failure to Restrict URL Access Flaws*: An application does not perform access control on resources or URLs. These vulnerabilities can be easily examined by checking webpage methods for authorization function calls. Dynamic analysis is required to check application responses for unauthorized URLs.
- *Insufficient Transport Layer Protection Flaws*: Sensitive data including credentials and customer data are transmitted in plain text. The signature of these vulnerabilities is that output data are transmitted without passing through appropriate encryption functions. Dynamic analysis is required to examine responses if protection is done on transportation layer.

8.2.2.1 Analysis of Security Vulnerabilities

A given software system, whether desktop, web, or embedded, needs to run on a hosting service – e.g. web server, operating system, virtual server, etc., as shown in Figure 8-4. A hosting service provides a set of APIs that the hosted system can use to read inputs from possible input sources (users, files, memory, database, etc.) or write outputs to possible output targets. Any vulnerability in the hosting service implies that an attacker can control inputs and/or outputs of the target system. The hosting media is a place where the hosted system runs – e.g. a process in case of web server, or memory in case of operating systems. If the hosting media was breached, it may be used to control the hosted system inputs, outputs, or even processing (overriding kernel data using buffer overflow). However, these entities are out of the software system control.

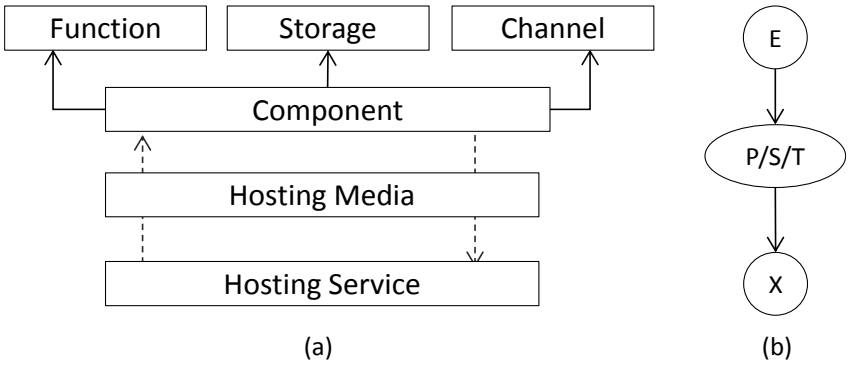


Figure 8-4. An overview of the host-system-component relations

Any target system is composed of a set of components. These components may be subsystems, composite components, or simple components. System components may be hosted on the same hosting service instance or different instances (different servers). In the latter case, they have to communicate through communication channels, which may be unsecure (an attacker may eavesdrop, or intercept messages). A system component may be an active component, a component that can take actions or perform operations such as system functions. Active components are able to secure themselves and their processed data – e.g. by authenticating users, authorizing users, encrypting data, etc. Alternatively, a passive component is a component that cannot take actions to protect or change data it maintains, such as storage components (databases and files – we are not talking here about the DBMSs, these are hosting software systems) or transmission components (communication channels). Passive components cannot secure themselves e.g. a file or table cannot enforce security access on its contents by itself. They depend on other components, such as the hosting service (OS, DBMS), or active system components to manage and secure such components. This is a big open issue in data security area – i.e. data leakage protection - where confidentiality of data moving between different applications with different security levels may be threatened. Both active and passive components might be breached by the hosting service e.g. read data in memory, files, or when it is on communication channels.

Each component, regardless of its type, has a set of entry points (E) and set of exit, output points (X), and is used in processing (P), storage (S), or as a communication channel (T). These entry and exit points can be compromised by an attacker who has control on the hosting service to read/write/modify/delete the data. Usually the number of entry points and exit points – the "attack surface" - is used as a security metric when assessing systems security. Furthermore, an active component may have vulnerabilities related to inputs (input validation - input coming from a user passing by the hosting service), outputs (output validation and exceptions – outputs may depend on malicious or modified inputs or passed through a vulnerable hosting service), or

processing (logical errors – e.g. race conditions, malicious data corruption, service overloading). We use this analysis in categorizing vulnerabilities according to the source of vulnerability, such as input validation, output validation, processing, and hosting service vulnerabilities. This helps in deciding which types of vulnerabilities can be identified by static analysis, dynamic analysis, etc. Moreover, it helps in deciding the mitigation actions that can be applied to block such vulnerabilities.

8.3 Signature-based Security Analysis

We base our security analysis approach on (i) a formal security weakness definition schema that captures every detail related to a given security flaw or vulnerability; (ii) a formal security weakness signature specification approach that can capture security flaw and vulnerability signatures; and (iii) an extensible security analysis tool that perform signature-based software security analysis.

8.3.1 Security Weakness Definition Schema

We studied the various security analysis tasks (vulnerability, attack and threat analysis) to identify the key items required in these tasks that should be included in a weakness definition schema, as shown in Figure 8-5. These weaknesses' definitions should be managed by security experts. Such definitions can be incorporated in CWE database. A security weakness definition should contain:

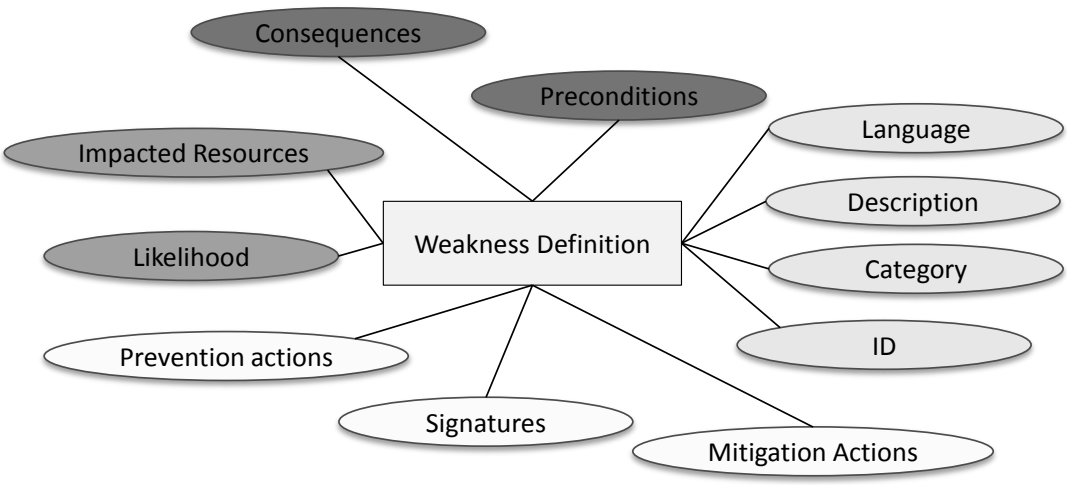


Figure 8-5. Weakness definition schema

– *Weakness ID*: Every discovered weakness instance, as in the NVD database, should have a reference to its parent weakness or vulnerability definition. This helps retrieving other

vulnerability details e.g. preconditions, consequences from the vulnerability definition stored in the CWE database.

- *Weakness Category*: Many categorization-schemas for software weaknesses do exist. Each categorization schema helps understanding weaknesses from a specific point of view e.g. developers or researchers. A categorization based on the root cause or source of the weakness, as shown in Figure 8-4, helps in deciding which technique is suitable to perform analysis, mitigation, and avoidance. We categorize vulnerabilities as input validation-related, processing logic-related, output validation-related, hosting service related, hosting media-related, communication channel-related, storage-related, and security control-related vulnerabilities.
- *Language/Platform*: Specifies enumeration of language(s) that a given weakness applies to - i.e. many languages C, C++, C#, Java. have language-specific weaknesses such as buffer overflow, sandbox breaching, etc. We also use this to describe the technology or architecture paradigm inherent with the weakness - e.g. client-server, web-based, service-oriented, or multi-tier, along with the underlying environment e.g. web server, client, application server, database server. This helps in threat analysis to identify possible weaknesses that may exist and start taking precautions to avoid such vulnerabilities.
- *Preconditions*: This attribute helps in both vulnerability analysis and attack analysis. Preconditions are a list of the capabilities that an attacker should possess, or the list of system configurations that need to be present in order to exploit such vulnerability e.g. to exploit a specific vulnerability, an attacker might have to have root access, user access, remote root access, public access, etc.
- *Consequences*: If a given vulnerability is exploited, what will be the benefits achieved by the attacker e.g. disclosure of system information, invalid processing, invalid results, execute an unauthorized function, elevate permission, bypass security, system crash, or Denial-of-Service. This can be used to analyze against planned attacks e.g. exploiting vulnerability V1 will give the attacker a set X of privileges. These privileges may be one of the preconditions to exploit vulnerability V2. The consequence of V2 may be the actual goal of the attacker.
- *Impacted Resources*: This specifies the resources that will be impacted if the given vulnerability is exploited including memory, configuration files, registry, customer data, credentials, cryptography keys.
- *Likelihood*: The probability that the given weakness is exploited by an attacker may be low, medium, or high. This depends on the complexity of the given vulnerability and attacker capabilities as defined in the vulnerability preconditions.

- *Vulnerability Signature*: A weakness signature describes constraints, invariants and patterns that when matched in a target system it means it is likely to suffer from the given weakness. This may be signature of software architecture or code snippets, or signature of system response for requests with specific signatures. Every single weakness may have different signatures that capture different forms (attack scenarios), or that are applicable with different weakness analysis techniques.
- *Prevention*: A list of precautions to be followed or checked during code review. These might be rules to check during system development or deployment; combinations of architectures; languages and platforms to use or to avoid.
- *Mitigations*: A list of actions that specify how we can modify the vulnerable system entities to block a discovered weakness. This may require modification of the vulnerable code parts; changing system configurations; or even changing system or security architecture.

8.3.2 Weakness Signature Specification

To address the different types of security analysis, we use a signature-based approach where the signatures of weaknesses to be analyzed are captured as invariants or constraints to be matched against appropriate target system artifacts. These artifacts may be lines of code, partial class/method signatures, architectural structures, or other suitable system models. In our approach, we use the Object Constraint Language (OCL) to specify such signatures (We introduced an overview of OCL in chapter 7, section 7.5.2).

8.3.2.1 System Description Meta-Model

To support specifying and validating software architecture and source code weaknesses' signatures, we have developed a system-description meta-model, shown in Figure 7-7 (discussed in chapter 7)**Error! Reference source not found.**. This model is inspired from our nalysis of security weaknesses and vulnerabilities as discussed in Section 8.2. It captures the main entities in an object-oriented program including:

- *Architecture Concepts*: Such as components, components' interfaces, communication channels, storage, hosting service (web server), deployment descriptors (configuration files), deployment packages, etc.
- *Source Code Concepts*: Including classes, instances, inputs, input sources, output, output targets, methods, method body, method parameters, method statements e.g. if-else statements, loops, new objects, etc.
- *Security Concepts*: Such as authentication, authorization, access control, input validation, auditing, cryptography and key management, and output encoder controls.

Each entity in the model has a set of attributes such as component name, class name, method name, accessibility, variable name, variable type, method call name, arguments, etc. This enables specifying OCL-based weakness and vulnerability signatures on different system entities other than source code such as deployment descriptors, hosting services, storage, output targets, or input sources. Of course, this requires developing different parsers other than source code parsers that can read such system description details.

A security analysis tool needs to have different profiles for different languages and platforms (ASP.NET, PHP, C#, Java, etc.). Thus weaknesses with signatures containing input source or output targets, security authentication, authorization, sanitization controls and other functions can be interpreted differently based on the platform or programming language used. If the system uses custom sanitization or security functions, developers have to mark their security functions in the resulting system model or add it to the platform profile member functions.

8.3.2.2 Examples of OCL-based Weaknesses Signatures

Table 8-1 shows example architecture attack scenarios, metrics, and vulnerabilities signatures specified in OCL using our system description meta-model, as shown in Figure 7-7. Each entry shows weakens or attack name, description, and signature. Before we discuss these signatures, it is worth mentioning that these signatures can be further improved to incorporate system design details and even more source code details, if available. The second point is that these signatures should be developed by security experts (captured in a knowledge base), while software developers can further extend such signatures using customized and user-defined scenario and metric signatures.

A key problem with these signatures is that they do not consider security solutions applied beyond the system source code. For example, a system might be using proxies to filter SQL queries or be using security controls deployed on the web server such as an http handler. However, these can be modeled by appending a dynamic signature forming a sequence of OCL constraints to be checked on system responses to malicious requests. Another workaround is to use the information available from system architecture to check for these scenarios. Another issue is that we may have different signatures with different complexities for the same vulnerability. We expect security experts to develop strong and complete signatures. Weak signatures mean more false positives, which may annoy developers, or more false negatives, which harm customers. However, weak signatures can sometimes be much easier to find and computationally inexpensive to locate matches compared to complex ones.

Table 8-1. Examples of OCL-specified weaknesses signatures and metrics

Man-in-the-middle attack
Any two components that communicate through an unencrypted channel and one or both of them operate in an untrusted zone or do not apply cryptography controls on their communicated messages.
context System inv MITM: self.components->select(C1|C1.DeploymentZoneType = 'Untrusted' and self.components.exists(C2 | C2.Channels->exists(Ch | Ch.TargetComponent = C1 and Ch.EncryptionCtlDeployed = false) and C1.EncryptionControlDeployed = false and C2.EncryptionControlDeployed = false))
Denial-of-service attack
Any publicly accessible component that does not operate input sanitization control (or application firewall), and does not have authentication control.
context System inv DOS: self.components->select(C1|C1.DeploymentZoneType = 'Untrusted' and C1.AuthenticationControlDeployed = false and (C1.InputSanitizationControlDeployed = false or C1.Host.Network.FirewallControlDeployed= false))
Data tampering attack
Any component that is deployed on an untrusted host (malicious insider) or zone, sends data in plain text, or does not operate authorization control.
context System inv DataTampering: self.components->select(C1|C1.DeploymentZoneType = 'Untrusted' and self.components.exists(C2 | C2.Channels->exists(Ch | Ch.TargetComponent = C1 and Ch.EncryptionControlDeployed = false) and C1.EncryptionControlDeployed = false and C2.EncryptionControlDeployed = false))
Attack Surface metric
Number of the functions defined in the provided interfaces of the public system components and number of functions defined in the required interfaces of the system public components that are used by other components.
context System inv AttackSurface: self.components->select(C1| C1. DeploymentZoneType = 'Untrusted')->collect(C2 | C2.Functions)->size()
Compartmentalization Metric
Number of architecture components that apply authentication and authorization controls on incoming requests and calls (work independent and do not trust other system components).
context System inv Compartmentalization: self.components->select(C | C.AuthenticationCtlDeployed = true and C.AuthorizationControlDeployed = true)->size()

Fail securely Metric
The average of critical methods and attributes in each system component.
context System inv FailSecurely: self.components->collect(C | C.Functions->select(F | F.IsCritical = true)->size())->sum()/ self.components->collect(C |C.Functions->select(F | F.IsCritical = true)->size())->siz()
Defense in depth Metric
The ratio of critical components that have layered security compared to the total number of critical components in the system.
context System inv Defense-in-depth: self.select(C | C.IsCritical= true and C.AuthenticationControlDeployed = true and C.AuthorizationControlDeployed = true and C.CryptographyControlDeployed = true and C.Host.AuthenticationControlDeployed = true and C. Host.AuthorizationControlDeployed = true and C. Host.CryptographyControl = true)->size() / self.select(C | C.IsCritical = true)->size()
SQLI Vulnerability
Any method that has method call statement "S" where the callee function is "ExecuteQuery" and one of the parameters passed to it is previously assigned to untrusted identifier coming from one of the input sources. This initial signature can be revised to incorporate taint analysis checking. Taint analysis can be defined as an OCL function that adds every variable assigned to a user input parameter to a suspected list. In this case, we update the vulnerability signature to use "Method.SuspectedList().Contains(X)" instead of X.Contains(InputSource)".
context Method inv SQLI: Method.Contains(S : MethodCall | S.FnName = "ExecuteQuery" and S.Arguments.Contains(X : IdentifierExpression | X.Contains(InputSource)))
XSS vulnerability
Any method statement "S" of type assignment statement where left part is of type "output target" e.g. text, label, grid, etc. and right part uses input from the tainted input sources.
context Method **inv XSS**: Method.Contains(S : AssignmentStatement | S.RightPart.Contains(InputSource) And S.LeftPart.Contains(OutputTarget))
Authentication Bypass Vulnerability
Any public method that has statement "S" of type "method call" where the callee method is marked as authentication function while this method call can be skipped using user input as part of the bypassing condition.
context Method inv ImproperAuthentication: Method.IsPublic == true And Method.Contains(S : MethodCall | S.IsAuthenitcationFn == true And S.Parent == IFElseStmt And S.Parent.Condition.Contains(InputSource))

Improper Authorization Vulnerability
Any public method that has statement "S" of type "expression" – i.e. any statement - where "S" uses data X without being sanitized, authorized, or simply taint data (Method.SuspectedList().Contains(X) == true).
context Method inv ImproperAuthorization: Method.IsPublic == true And Method.Contains(S : Expression | S.Contains(X: InputSource | X.IsSanitized == False Or X.IsAuthorized == False)

8.3.3 Signature-based Security Analysis Tool

After formalizing security attack scenarios, metrics signatures, and vulnerability signatures using OCL, an OCL-based analyzer component is used to perform the security analysis of the target system and its security details to locate and evaluate the specified security scenarios vulnerabilities, and metrics. This includes system source code, system design, architecture, and security models. Figure 8-6 shows the architecture of the analysis component. Figure 8-6(a) shows the main components of our analyzer, including the signature locator interface. Figure 8-6(b) shows different possible signature locators that can be plugged into our security analysis tool. This list is extensible to incorporate new customized signature locators. Below we discuss details of each component in the security analysis tool.

- *System Model*: Instead of using only the system architecture model to capture and apply security metrics, we use our proposed system description model – SDM explained in details with examples in the security engineering chapter (chapter 6). This model is developed by software engineers using UML to describe the details of the software system under analysis. The system SDM should cover system features (using use case diagrams), system architecture (using component diagrams), system classes (using class diagrams), system behavior (using sequence diagrams), and system deployment (using deployment diagrams). These models cover most of the perspectives that may be required in analysing system architecture security soundness. However, not all these models are mandatory for the analysis. It depends on the system engineers and which attack scenarios or metrics they want to evaluate or make it available for their tenants to evaluate or analyze – i.e. software engineers, during their analysis, may start with an initial system architecture and then develop system design to include in their analysis. Later, they may incorporate system source code. Some of these system description details, for example class diagrams, sequence diagrams, can be reverse-engineered from source code, if not available – e.g. in case of legacy systems.
- *Source Code Abstract Program Representation*: To try and avoid signatures being overly specific to programs written in a specific programming language or with a specific coding

style, we transform the given system code into an abstract syntax tree (AST) representation. The program AST abstracts most of the source code details away from specific language constructs. This requires having different source code parsers for different programming languages that should be supported by the security analysis platform. If the software source code is not available and only software binaries are available, we can use the de-compilation tools such as ILSpy to reverse engineer source code from software binaries.

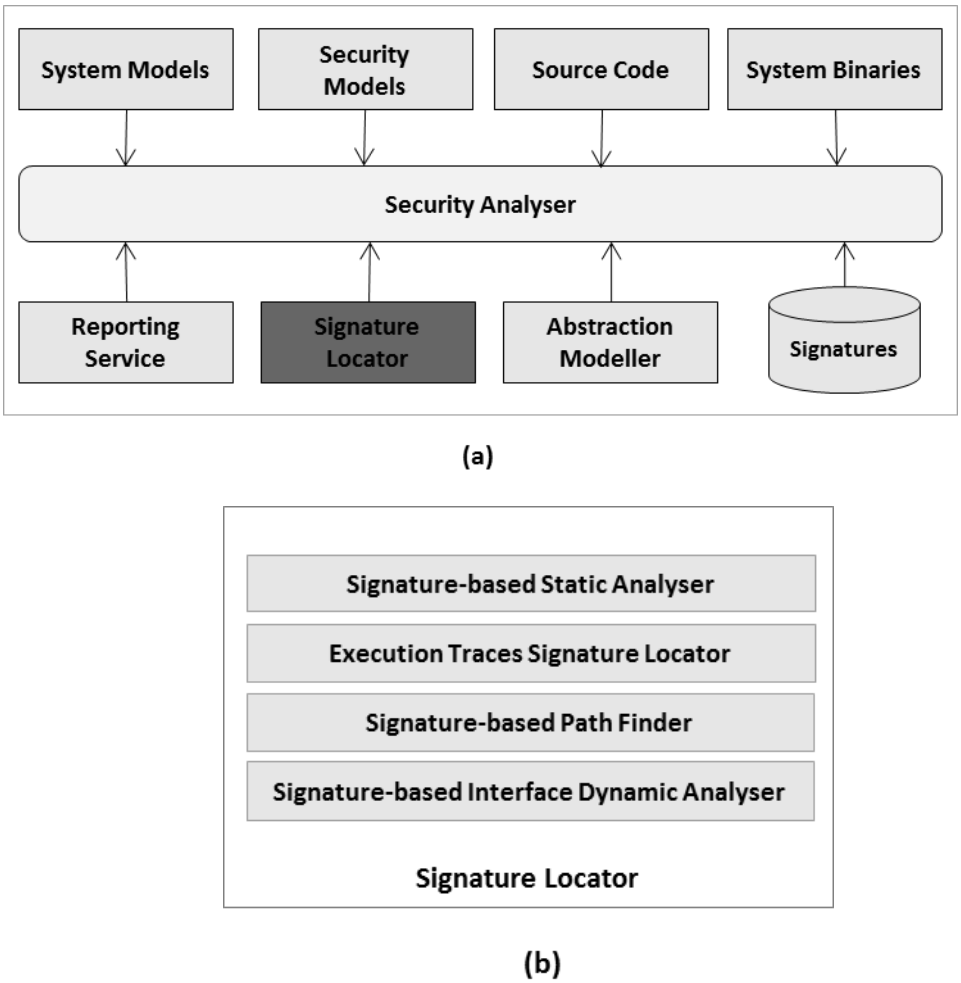


Figure 8-6. Signature-based security analysis tool

- *Security Model*: The service provider and service tenants' security engineers capture the security details developed in the software or defined on their own using our model-driven security engineering at runtime approach in separate security specification model (SSM), explained in details in Chapter 6. This enables evaluating system architecture details and security architecture details separately and combined – i.e. where we have security requirements already mapped to system entities. We use our SecDSVL as a comprehensive security domain-specific visual language. SecDSVL covers most of the details required during the security engineering process including: security goals and objectives, security

risks and threats, security requirements, security architecture for the operational environment and security controls and patterns to be enforced. Not all these models are mandatory to use. Engineers decide which models they need to check or incorporate in their security analysis.

- *Abstraction Modeler*: The system description meta-model captures all the concepts and entities around the system and security details we have explained above along with the relations between them. As discussed earlier, this model helps in validating specified signatures and in generating analyzers that will pinpoint these signatures in the software under test. To consolidate different system details in one model as described in the system description model we do *System-and-Security model* reconstruction covering system, security, and security-system mappings (specified using our UML profile, discussed in chapter 6). The UML profile extends UML models with attributes for: *(i)* relations between different system entities in different models – e.g. a feature entity in a feature model with its related components in the component model and a component entity with its related classes in the class diagram; and *(ii)* security entities (objectives, requirements, controls) mapped on system entities. The source code AST is transformed into more abstract representation that summarizes AST nodes into abstract system description model.
- *Signature Locator*: This is the main component in our security analysis tool. It receives the system and security details, security scenarios, vulnerabilities, and metrics signatures to be evaluated, platform profiles, and generates a list of the found potential flaws, vulnerabilities, security holes, and security measures. Our security analysis tool is developed to support different types of analysis techniques including static analysis, white-box analysis and dynamic analysis. The signature locator is designed to support extensibility in terms of new analysis techniques that can easily plugged-in. However, in our research project we focus on the static signature locator that can analyze the architecture and source code details statically.
- *Static Signature Locator*: This component loads OCL-based weaknesses and metrics from the signatures database and compiles these signatures into runtime analysis modules (using OCL_2_C# transformation that generates C# code from these signatures). These generated analysis modules analyze the fed in system and security models and locate entities that match the specified signatures and calculate measurements specified.
- *Execution Traces Signature Locator*: An execution trace signature locator works on the execution traces collected from the execution of the software – i.e. logs of the system functions' calls along with the arguments' values used. These execution logs attributes are already abstracted in the system description model. Thus security experts can specify signatures on such execution traces attributes. This signature locator works in the same approach like the static signature locator – i.e. it generates the corresponding C# analysis module that analyses the software model.

- *Dynamic Signature Locator*: A dynamic signature locator depends on two key attributes of the software entities (including components, classes, and methods). These attributes are requests and responses. Each of these attributes has sub-attributes including request time, values, requester, response time, values, etc. Security experts use these two attributes to specify signatures of the malicious requests that satisfy specific vulnerabilities or attacks – e.g. use "' or 1 =1" as a part of the query string or the http request sent to the server. The dynamic vulnerability analysis component uses such signatures to generate malicious requests. Then, the signature locator analyses the software responses looking for flaws in the software responses. More details are available in the security monitoring work in chapter 9.

8.4 Implementation

To help in developing and testing weaknesses scenarios, metrics and vulnerability signatures, we have developed a GUI, as shown in Figure 8-7, where security experts can write OCL expressions, check it for syntax errors, semantic errors (i.e. concepts, attributes, navigations specified), and test the specified signatures on sample data provided by the tool users. We use an existing OCL parser [272] to parse and validate signatures against our system description model. Once validated, signatures are stored in the signatures database.

To parse the given program source code and generate the corresponding Abstract Syntax Tree (AST), we use existing .NET parser *NReFactory* Library, which supports parsing VB.NET and C#. For software systems developed in C, we have used *pycparser* (a parser written in python). As a further extension, we plan to incorporate parser for PhP and Java to enable parsing programs written in these languages as well. For software systems with executable or binaries only available, we use existing de-compilation tool *ILSPY* to generate source code from binaries. This is currently supported for C# and VB.NET only. This generated source code will be parsed using *NReFactory* library.

For the system and security models, we assume that all these models will be captured either using our own system and security modelers developed using Microsoft Visual Studio (discussed in chapter 6) or by using system models (in UML) developed by any third-party modeling tool represented in XMI (XML Metadata Interchange).

We have developed a class library to transform the generated source code AST into a more abstract (summarized) representation as specified in our system description meta-model (shown in **Error! Reference source not found.**). This reduces its size and complexity to reflect only ecessary details required in signatures' matching. Our class library takes the system and security models (in XML format) and appends them to the system description model. The output of this class library is a complete model with all software system and security details.

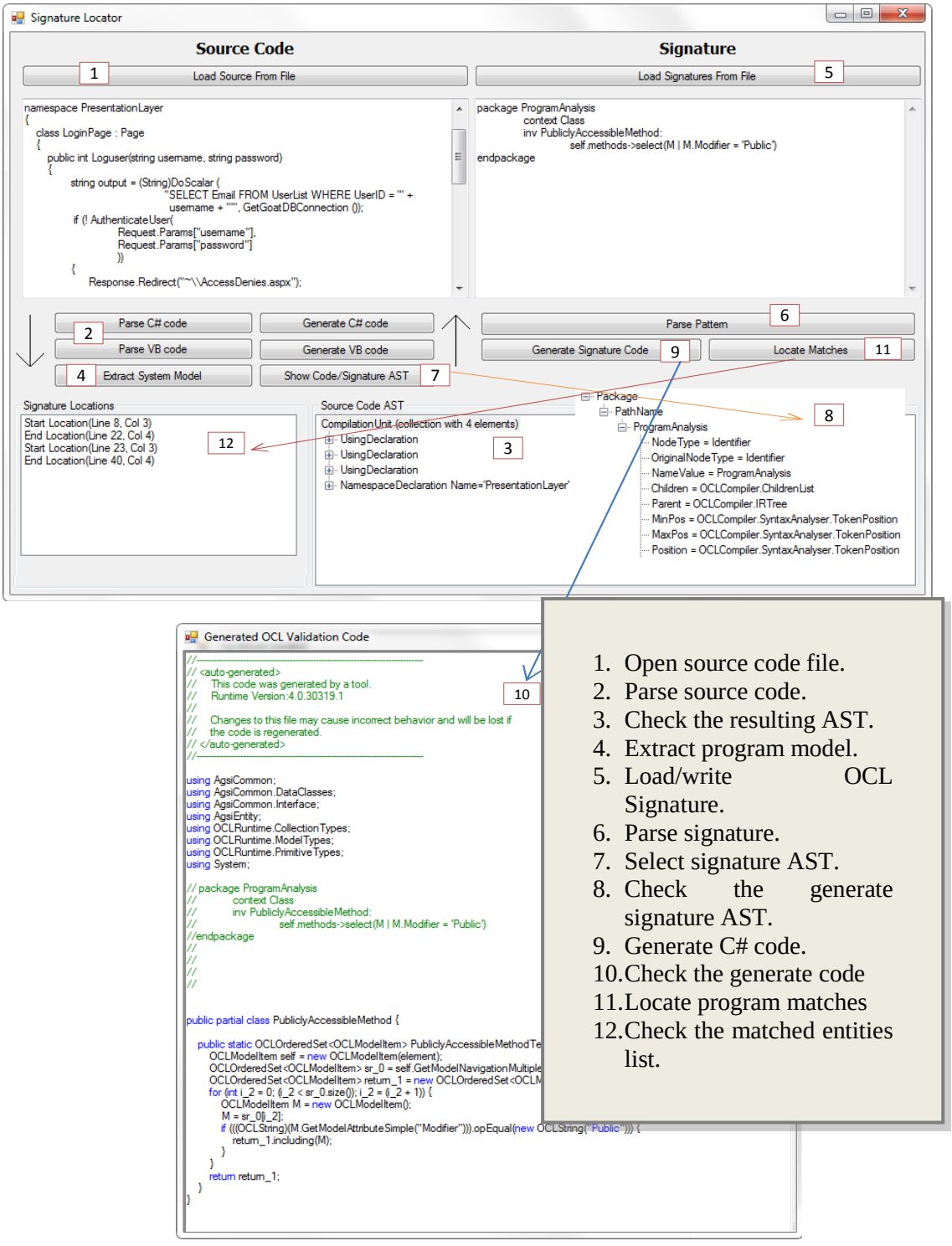


Figure 8-7. Security analysis signature locaotor UI

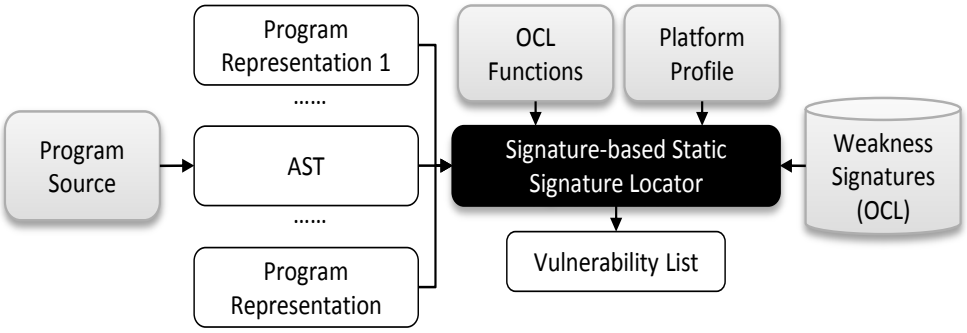


Figure 8-8. Architecture of our signature-based static analysis

```
Context Method::SuspectedList(): Collection(Identifier)
 Let userInputs: Collection(Identifier) = Method. Parameters
 Post:
   result = Method.Body->select(stmt:AssignmentStmt |
              RightPart.Contains(userInputs)->select(id: IdentifierExp))
```

Figure 8-9. Sample user-defined OCL function for taint-data

```
<Profile platform="ASP.Net">
    <InputSources>
        <Source> Web.HttpRequest.get_QueryString</Source>
        <Source>Web.HttpRequest.get_Cookies</Source>
    </InputSources>
   <OutputTargets>
        <Target>System.Web.HttpResponse.Write</Target>
        <Target> UI.WebControls.TextBox.set_Text</Target>
       <Target> WebControls.HyperLink.set_NavigateUrl</Target>
   </OutputTargets>
</Profile>
```

Figure 8-10. Sample of the platform profile for ASP.NET

The signature locator manager is developed as a class loader; it reads the list of registered signature locators from a configuration file. According to the weakness signature type, it loads the corresponding signature locator (static, dynamic, etc.) to start analyzing the system description model. New signature locators can be developed and registered with the security analysis manager. Any signature locator has access to the system description details (as a model) as well as the signatures repository. We have developed a signature-based static analysis component, as shown in Figure 8-8. This component translates the signatures expressed in OCL

to C# code using the OCL parser we discussed above. This C# code is then used by the static analysis component to traverse the system model looking for matching entities.

The static analysis component supports specifying signatures using some user-defined functions that are stored as OCL functions including control-flow analysis (CFA), data-flow analysis (DFA), Tainted-data analysis, etc. The OCL to C# library translates these user-defined functions as well as new OCL signatures once defined. Program slicing and taint analysis techniques (core techniques in program and security analysis area) can be easily captured in OCL. Figure 8-9 shows a sample tainted-data analysis function defined in OCL. This can be extended to filter sanitized variables (variables processed by sanitization functions). The static analyzer depends on platform profiles to set the analysis context. A platform profile is an XML document that contains information about a specific platform. Figure 8-10 shows an example of a platform profile for ASP.NET. This is different from Java or PHP profiles. These functions are used by the signature locator as values for the abstract concepts defined in the system meta-model (input sources, output targets, etc.).

8.5 Evaluation

In this section we summarize evaluation experiments we performed on our security analysis toolset to assess their capabilities in capturing as well as identifying security flaws and bugs. In these experiments we applied the set of exemplar OCL-based security attack scenarios, metrics, and signatures that we introduced in Section 8.3.2.

8.5.1 Evaluation Setup

We could not find a repository or benchmark set of software architectures to evaluate our approach in security architecture risk analysis. Therefore we decided to use the benchmark applications we introduced in chapter 4 section 1.3 including Galactic (ERP system developed for internal testing purposes); SplendidCRM (open source CRM); KOOBOO (open source Enterprise CMS for websites); BlogEngine (open source ASP.NET 4.0 blogging engine); BugTracer (open-source, web-based bug tracking); and NopCommerce (open-source eCommerce solution). Except for our own Galactic exemplar application we did not have detailed prior knowledge of the architecture, design, and security details of the open source applications that we analyzed. We used reverse engineering to retrieve parts of the system description models – SDM - (mainly class diagram, sequence diagram and component diagram) from the benchmark applications source code using Altova UModel. All of these benchmark applications were already developed with their own built in security functions. We performed a detailed, manual analysis to identify security controls used in such systems. We use these details

to develop benchmark applications security specification models and where they currently applied mappings between security entities and system entities. In our evaluation, we used a set of effectiveness evaluation metrics including precision and recall discussed in chapter 4.

8.5.2 Experimental Results

8.5.2.1 Architecture Security Risk Analysis

Table 8-2 is divided into two parts: security attack scenarios, and security metrics. Columns represent the benchmark applications. Rows represent security flaws and metrics. We summarize for each application and each attack scenario or security metric analyzed the number of discovered flaws or the metric measured value, number of false positives (our prototype reported as a flaw but it is not), and number of false negatives (a flaw, but missed by our prototype). Moreover, for each security scenario or security metric we indicate using (↑ and ↓) whether it is recommended to minimize or maximize the reported instances. If the indicator is (↑), it means that the higher the metric value, the more secure the architecture. The (↓) indicator means that the lower the metric value, the more secure the architecture.

Table 8-2 summarizes the results of our experiments in security scenarios and security metrics analysis and evaluation. From our experiments we found that our approach achieves on average a (90%) precision over both security scenarios analysis and security metrics measurement. This means that in every reported (100) scenario instances (90) scenarios are valid scenarios. It also has an average (89%) recall rate. This means that in every reported (100) scenario instances approximately (11) scenarios are not actual cases. These values depend on the soundness of the scenarios and the metrics' signatures used to detect them.

Table 8-2 shows that the man-in-the-middle attack is the most frequent attack in the benchmark applications. We also found a number of injection attack vulnerabilities that include SQL Injection, OS Command Injection, XPath Injection attacks. The denial-of-service attack was the least frequent attack. When we compare these results with OWSAP TOP10 vulnerabilities, we found that they reflect closely the same ranking where injection attacks are ranked number (1) common vulnerability in web applications according to OWSAP Top10.

However, from these experiments and our analysis we note that, simple totaling of the security metrics has no sensible meaning as they have different units (some count, others use average or ratio). Although security metrics are helpful in comparing two different architectures for the same system (trade-off analysis); they are misleading as they depend on the application scale.

Table 8-2. Results of our OCL-based architecture security analysis

Scenario / Metric		Galactic	SplendidCRM	KOOBOO	BlogEngine	BugTracer	NopCommerce	Total
***** Security Scenarios *****								
Man-in-The-Middle (↓)	D	1	1	4	8	3	5	22
	FP	0	0	0	1	0	0	1
	FN	0	0	0	1	0	1	2
Denial of Service (↓)	D	1	1	3	2	1	2	10
	FP	0	0	0	0	0	1	1
	FN	0	0	0	1	1	0	2
Data Tampering (↓)	D	1	1	3	5	3	3	16
	FP	0	0	0	2	0	0	2
	FN	0	0	1	0	1	0	2
Injection Attack (↓)	D	2	1	3	5	4	3	18
	FP	0	0	1	1	0	1	3
	FN	0	1	1	1	0	0	3
Total	D	5	4	13	20	11	13	66
	FP	0	0	1	4	0	2	7
	FN	0	1	2	3	2	1	9
Average Precision = 90% Average Recall = 87% F-Measure = 88%								

***** Security Metrics *****								
Attack Surface (↓)	M	8	11	17	23	18	24	101
	FP	1	2	2	1	2	4	12
	FN	0	0	1	3	2	1	7
Compartmental-ization (↑)	M	1	1	3	3	4	3	14
	FP	0	0	0	0	1	0	1
	FN	0	0	1	1	0	0	2
Fail Securely (↓)	M	0.3	0.2	0.5	0.5	0.4	0.6	-
	FP	2	1	0	0	0	1	4
	FN	1	0	0	0	1	1	3
Defence-in-Depth (↑)	M	0.5	0.5	0.8	0.4	0.3	0.5	-
	FP	0	1	0	0	1	0	2
	FN	0	2	0	1	0	1	4
Average Precision = 91% Average Recall = 89% F-Measure = 90%								

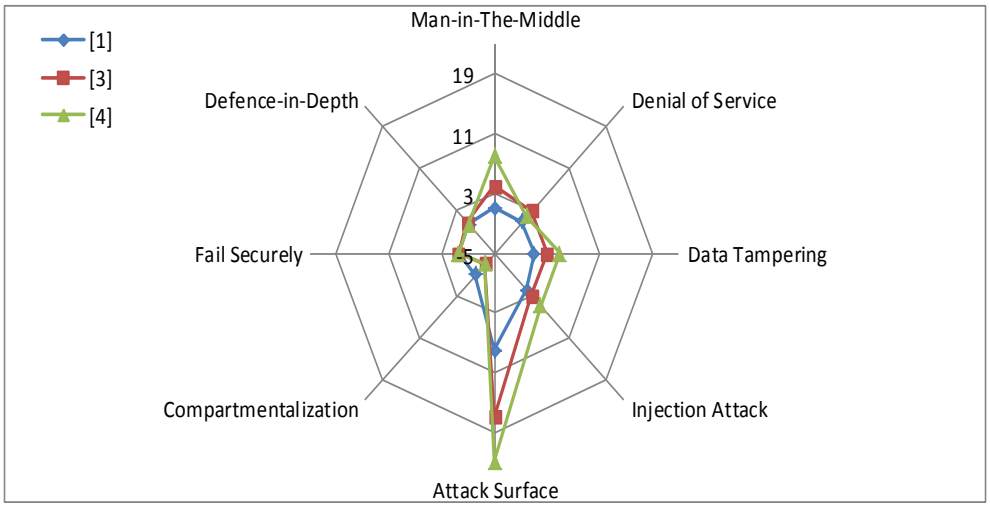


Figure 8-11. Example of radar chart of benchmark applications

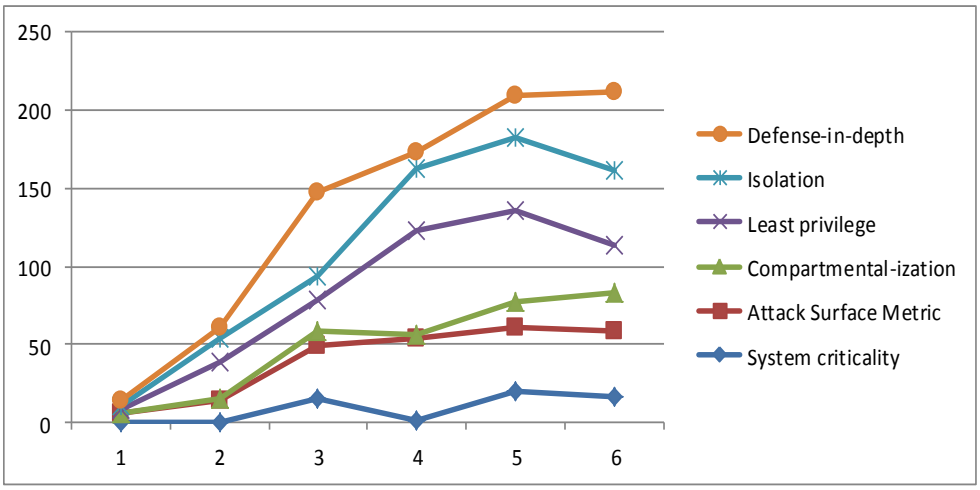


Figure 8-12. Performance of the security analysis component

Regarding the performance of our approach, Figure 8-12 shows the time (in seconds) required to analyze the benchmark applications' architectures to assessing specified security attack scenarios and metrics using the given set of scenarios and signatures Table 8-1. It is clear that the defense-in-depth metric takes much more time to identify than other metrics. The system criticality takes the lowest time. This is because the time required estimating a given security metric expression depends on the complexity of the specified OCL signature (transformed into C# code) and system size.

8.5.2.2 Vulnerability Analysis Result

Table 8-3 summarizes the results of our experiments in source code vulnerability analysis applied on the set of open source benchmark suite against seven of the OWASP Top10 web applications vulnerabilities. The other three vulnerabilities could not be specified using static signatures (i.e. could not be analyzed using static program analysis). These vulnerabilities are

security misconfiguration because it requires developing XML parser that can extract entities in the system configuration file and then we can apply signatures on these entities; *insecure communication* because it requires dynamic signatures; and *insecure cryptographic storage* because it requires dynamic signatures.

Table 8-3 summarizes, for each application and each vulnerability analyzed, the total time taken, number of found vulnerability instances in the codebase, FPs (analyzer thought vulnerability but there is not on manual analysis), and FNs (manual code analysis indicates a vulnerability but our tool did not discover it). Table 8-3 shows that SQLI represents the most frequent vulnerability in all applications, then the cross-site reference forgery (CSRF) vulnerability. After that, cross-site scripting (XSS) and authorization bypassing vulnerabilities are relatively equal in frequency. These results mostly (in terms of ratios) conform to the ranking reported by OWSAP2010. Table 8-3 also shows the number of vulnerabilities identified per application. It is clear that nopCommerce and KOOBOO are the most vulnerable applications in our benchmark suite using these vulnerability signatures. However, if we consider the application size factor, we see that the ratio of vulnerabilities discovered compared to application size is about equal. Moreover, some applications such as BlogEngine use Microsoft membership for access control, which eliminates the authentication bypassing vulnerabilities.

Figure 8-13 shows the precision, recall, and F-measure rates for each vulnerability type. This chart shows that we achieve a high precision rate for most of the vulnerability types. The precision metric is on average (93%). This means that for each identified (100) vulnerabilities we have (7) false positives. This chart also shows a good recall rate, although it is relatively lower than precision rate we achieved. The recall metric is on average (82%). This means that in every (100) vulnerability instances, we can correctly identify (82) and we missed (18) instances. This value could be improved if we use a hybrid dynamic and static analysis approach. The overall effectiveness of our vulnerability analysis approach (F-measure) is around (87%). A key result from this chart is that the recall metric is higher in SQLI, XSS, Information disclosure, and URL redirection than in the other vulnerabilities. This justifies our initial supposition that although we succeeded in developing a static signature for these signatures (CSRF, improper authorization and authentication bypass), it is difficult to achieve a high correct detection rate without also utilizing complementary dynamic analysis techniques.

Figure 8-14 shows the time (in seconds) required to analyze the benchmark applications to locate the existing vulnerabilities' instances for the given set of vulnerability signatures. It is clear that the SQLI vulnerability takes much more time to identify than XSS and authorization bypassing. The authentication bypass takes the lowest time. This is because the time required to identify a given vulnerability depends on number and complexity of specified OCL signatures.

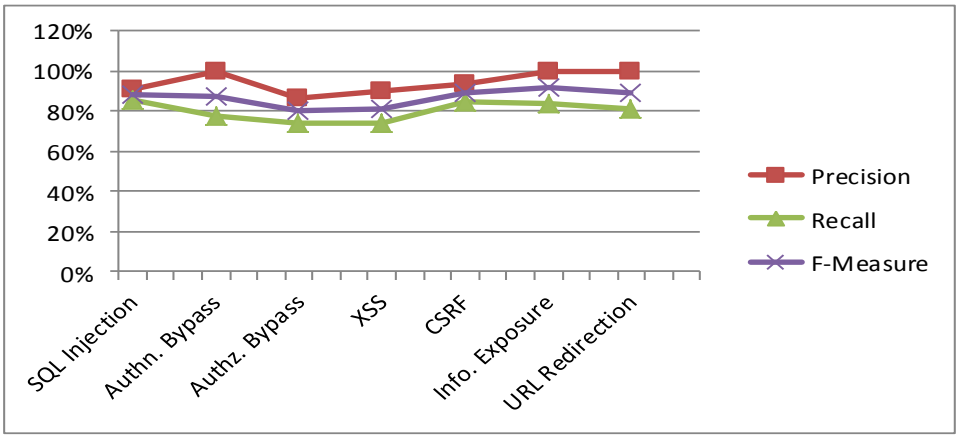


Figure 8-13. Achieved precision, recall, F-measure rates

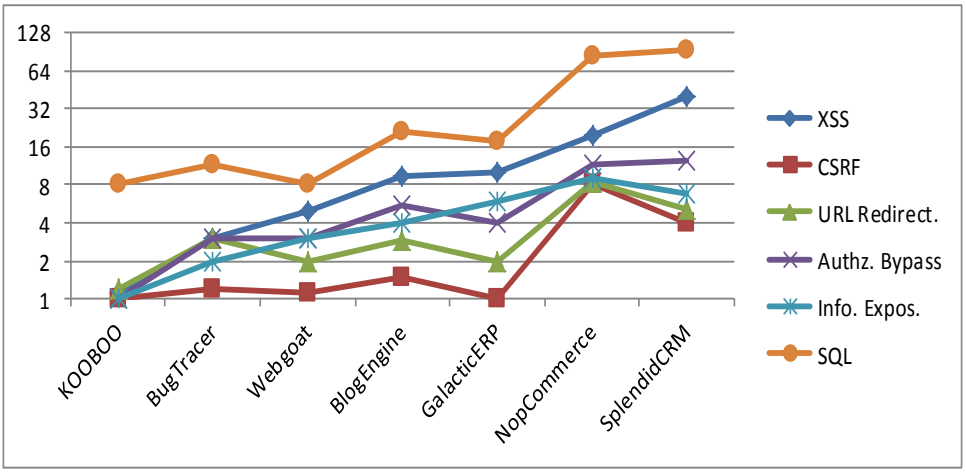


Figure 8-14. Performance of approach per vulnerability

Table 8-3. Results of our OCL-based security vulnerability analysis

Security Issue		Galactic	SplendidCRM	KOOBOO	BlogEngine	BugTracer	NopCommerce	Webgoat	Total
SQLI	D	2	12	14	3	9	19	8	67
	FP	0	2	2	0	0	2	0	6
	FN	0	2	2	1	3	1	1	10
Authentication Bypass	D	2	2	1	0	0	0	2	7
	FP	0	0	0	0	0	0	0	0
	FN	0	0	0	0	1	0	1	2
Improper Authorization	D	2	3	11	4	0	0	3	23
	FP	1	0	2	0	0	0	0	3
	FN	0	0	2	0	2	3	0	7
XSS	D	3	5	10	2	0	4	5	29
	FP	0	1	1	0	0	0	1	3
	FN	1	2	2	1	2	1	0	9
CSRF	D	5	6	13	10	0	12	3	49
	FP	1	0	1	0	0	1	0	3
	FN	0	1	2	0	4	1	0	8

Info. Expo.	D	3	0	0	10	0	0	3	16
	FP	0	0	0	0	0	0	0	0
	FN	0	0	0	0	2	1	0	3
URL Redirect	D	1	0	2	8	0	6	0	17
	FP	0	0	0	0	0	0	0	0
	FN	0	0	0	0	3	1	0	4
Total	D	18	28	51	37	9	41	24	208
	FP	2	3	6	0	0	3	1	15
	FN	1	5	8	2	17	8	2	43

8.6 Chapter Summary

In this chapter we introduced a new security analysis approach. Unlike other existing approaches, ours is signature-based where the security flaws, attacks, vulnerabilities, and metrics are captured as a set of declarative invariants. When matched, our approach confirms the existence or absence of the given security flaw in the software under test. We summarized the key subtasks involved in the security analysis e.g. architecture security threat and threat analysis, attack analysis and vulnerability analysis. We gave examples of such flaws and vulnerabilities along with our proposed signatures for such flaws/bugs. We summarized the experimental evaluation we did to assess the effectiveness of our approach. These experiments show that our approach can easily analyze software systems against a set of vulnerabilities and metrics that never seen before, given that we can formulate signatures of such vulnerabilities or metrics using OCL. Moreover, the experiments show that our approach has a high precision and recall rates for both architecture risk analysis and system source code vulnerability analysis. Finally, some of the existing vulnerabilities could be expressed as static signatures, while other need to be specified in terms of dynamic signatures that can be analyzed using dynamic analysis of the system under test.

Chapter 9
Cloud Applications Security Monitoring

In previous chapters we introduced our approaches to help stakeholders in analyzing their services security to identify threats against their assets security objectives. We also introduced an approach to help in modeling and enforcing security requirements and controls according to current needs and how these security capabilities could be changed at runtime to reflect or incorporate new needs. In this chapter, we discuss how cloud stakeholders can assess the strength and stability of their enforced security controls, where we might need to add security controls, and where we may need to change deployed security controls with stronger security controls. It is impossible to assess complex software systems and prove that they meet tenants' absolute level of required security. However, developing relevant and practical security metrics that help in abstracting and visualizing system security status is an alternative solution. Security monitoring is the task of quantifying security using appropriate metrics to help in taking corrective actions on the identified security weaknesses. Another key aspect of security monitoring is detecting possible trends of system security status, which helps in taking proactive actions. Most existing efforts focus on developing security metrics depend on formal languages to capture properties to be assessed. Such efforts usually require design-time preparation to support monitoring of system security properties. Our unified monitoring approach enables enterprise security engineers to specify, update, and remove their security metrics at runtime, without any design time preparation. Our developed platform is responsible for automatic conversion of these security metrics' specifications into security probes and integration of these metrics within target enterprise IT systems at runtime. Measurements collected are fed into an analysis component that applies aggregation functions, visualizes metrics, and reports deviations from expected behaviors, indicating possible vulnerability to attack. We have validated our approach expressiveness, usability, soundness, and performance overhead. This chapter is organized as follows. Section 1 gives overview of the security monitoring problem and key limitations of the existing efforts. Section 2 discusses details of our unified security monitoring approach. Section 3 discusses architecture and implementation of underlying security monitoring platform. Section 5 summarizes implementation details of our approach. Section 6 summarizes the experimental evaluation results. Section 7 discusses capabilities, limitations, and future work.

9.1 Introduction

Monitoring software systems behaviour is a crucial source of information reflecting details of the executing system and its operational environment. These information are used in assessing the satisfaction of system requirements [201, 202, 273], discovering and reporting any system violations [191, 194], and adapting system behaviour and structure based on current system context [213] (in case of context-aware and adaptive systems) or through proactive or corrective actions that involve modifying the system or its operational environment [274].

One of the key attributes that we usually want to monitor is the security status of the executing system and how it behaves if under attack. Although the area of security monitoring is not new [275], there is currently no way to prove that a given system is (100%) secure [183]. Using subjective and qualitative approaches usually requires deep involvement of security experts and is thus usually error prone, time-consuming and difficult to repeat. Security metrics represent a more quantitative basis for security assurance [275].

There is different categorization of system (and security) monitoring approaches including: (i) real-time and log-based monitoring; and (ii) active and passive monitoring. Real-time monitoring approaches focus on reporting the current system status while the system is executing. On the other hand, log-based approaches focus on using system generated logs and execution traces to analyse system behavior after events have happened. Active monitoring efforts intercept system execution to collect necessary measures. Active monitoring blocks system execution or put it on hold until the monitoring platform verifies the received request is not an attack. In contrast, passive monitoring efforts focus on collecting measures asynchronously and cannot take actions on current system requests, but instead inform longer-term corrective measures.

The area of security metrics (assessing system security using quantitative measures rather than qualitative measures) is relatively new area [275]. It is challenging in that there is not an "absolute" level of security [183] – i.e. it is too hard, or mostly impossible, to prove that a given system is 100% secure. Developing meaningful, relevant, and practical security metrics that help in abstracting and visualizing system security status is not an easy task. In our literature review we found relatively few efforts in the area of security monitoring. However, we did find a number of related efforts in different areas such as requirements monitoring, runtime verification, and SLA management.

Most existing efforts in the dynamic security metrics and security monitoring area focus on providing guidelines and frameworks that help in conducting security metrics development and analysis processes [28-31, 187]. Using such subjective and qualitative approaches usually

requires deep involvement of security experts and again tends to be both time-consuming and error prone. A number of related efforts have been made in the service level agreement (SLA) monitoring and management area. These efforts depend on the idea that SLAs are usually limited in properties to be assessed and thus predefined templates could be used. Moreover, most of the SLA measurements can be extracted from the hosting service – e.g. service performance usually measured at the webserver level. Software requirements monitoring efforts are also relevant to our research, though they focus on assessing certain system properties (usually developed in event-calculus) that are validated against system execution traces. Jansen et al [275] introduce a set of security metrics that could be used to assess system security status. A key problem with these efforts that limits the automation and extensibility of the security monitoring tools is that they depend on informal metrics' definitions. Thus, security experts have to be involved in developing required monitoring tools.

The formality, familiarity, and extensibility of the language used in developing security properties and metrics to be monitored are key issues in the security monitoring area. In order to facilitate the automation of the monitoring and analysis tasks, most existing efforts use formal languages to capture these properties, such as Event-Calculus [188, 191]. The Event-Calculus is a formalism based on first order logic that helps in representing events and effects [190]. Thus, most of the existing monitoring efforts are event-based – i.e. they depend on the occurrence of specific events in the system. Moreover, such languages are hard to use by software developers, security engineers, and security administrators. New easier domain specific languages have been introduced to help in capturing system metrics and properties to be monitored and assessed [203, 205]; however they do not help with security metrics and properties.

In our research, we focus mainly on the security metrics and monitoring of software systems' security status. We do not consider collecting measures of other security solutions such as vulnerability assessment tools or patch management tools, etc. Moreover, we do not address the managerial or implementation security metrics. We have defined four key research questions we need to address in order to tackle the security monitoring problem under the cloud computing umbrella:

- What details do we need to capture to fully describe a given security metric?
- How can we formalize the signatures of such security metrics?
- How can we effectively use such formal specifications in automating the security monitoring process?
- How can we enable different tenants to specify and notified with their cloud services security status?

In the next sections we introduce our security monitoring approach and its underlying security monitoring platform. Our approach is based on using OCL as a formal language to express and specify formalized security metrics' signatures. Based on these metrics' signatures we generate security probes, deploy at the critical system points, and generate security analysis procedures/functions that inspect the collected security measures, and generate security status reports summarizing metrics' updates. We discuss the key evaluation experiments we did so far to assess the capabilities of our approach in capturing metrics' definitions, collecting measures and analyzing collected measured, and performance overhead of our approach. Finally, we discuss the limitations of our approach and future work.

9.2 Security Monitoring Process

Before we introduce our refined security monitoring process, it is worth mentioning different categorization of security metrics. In our approach we focus on dynamic security metrics only; however, the other metrics still could be supported as we will discuss later. Security metrics are usually categorized as:

- *Static and Dynamic Metrics*: Static metrics assess static system structure properties such as system architecture security [98], system design security [101], security quality of the system source code [205]. We have addressed this type of security metrics in our security analysis Chapter 8. On the other hand, dynamic security metrics focus on assessing dynamic security properties of the system behaviour such as reported attacks, found runtime vulnerabilities [183, 276].
- *Technical, Operational, and Management Metrics [277]*: Operational metrics cover risk assessment metrics, time to patch vulnerabilities, number of stakeholders committed to tasks, and other day-to-day activities. Technical metrics cover numbers of vulnerabilities and threats reported by security analysis tools. Management metrics focus on measuring the effectiveness of the organisational security programs and processes.
- *Implementation, Effectiveness and Efficiency, and Impact metrics [275]*: Implementation metrics focus on progress achieved in the implementation of enterprise security program. The effectiveness and efficiency metrics focus on how the deployed and followed security programs achieve the defined goals and provide the required protection and how efficient they are in terms of cost. The impact metrics focus on how the operated security systems help in achieving organization missions.

From our understanding of the security monitoring area, we highlighted three main tasks that must be addressed by any software security monitoring platform as shown in Figure 9-1:

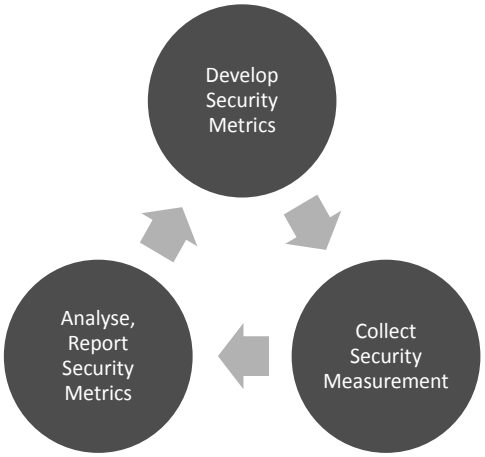


Figure 9-1. Security metrics realization phases

- *Developing Security Metrics*: In this phase, key stakeholders including management and security engineers define what metrics they need to measure about their software systems behaviour. This task is usually guided by the stakeholders' goals (in case of security metric, this should be the security objectives such as confidentiality, integrity, accountability, and availability). This also includes more details about metrics' definitions including frequency, owner (responsible person), unit of measure, *etc*.
- *Collecting Measurements*: This phase focuses on how to refine the metrics specified into necessary security probes (captors) that can collect raw measurements (system events) with necessary details. Moreover, it focuses on how to deploy these probes in an optimized way to reduce the performance overhead of the monitoring task. It also focuses on how to reason and control probes to turn on and off, at what time, and the suitable measurements rate according to system current system behaviour – adaptive monitoring.
- *Analysing Measurements and Improving Metrics*: Once the raw measurements have been collected, the analysis phase starts tracing any deviations or violations of the specified system metrics' normal boundaries. Further actions may be required to modify the specified metrics, or adding new metrics if needed. Analysing these measurements may range from applying simple set of rules to using some artificial intelligence techniques such as game theory, case-based reasoning, or fuzzy logic.

9.3 Unified Security Monitoring Platform

In chapter 8 we introduced an OCL-based static security analysis approach supported with a toolset. Our approach is based on capturing security vulnerabilities and flaws signatures as OCL invariants. These expressions are used in conducting security analysis of program artifacts including architecture models, source code, and binaries to identify matches to OCL-specified

signatures. Our approach succeeded in locating static vulnerabilities with high precision and accuracy rates. In this chapter, we further extend this work to support runtime security monitoring and dynamic security metrics.

We base our SaaS applications security monitoring approach on (i) a comprehensive security metric definition schema that captures every detail related to a given security metric. This security metric definition schema includes a formalized security metric signature specification approach to help in capturing security metric's signatures; (ii) externalizing security monitoring and measurement from the target application(s), such that the application and security monitoring could be easily changed without a need for customizations; and (iii) automating security monitoring probes' generation and deployment at runtime using metric's attributes. Stakeholders including service tenants and service providers specify the security metrics they are interested to measure in their cloud services as a part of their security specification model (SSM) introduce in Chapter 6.

9.3.1 Security Metric Definition Schema

We studied the key attributes that could be required in developing security metrics and come up with a security metric definition schema covering all possible attributes, as shown in Figure 9-2. Managing security metrics' definitions repository is the responsibility of the cloud service and platform stakeholders. Our security metric definition schema contains:

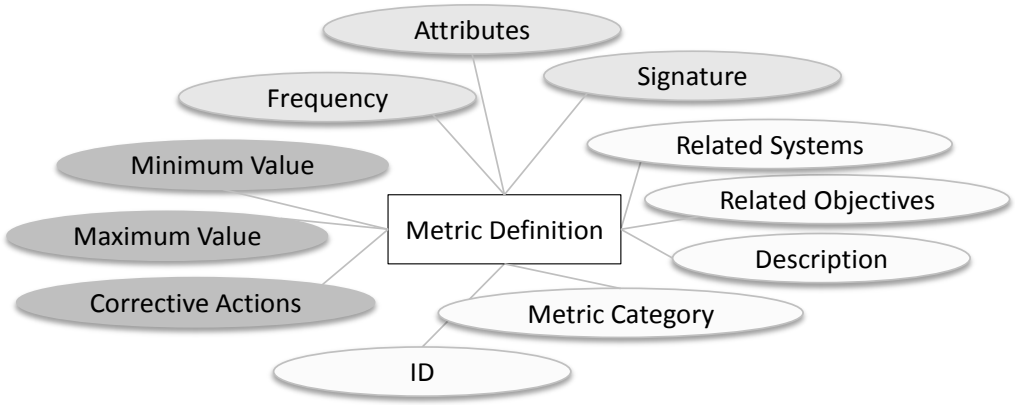


Figure 9-2. Security metric definition schema

- *Metric ID*: Every security metric should have a reference ID that helps in linking collected measurements generated or collected from system(s) together. It also helps in uninstalling security probes whenever the metric is no longer needed.
- *Metric Category*: This attribute helps in categorizing enterprise security metrics into e.g. operational metrics, management metrics, static metrics, dynamic metrics, etc.

- *Metric Description*: This describes the security metric to be evaluated. This description is used as a part of the security configuration, status reporting and for reviewing.
- *Metric Related Security Objectives*: Each security metric should be linked to one or more of enterprise security objectives that need to be assessed using the security metric. This is also helpful when assessing satisfaction of security objectives or highlighting issues with security objectives.
- *Metric Related Systems*: Enterprise security officers may be interested in applying different security metrics on different systems. This attribute helps in deciding which enterprise software systems this metric applies on.
- *Metric Signature*: The security metric signature specifies the metric formula, property, rule, or expression to be evaluated. The metric signature helps in identifying which service objects or security controls to monitor and what aggregation functions to apply *e.g.* minimum, maximum, average, top, last, etc. These metrics' signatures should be extensible enough to capture different stakeholders' metrics of interest. We use OCL in our framework to describe security metric signatures.
- *Metric Attributes*: Each metric has a list of relevant attributes to be set by the metric user. These attributes should be calculated by the monitoring platform when generating a new measurement – i.e. whenever the software system receives a request to access resource X, the monitoring platform generates a new measurement record. The attributes to be included in the measurement record should be extensible to support user defined attributes. These attributes depend on the planned usage of the metric collected measurements. Some of the key metric attributes to be included in every measurement include: Metric ID, Timestamp, Source of the measurement (method name, component name, system name, etc.), and identity of the system user at time of measurement. Other user-defined metric attributes (such as method input parameters, variables, etc.) should be easy to add, to metric definition, and collect by the security monitoring platform.
- *Metric Frequency*: Each security metric definition should include the measurement frequency required. This may be every X-hours, X-days, X-weeks, X-months, and so on. The results collected by security monitoring probes are grouped, evaluated, and consolidated in a security status report to the security metric owner.
- *Minimum-Maximum Values*: Each security metric should have the minimum and maximum values that define valid boundaries of the security metric. Whenever the security metric value becomes (or is forecasted to be) below the minimum value or above the security metric maximum value, security alerts should be reported to the security metric owner.
- *Corrective Actions*: Security officers may decide to specify a set of corrective actions to be fired automatically when the current security metric comes below or above the security

metric boundaries specified above. In our framework, these actions are realized by a set of model-based configuration specifications as we introduced in [43].

9.3.2 Security Metric Signature Specification

A key problem that limits the capabilities of the existing security monitoring efforts is the lack of security metric specification language that could be used in capturing security metrics' details. This problem impacts the whole security monitoring process as it usually requires manual involvement to help developing and deploying required security probes that measure and collect required system properties. In our approach, we use Object Constraint Language (OCL) to specify such security metrics signatures. We use OCL as a well-known, extensible, and formal language to specify semantic signatures of security metrics. To support specifying and validating OCL-based signatures, we have reused the system-description meta-model introduced in the previous chapters and shown in Figure 9-3. The system description meta-model captures system and security details from the high-level objectives down to the source code entities and realization security controls. This model captures main entities in an object-oriented system including components, deployment package, hosting services (web server), storage, communication channels, classes, instances, inputs, input sources, output, output targets, methods, method body, method statements e.g. if-else statements, loops, new objects, objects interactions, etc. Moreover, it captures security concepts such as security objectives, requirements, architecture, zones, mechanisms, authentication, authorization, audit controls, etc. Each entity has a set of attributes such as component name, provider, platform used, class name, accessibility, method name, accessibility, variable name, variable type, method name, etc.

However, these features and concepts represent static details of the application. To capture the behavior properties of the application and its entities, we extended the system description meta-model with two concepts (request and response) along with the details involved with such concepts according to the system entity – i.e. both requests and responses are linked to the application level, component level, class, method level, security entities. We have defined a set of attributes related to requests and responses such as input parameters, class and object status, sender, receiver, timestamp, etc. These attributes are defined in an XML file. Thus, it is easy to extend according to current needs. This requires specifying how to get request/response new attribute value. The system description meta-model is also extensible to incorporate new concepts that need to be analyzed with the same concept.

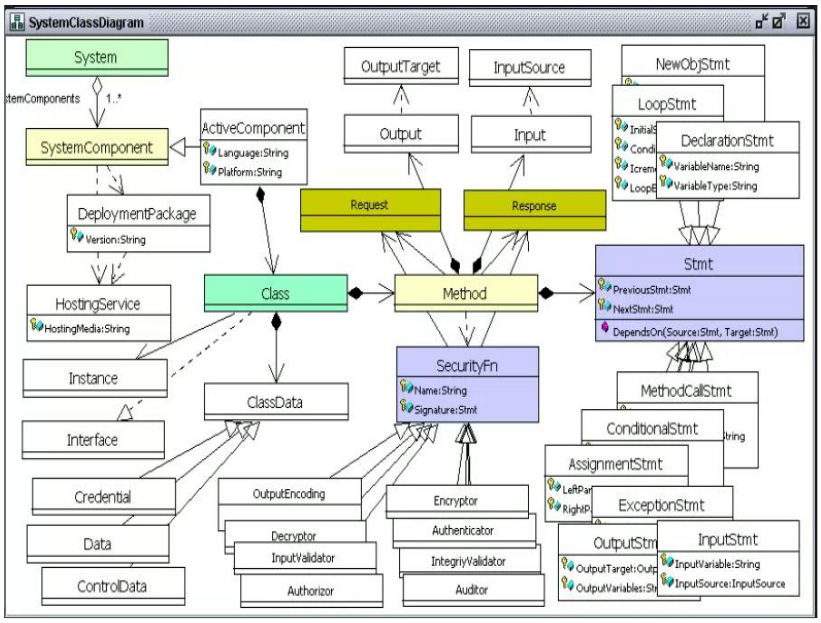


Figure 9-3. Our system description meta-model

9.3.3 Derived Security Metrics

Developing complex metrics is always a requirement in any monitoring and analysis domain. To support capturing more complicated security metrics that make use of the deployed security metrics, we incorporate stakeholders' specified security metrics into our system description meta-model. This in turn means that we can use these metrics as if they were system entities and attributes in developing more complicated metrics. Table 9-2 shows examples of derived security metrics based on base security metrics introduced in Table 9-1.

9.3.4 Examples of Security Metrics Signatures

Table 9-1 shows some security metrics' signatures specified in OCL using our system description meta-model, shown in Figure 9-3. Before we discuss these signatures, it is worth mentioning that these signatures can be further improved to incorporate different tenants' security metrics requirements.

Table 9-1. Examples of OCL-specified security metrics signatures

Authenticated Requests Metric
This metric measures the ratio of system requests against number of requests that have been received by the security authentication control. The higher the ratio, the more secured (authenticated) the system.

context System inv AuthenticatedRequests: self.AuthenticationControl.Requests->select()->count()/ self.Request->select()->count()
Authentic Requests Metric
This metric measures the ratio of invalid authentication requests out of the total number of requests received by the security authentication control. Any increase in this ratio reflects the possibility of being under attack to break the application operated authentication control. Some corrective actions may be to incorporate a more complicate (second stage) authentication control to block such attacks. Furthermore, we may add the user IP to the authentication control black list.
context System inv AuthenticRequests: self.AuthenticationControl.Response->select(R | R.IsValid = false)->count()/ self.AuthenticationControl.Request->select()->count()
Last(10) Requests to Authorization Control Metric
This metric is used to take a random sample of the recent requests sent to the authorization security control. This metric could be used by system administrators to check the details (e.g. identity of requesters) of requests sent to the authorization security control after certain period of the day – e.g. out of the working hours.
context System inv Last10AuthzCtl: self.AuthorizationControl.Requests->select()->Last(10)
Top(10) Request to Authentication Control By Admin Account Metric
This metric could be used by the management to check how frequent administrators login to the system in the last period, this metric could be detailed as well to reflect details of these requests sent to the system such as time of these requests, source (IP of the request).
context System inv Top10AuthnCtl: self.AuthenticationControl.Responses->select(R | R.UserID = 'Admin').count()
Mean Time Between Unauthentic Request Metric
This metric helps in assessing the average time between consecutive unauthentic requests that have been reported by the authentication control. A high metric value means more stable and secure the underlying system.
context System inv MTBUnauthenticRequests: self.AuthenticationControl.Responses->select(R | R.IsValid = false)-> differences('Measurementtime')-> sum() / self.AuthenticationControl.Responses->select(R | R.IsValid = false)-> count()
Logging Activities
This metric helps in assessing the ratio of logging activities generated by the monitored system
context System inv LoggingActivities: self.Auditor.Requests->select()->count / self.Requests->select()-> count()

Table 9-2. Examples of derived security metrics

Authenticated Requests Metric Trend
This security metric helps in assessing the trend of metric values over a period of time. Here, we apply it on the authenticated requests metric. This helps in figuring out whether there is an increasing or decreasing trend in the number of unauthenticated requests or not.
context System inv Authenticated RequestsTrend: self.AuthenticatedRequests.Differences('AuthenticatedRequests')->sum()/ self.AuthenticatedRequests-> count()
Security Metric over Multiple Systems
This metric helps in following up the security status over multiple systems/services. Here, we apply it on the average of mean time between unauthentic requests over multiple systems.
context System inv MTBUROverSystems: self.MTBUnauthenticRequests->sum()/ self.MTBUnauthenticRequests->count()

9.4 Security monitoring platform

After formalizing security metrics specification, we need to develop the underlying security monitoring platform which is responsible for realizing these metrics and reporting the measurements collected to the corresponding metrics' authors. We have figured out five key challenges we need to address in our security monitoring platform:

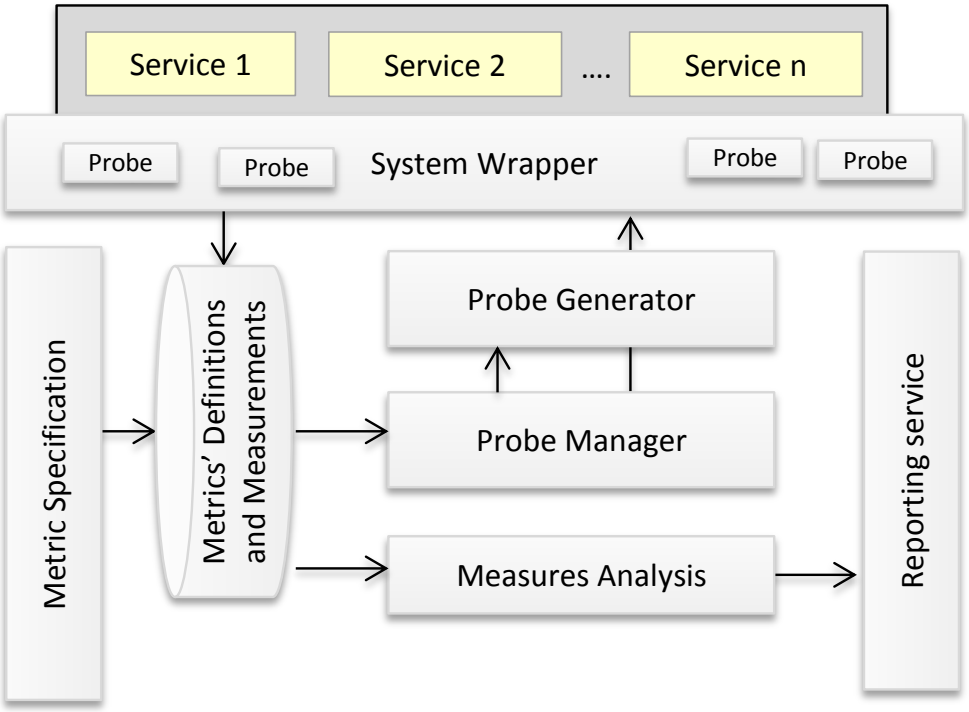


Figure 9-4. Security monitoring platform architecture

- Security probes: How to extract entities to be monitored given the specified metric OCL?
- How to deploy these security probes within the target system at the specified system entities?
- How to extract metrics' values from the generated security measurements?
- How to enable/disable security metrics (in case they are no longer used)?
- How to fire security metrics' analysis service according to metrics' frequencies?

To address these challenges, our security monitoring platform is designed to be extensible in supporting new security metrics, new measurement attributes, and new entities to monitor without a need for patching or maintenance. The architecture of the security monitoring platform shown in Figure 9-4 and is discussed below.

- *Security Metrics Specification*: This is a UI where security officers can develop their security metrics including the metric signature and corrective action specifications. These metrics are validated against the system description meta-model discussed above. Once validated, the metric is registered in the metrics repository that is managed by our monitoring platform.
- *Probe Manager*: Once a security metric is added or updated in the metrics repository, the security probe manager does the following: (i) Triggers the probe generator component to generate security probes that collect required measures with corresponding attributes; (ii) Deploys the generated security probes within the system using system wrapper component and removes deployed probes if the metric is no longer required; and (iii) Adds a new entry in the metrics analysis service timer according to the metric specified frequency. This is responsible for triggering the metric analysis service regularly to analyze new measurements.
- *Probe Generator*: The main responsibility of the probe generator is to extract security probes from a given metric definition. The probe generator extracts: (i) entities to be monitored from the metric signature OCL expression (the context section of the signature); (ii) attributes to monitor from the attribute list of the metric; (iii) what requests/responses to monitor (probe filter) from the metric signature OCL expression (conditions part – e.g. only unauthentic requests). Given a security metric signature "self.Authenitcation Control.Request…", will result in a security probe to be deployed in the system authentication control to intercept and report requests to the authentication control. Moreover, to optimize the performance of the probes' reported measurements; we extract the specified conditions in the security metric signature to use in filtering which requests to report and log. Measurements generated by a security probe include attributes defined on the security metric e.g. Metric ID, timestamp, inputs, outputs, user identity, host IP address. The outcome of the probe generator is a probe class that is managed by the probe manager.
- *System Wrapper:* The system wrapper is responsible for injecting interceptors (using dynamic aspect-oriented programming - AOP) within the target system/service at runtime at

the critical points (system entities that have security metrics defined on them). The list of critical points is managed by the probe manager. The system wrapper supports two modes of interception: synchronous where the system is intercepted and put on hold until the security analysis service confirmation (this helps in active monitoring tasks, such as introduction prevention systems or application firewalls) or asynchronous to reduce the performance overhead (passive monitoring). The system wrapper that we have implemented currently supports intercepting requests at the system level, component level, and method level, which is adequate for our goal of the security monitoring and analysis. However, we plan to extend this system wrapper to intercept requests on a block of code level (i.e. blocks of code with a specific signature pattern). This increases the usability of our approach in deep security analysis and in addressing different QoS attributes other than security.

- *Metrics Analysis Service:* The analysis service parses the specified security metric signature developed in OCL and generates a C# analysis class. These security analysis classes are loaded at runtime according to the metric frequency that is registered (by the probe manager) in the security metrics analysis and timing service. These security analysis classes check the measurements repository for metric collected measures. These measures are then analyzed and aggregated. The outputs of this analysis service are sent back to the repository for further use by other metrics (e.g. by other derived metrics), for historical analysis, and for the reporting service that use these metrics' values to generate status reports.
- *Reporting Service:* this takes the aggregated results stored in the repository for the target system and provides a set of visualizations for security and systems engineers. Currently a set of tabular and chart visualizations are supported and accessed via a web page. A further extension of our platform is to provide security officers with a visual designer where they can specify how they want these metrics to be visualized [278].

9.5 Implementation

We briefly describe some implementation details of our automated, formal security monitoring and analysis tool. *First*, we developed a UI component, show in Figure 9-5, to assist security experts in developing their security metrics definitions and signatured using OCL (Figure 9-5-A). This provides security metric specification and signature editing including checking validity of OCL expressions (Figure 9-5-B and Figure 9-5-C) and testing of specifications on sample measurements. We use an existing OCL parser [279] to parse and validate signatures against our system description model. Once validated, the metric definition and signature is stored in the signatures database. *Second*, we developed an OCL-to-C# translator library that transforms the developed metrics' signatures into C# analysis classes. Each class has a single static method that accesses the metrics' and measurement repository and applies the C# code on these

measurements (Figure 9-5-D). *Third*, we developed a probe generator library that analyses OCL-based metric definitions and extracts a list of attributes and list of entities to monitor. Both lists are used by a probe class template to generate the metric probe class. These are currently C# implementations that can be deployed at run-time against the target software system. Fourth, we reused our system wrapper, introduced in Chapter 6, to help in injecting security probes at the critical system entities. To support runtime system interception, our platform combines both dependency injection and dynamic-weaving AOP approaches.

The system wrapper supports wrapping of both new developments and existing systems. For new development, we use the Microsoft Unity application block delivered by Microsoft PnP team to support intercepting any arbitrary system entity. Unity supports dynamic runtime injection of interceptors on methods, attributes and class constructors using system configurations. For existing systems we adopted Yiihaw AOP tool to modify application binaries (dll and exe files) by adding security aspects at any arbitrary system entity. In the latter case, we add a call to our system wrapper. The communication between the system wrapper and security measurements repository are implemented using Microsoft Windows Communication Foundation (WCF) based services. Figure 9-5-E shows a sample security status report showing metrics' values and trends.

9.6 Evaluation

In this section we summarize our evaluation experiments we performed to assess the capabilities of our approach in capturing, generating, deploying, collecting measures, and analyzing security metrics details. We apply the OCL-based security metrics signatures as illustrated in Section 3. We defined three aspects to address in our approach evaluation. This includes expressiveness and usability, soundness and effectiveness of the approach, and performance overhead. These aspects are discussed in the next subsections.

9.6.1 Expressiveness and Usability

In this experiment, we assess the expressiveness and usability of our security metrics specification language in capturing definitions of different security metrics. These range from simple counting of raw measures collected from certain system entities up to complicated security metrics that incorporate results from different base metrics. We decided that the best approach to assess the expressiveness of our approach was to use it in capturing definitions and signatures of a set of benchmark security metrics. However, we unfortunately could not find such benchmarks. Currently there is a new project led by OWASP [276] to come up with critical security metrics to be used in assessing web-based software systems.

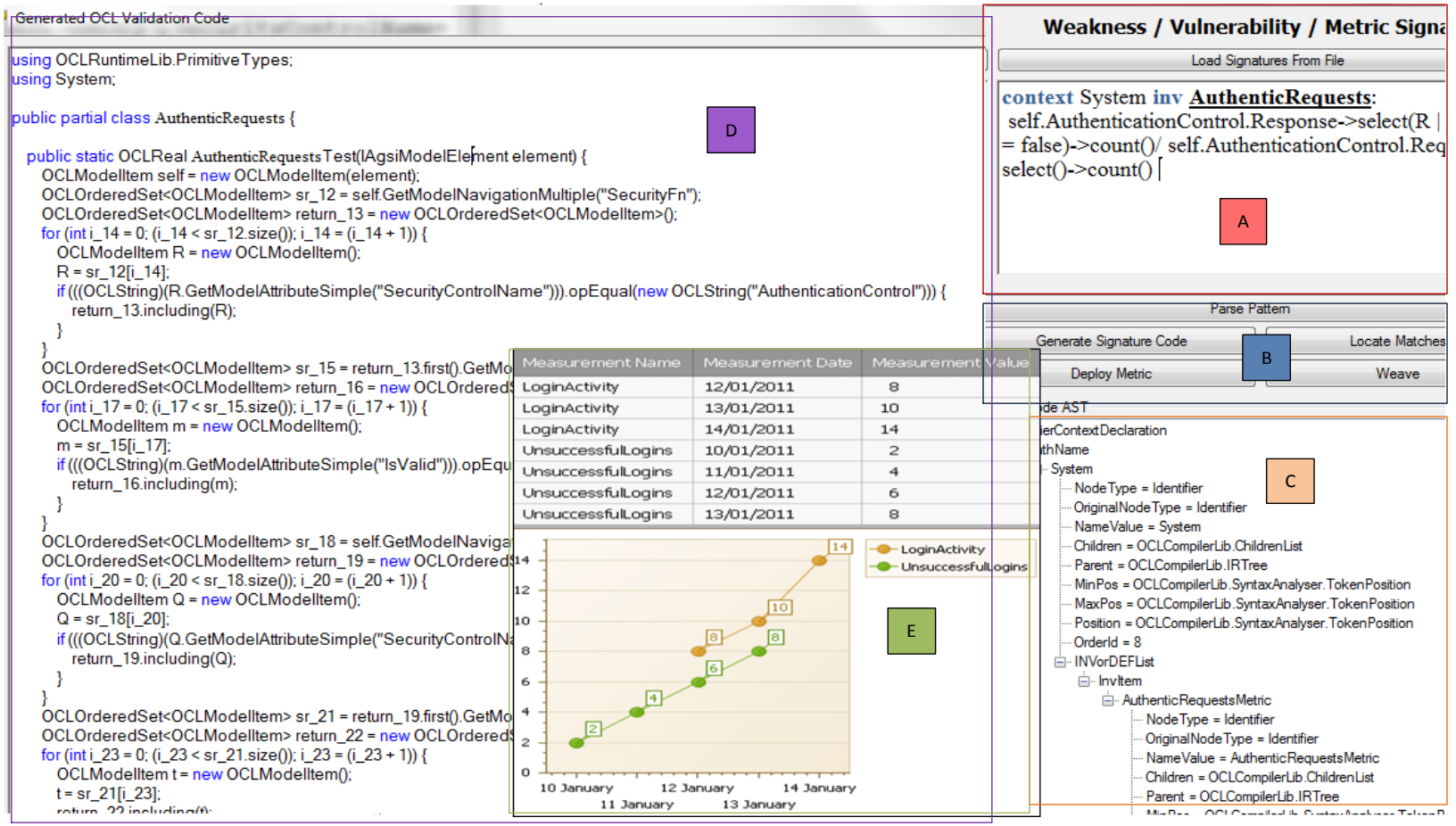


Figure 9-5. Snapshots from our security monitoring tool

Table 9-3. Comparison between metrics specification languages

Criteria	EC-Assertions	Our Language	PMSL	GMSL
Applications	Reasoning and verification of system properties	System properties + Metrics specification and evaluation	Parallel systems performance metrics	Static program quality metrics
Supported Features	Events, properties, relations	Declarative, properties, relations, set theory	Declarative, Functional, Built-in attributes and metrics, statistical fns.	Declarative, built-in code analysis functions.
Boolean connectives	✓*	✓	×	×
Quantifiers	✓*	✓	✓	✓
Modalities	✓*	✓	✓	Not Required
Temporal Events	✓*	✓	✓	×
Preconditions	✓*	✓	✓	✓
Post conditions	×	✓	×	×
Complexity	×	✓	✓	✓
User-Extensibility	×	✓	×	×
Limitations	No aggregation functions, no historical data		No control flow, no alterable state	Work on source code AST

*****: **Feature supported through language extensions**

To find a workaround to this problem, we have compared our approach expressiveness and usability with different system properties and metrics specification languages including the Event calculus with different extensions as explained in [190], PMSL (performance metrics specification language) [203] , GMSL (Goanna Metric Specification Language) [205]. Details of these metrics' and properties' specification languages are covered in the related work chapter. Table 9-3 shows that our OCL-based security metrics' specification language is more rich and expressive in developing different types of metrics. The main observations from this comparison are: the usability (complexity feature) and extensibility of our language compared to others mainly event Calculus. Another key feature is the support of aggregation functions that are mainly used in data reduction and extraction of meaningful metrics from the collected measurements.

9.6.2 Approach Soundness

In these experiments, we assess our approach accuracy and soundness in two key points: the security probes automatic generation from the security metrics' signatures; and analysis results of the security analysis service which is based on metrics' signatures. Other relevant points to be evaluated include the deployment of generated security probes (this depends on the MDSE@R system wrapper component which is based on Microsoft application blocks), and the extraction of security measurements from current system requests and status (this depends on accuracy of the user defined attributes and expressions specified to extract such attributes). Thus, we focus on the generation of security probes and evaluation of metrics' expressions.

A key problem we faced in this experiment is that we need to consider different variables related to system usage and our security monitoring soundness including number of concurrent users, number of requests per second, number of malicious requests sent to the software system, and system entities to be accessed. A possible solution is to conduct a set of planned experiments with different sets of variables' values to assess the security monitoring platform. In our evaluation, we have used a random number generator to generate random numbers for each of experiment variables – i.e. number of users, requests, etc. At every time step, we generate a random number that is used to represent number of concurrent users. Then we generate a random number for the number of requests to be issued for each concurrent user. The same applies for each experiment variable. For system entities to be accessed, we generated a hash map of system entities with IDs. Based on the generated random number we retrieve the system entity to be requested.

Table 9-4 shows the experimental evaluation results of our platform on GalacticERP service (our motivating example) using a set of four security metrics shown in Table 9-1. We have done three consecutive trials (time steps). For each experiment we assessed our platform capability in generating security probes (column "P"), generating metric evaluation expression (column "E"),

and testing the system with the metric deployed using a random number of users, requests, and malicious requests (column "A"). This column shows the metric value calculated using metric evaluation expression generated from the metric signature. Each experiment has a set of attributes including number of concurrent users, number of generated requests, how many of these requests are malicious. These attributes' values are set using random number generator. Furthermore, we assume that all requests are not within the same session. Thus, every request sent by the user need to be re-authenticated and re-authorized.

The metrics values show that monitoring platform successfully intercepted requests, generated measurements, and analyzed these measurements correctly. For example the authenticated request metric value was 100% which means that all system requests have been authenticated. The ratio of the authentic requests also conforms to the ratio of malicious requests in each experiment. The ratio of logging activity reflects how many requests were sent to the logging control compared to the total number of system received requests.

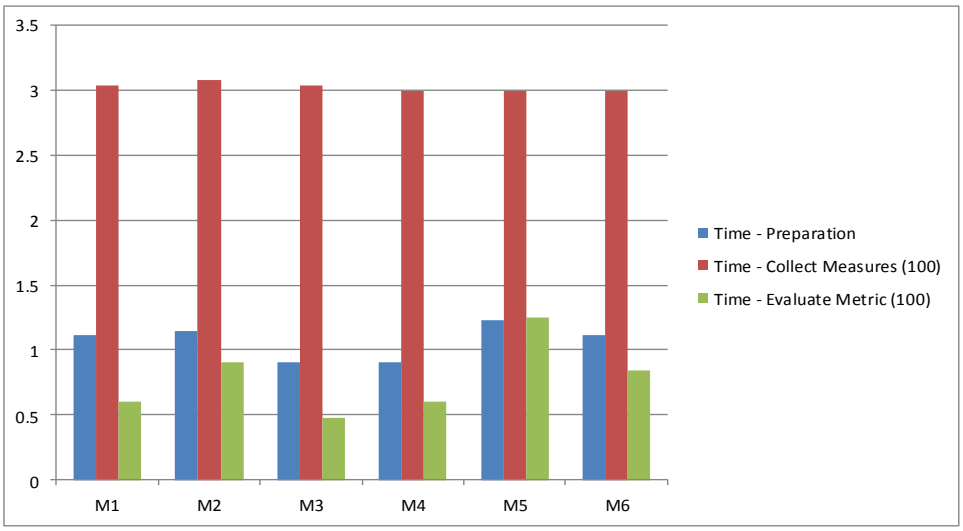


Figure 9-6. Performance overhead grouped by monitoring stage

9.6.3 Performance Overhead

In these experiments, we aimed to assess the performance overhead of our security monitoring platform in five points: generating security probes and metric evaluation function; deploying probe; intercepting system execution; extracting system measurements required by specified security metrics; and evaluating metrics from collected security measurements. The system interception and measurement collections have impact on systems performance. The other efforts are done offline without impact on system at all. Table 10-5 summarizes the time taken in each of these points in milliseconds. It is worth mentioning here that measurements extraction is repeated according to the usage of the system – i.e. number of system requests. Figure 9-6 summarizes the performance

overhead incurred in the metric preparation step, measurement collection, and metric evaluation. We measure the performance overhead of the measurement collection with 100 system requests. The same with the metric evaluation, the input to the evaluation function is (100) measurements. The time displayed is scaled using (log10) for visualization.

9.7 Discussion

We introduce a security monitoring approach that helps in automating the realization and analysis of security metrics. Our approach is based on adoption of OCL supported with a system description meta-model to help in capture security metrics' signatures. Our platform uses these signatures to generate probes, deploy probes at critical system entities, and generate security analysis classes that analyse probes' generated measurements. We have evaluated the approach expressiveness, usability, soundness and performance overhead.

Extensibility to support automation of operational and managerial security metrics: enterprises usually have different systems other than IT systems (either used for operational or managerial purposes) where security engineers would like to assess their security level as well. Moreover, different security systems are usually operated in these enterprises where security engineers would like to aggregate their reported results. A possible way to address this issue in our approach is to add those systems' logs to our measurements repository. This enables security engineers to develop operational and managerial security metrics [275] that work on these measurements. A possibility for automation is also feasible given that we can develop adaptors that integrate such systems with our security management platform.

A key further extension of our approach is to develop an automated adaptive security approach that uses the results of the security monitoring platform along with the corrective actions to address reported deviations from the normal behavior of the system. Furthermore, we plan to extend our platform with more abstract metric specification language (may be based on natural language or using model-driven techniques) to help security engineers in developing metrics without a need to learn new languages. This will require development of a parser that can extract metric signatures (in OCL) from such abstract definitions.

Table 9-4. Security monitoring evaluation results

Time Step		1			2			3		
		P	E	A	P	E	A	P	E	A
Experiment Attributes	#Users	–	–	69	–	–	56	–	–	84
	#Requests	–	–	3429	–	–	3180	–	–	4455
	#Malicious Requests	–	–	2096	–	–	1921	–	–	2631
Security Metrics	Authenticated Requests	✓	✓	100%	✓	✓	100%	✓	✓	100%
	Authentic Requests	✓	✓	61%	✓	✓	60%	✓	✓	59%
	Mean Time Between Unauthentic Requests (sec)	✓	✓	2	✓	✓	1	✓	✓	2
	Logging Activities	✓	✓	85%	✓	✓	87%	✓	✓	88%

Table 9-5. Performance overhead of our security monitoring platform

Aspect / Metric	Generate Probe	Deploy probe	Intercept Exec.	Extract Measures	Evaluate Metric
Authenticated Requests	10	3	5	6	4
Authentic Requests	11	3	5	7	8
Last(10) Requests to Authorization Control	5	3	5	6	3
Top(10) Admin Requests to Authent. Control	5	3	5	5	4
Mean Time Between Unauthentic Request	14	3	5	5	18
Logging Activities	10	3	5	5	7

9.8 Chapter Summary

In this chapter we introduced our new security monitoring approach that we developed to complete a full security management cycle, after previously defining security (security analysis and security models) and enforcing security (security engineering and retrofitting). The security monitoring component covers the security dynamic analysis part. The security monitoring approach is based on the same concept used in the system security analysis and security retrofitting which is to abstract system details in a system description meta-model and using OCL to develop security metrics' signatures (invariants and constraints) on this abstract level. Using our extension of the OCL parser we extract security probes and conditions to apply. Furthermore, we extract the security measurements' analysis module that analyse and summarize collected metric measurements. We have evaluated our approach expressiveness, soundness, and performance overhead.

Part 3

Case Studies

Chapter 10
Case Studies

Throughout this thesis, we have explained in detail how our model-based cloud computing security management approach works and how we evaluated each component individually. In this chapter we introduce a set of case studies as a part of evaluating our platform. We have selected three different security problems that arise from the adoption of the cloud computing model. These problems are critical, and represent hot research areas in the cloud computing area. Moreover, our approach to address these case studies depend on using multiple components from our platform. This also justifies why we introduce these case studies in a separate chapter and not as an integrated part of the approach chapters (5-9):

- *Case Study No.1: Online Automated Cloud Applications Security Virtual Patching:* This case study addresses the problem of public accessibility of the cloud platform which increases the potential of being under attack and exploiting cloud services vulnerabilities. To address this problem we introduce VAM-aaS as a comprehensive and integrated solution composed of the vulnerability analysis and MDSE@R components of our security management platform. This enables VAM-aaS to work as an online vulnerability analysis and mitigation service that keeps analyzing cloud services looking for vulnerabilities. Whenever a new vulnerability is found a set of agreed on actions are applied to block such new security hole.
- *Case Study No.2: Supporting Multi-tenancy Reengineering using Re-aspects:* This case study addresses the security isolation problem that arises from adopting cloud computing model. Getting tenants to share the same service instance means that we have to filter data they can access which is specific to them and according to their assigned roles and permissions. To address this problem we introduce SMURF as an easy to use tool to help reengineering legacy applications to support multi-tenancy.
- *Case Study No.3: Supporting Multi-tenancy Reengineering using Re-aspects***:** This case study addresses the whole problem of getting cloud services to reflect different sets of security requirements for different tenants and getting these sets to be changed at runtime. Moreover, it addresses how to adapt security requirements according to current security status. Finally, to incorporate security controls relevant to mitigate specific vulnerabilities. This case study covers the whole process of tenant-oriented cloud services security management.

10.1 Case Study No.1: Online Automated Cloud Applications Security Virtual Patching

However, the potential benefits reaped from the adoption of the cloud computing model, these are threatened by the public accessibility of the cloud-hosted services and sharing of resources among different tenants. This increases the possibility of malicious service attacks. Existing cloud platforms do not provide a means to validate the security of the offered cloud services. Moreover, the public accessibility of cloud services increases the potential for exploitation of newly discovered vulnerabilities that usually take a long time to discover and to mitigate. We introduce VAM-aaS, Vulnerability Analysis and Mitigation as-a-Service, as a novel, integrated, and online cloud-based security vulnerability analysis and mitigation service. VAM-aaS performs online service analysis to pinpoint new vulnerabilities/weaknesses. It then uses this information to generate security control integration scripts to block these discovered security holes at runtime. Our approach is based on the vulnerability signature and mitigation-actions specification approach discussed in Chapter 8. This case study is organized as follows. Section 1 explains why automated vulnerability mitigation becomes a key requirement. In Section 2, we introduce our approach and the proposed VAM-aaS architecture details. In Section 3, we summarize evaluation results from evaluating our approach.

10.1.1 Introduction

The cloud model is based on service outsourcing for hosting on third-party platforms outside of the enterprise network perimeter. However, the cloud model also introduces new opportunities for attackers to exploit the publicly accessible valuable cloud services. Adopting the multi-tenancy model increases the exploitability of service vulnerabilities because one of the service tenements (who has been granted privileged access on the cloud service) may be malicious users. This means that they can exploit complicated vulnerabilities that require higher privileges rather than being a public user. Moreover, the number of newly discovered vulnerabilities is increasing rapidly. Web applications (the prominent application delivery model used in SaaS applications) continue to make up the largest percentage (63%) of the total reported vulnerabilities [60].

Commercial vulnerability scanners such as IBM-AppScan, HP-Web inspect, McAfee tools focus mainly on black-box vulnerability analysis to avoid being limited to specific programming language or platform. However, none of these scanners cover all known vulnerability types [116]. On the other hand, existing research efforts [60, 109-111, 113, 117] focus on discovering specific vulnerability types including SQLI [107, 115], XSS [112, 115, 118], or input sanitization [119, 121] using static analysis [114, 117], dynamic analysis [115], or hybrid techniques [120, 264].

The key problems with these efforts include: they provide specific techniques for specific vulnerability types; proposed techniques apply on specific platforms or programming languages; they do not support analyzing for new vulnerability types. On the other hand, these limitations are key requirements for cloud services' vulnerability analysis tools. An online vulnerability analysis approach that supports locating well-known as well as new vulnerabilities without waiting for new tool patches is a must to have in the cloud computing environment.

On the other hand, mitigating application vulnerabilities is usually done manually by modifying application source code and deploying new patches; however, this takes a long time as shown in Figure 10-1. This lagging time between vulnerability detection and patching means that the service remains vulnerable to security breaches exploiting such vulnerabilities. The possibility of vulnerability exploitation increases dramatically in the cloud, given the public accessibility of the cloud services and sharing of services with multiple tenants. Thus, the cloud computing model requires an online vulnerability patching approach that can block such vulnerabilities once reported.

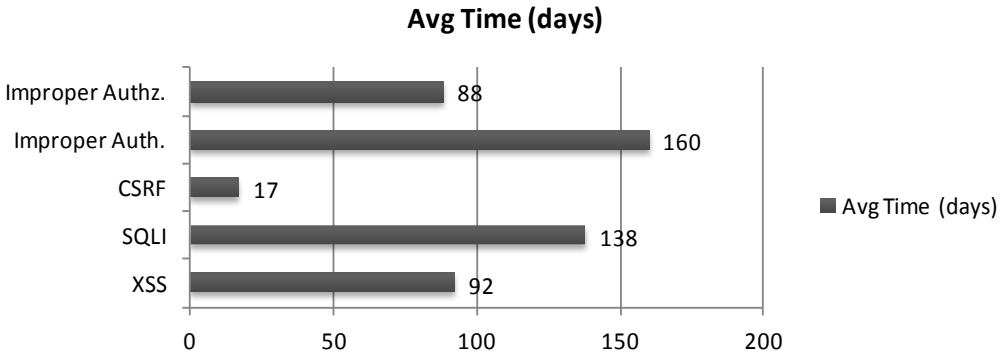


Figure 10-1. Average time to fix security vulnerabilities (in days)

We introduce VAM-aaS as a new integrated solution to cloud-based services vulnerability analysis and mitigation problems. VAM-aaS is based on the formalized vulnerability signatures as well as enumerated mitigation actions to block such vulnerabilities. Vulnerability signatures, developed using OCL, are specified as invariants, when matched; it means that the specified vulnerabilities do exist in the application/service under analysis. These signatures are validated against a comprehensive system description meta-model (represents language semantics) covering most of the object oriented program concepts/entities. To support locating new types of vulnerabilities, security experts will need to update the vulnerability analysis service repository with the OCL-signatures of the new vulnerability.

The vulnerability mitigation actions specify a set of security solutions that can be used to block "virtual patching" the discovered vulnerabilities reported by the analysis component. It also specifies the configurations and rules that should be applied when activating security controls. We

modified MDSE@R to work as a vulnerability mitigation component that uses these vulnerability mitigation actions (instead of tenants' security requirements as explained in Chapter 6) to plug-in the specified mitigation security controls within the target vulnerable service/application online. Thus, our proposed mitigation component is not limited/hardcoded to specific security controls as it depends on a simplified security interface that security controls should satisfy in order to be integrated with our mitigation component explained in Chapter 6.

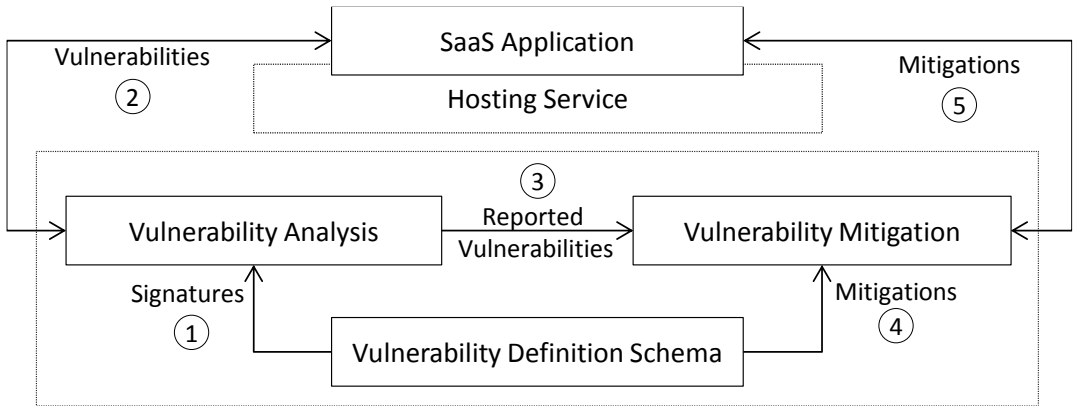


Figure 10-2. VAM-aaS Key components, relations and possible interactions

10.1.2 VAM-aaS

Our security vulnerability analysis and mitigation approach is based on (i) our formalized vulnerability signature and potential mitigation actions specification approach; (ii) an extensible vulnerability analysis tool that performs OCL-based vulnerability signature-based program analysis; and (iii) a vulnerability mitigation component that blocks service/application security vulnerabilities by generating configuration and integration scripts that integrate security controls at the application/service reported vulnerable points. In Figure 10-2, we summarize the possible interactions between the vulnerabilities definition repository, analysis and mitigation components, applications/service, and the hosting services (Web Server, Operating System, another PaaS, etc).

10.1.2.1 Vulnerability Definition Schema

Existing software security weaknesses, or vulnerability definitions, in the Common Weakness Enumeration (CWE) [27] database help in understanding the nature of a given vulnerability. However, these vulnerabilities' definitions are informal. This requires manual analysis (by security experts) to locate such vulnerabilities in the applications under analysis. This is very hard to satisfy in the cloud computing model as services are already outsourced. Formalizing these vulnerability definitions helps automating the vulnerability analysis and mitigation process. In chapter 8, we gave a detailed explanation of our proposed vulnerability definition schema which include vulnerability signature, category, preconditions, consequences, mitigation and prevention actions, and so on. In

this case study we focus on the vulnerability signature specification and vulnerability mitigation actions attributes in a given vulnerability definition.

As we explained before, a formal vulnerability signature should be specified on an abstract level far from the source code and programming language details, enabling locating of possible vulnerability instances in different programs written in different programming languages. We use Object Constraint Language (OCL) as a well-known, extensible, and formal language to specify semantic rather than syntactical signatures of security weaknesses. To support specifying and validating OCL-based vulnerabilities' signatures, we have developed a system-description meta-model. It captures the main entities in any object-oriented program and relationships between them including components, classes, instances, inputs, input sources, output, output targets, methods, method bodies, statements e.g. if-else statements, loops, new objects, etc. Each entity has a set of attributes such as method name, accessibility, variable name, variable type, method call name. This model helps conducting semantic analysis of the specified vulnerability signatures.

Discovered application/service security vulnerabilities can be mitigated in different approaches including: modifying application source code to block the identified problems (patches); however, this solution is hard to adopt in the cloud model as it may take long time to deliver patched version as shown in Figure 10-1. A quick solution is to use Web application firewall (WAF) to filter requests/responses that exploit such vulnerabilities; however, WAF has many limitations including it does not help in output validation, cryptography storage, and mitigating improper authorization. We introduce a new approach that supports integration of different security controls including identity management, authentication controls, authorization controls, input validation, output encoding, WAF, cryptography controls, etc. Each vulnerability definition has a set of mitigation actions that specify how to mitigate such vulnerability. Each mitigation action defines a security control type/family to be used in mitigating the related vulnerability, its required configurations, and application/service entity where the security control will be integrated with (hosting service including web servers or operating systems, components, classes, and methods). Thus, a reported SQLI vulnerability in a method (M) that belongs to component (C) can be mitigated by adding input sanitization control (Z) on component (C) that filter out SQL keyword from every single request to the method (M).

Table 10-1 shows examples of mitigation actions for some of the well-known security vulnerabilities. These actions should be specified in XML and included as a part of the formalized vulnerability definition. In Chapter 8 we introduced a set of proposed signatures that could be used to identify vulnerabilities in a given service/application.

Table 10-1. Examples of vulnerability mitigation actions

Vulnerability	Security Control	Entity Level
SQLI	Input sanitization	Method level
XSS	Input encoding	Component level
Authn. Bypass	WAF	Component level
Improper Authz.	Authorization	Method Level

10.1.2.2 OCL-based Vulnerability Analysis

Given that vulnerability signatures become now formally specified using OCL, the static vulnerability analysis component simply traverses the given program looking for code snippets with matches to the given vulnerabilities' signatures. The architecture of our formal and scalable static vulnerability analysis component, as shown in Figure 10-3, is already explained in Chapter 8.

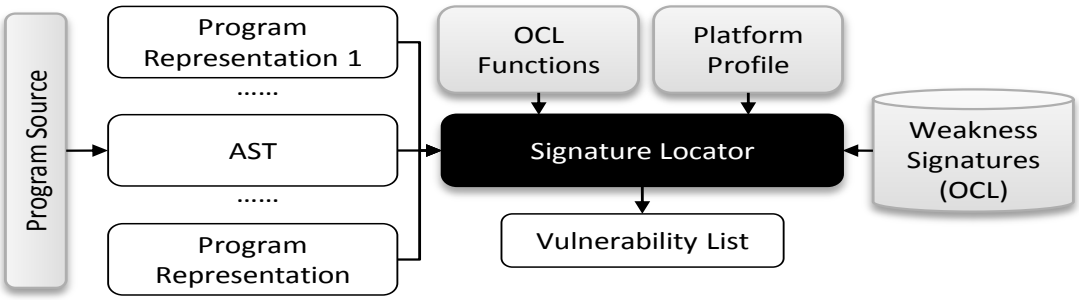


Figure 10-3. OCL-based vulnerability analysis component

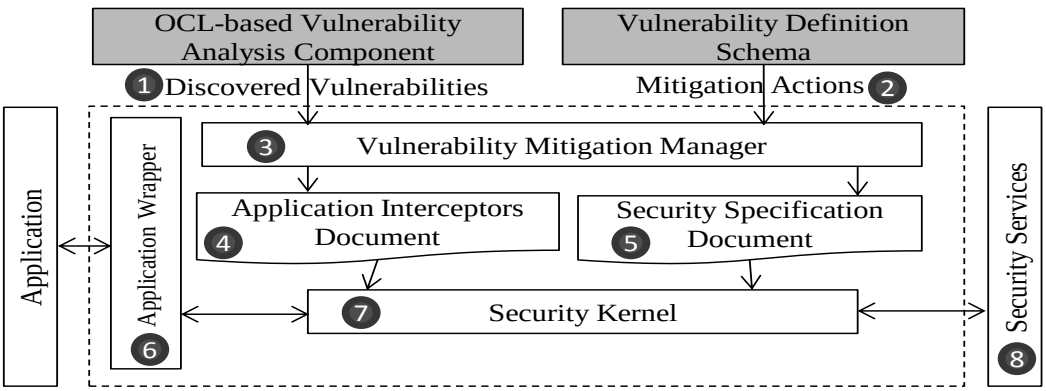


Figure 10-4. Vulnerability Mitigation Component

10.1.2.3 Vulnerability Mitigation

The analysis component outputs a list of the newly discovered vulnerabilities in each of the cloud hosted SaaS applications (Figure 10-4-1). Each entry in this list has a service/application vulnerable entity (method, class, or component) along with the list of discovered vulnerabilities. Given this list of vulnerabilities, the security vulnerability mitigation manager queries the vulnerability definition schema database (Figure 10-4-2) to retrieve the appropriate actions to be taken in order to mitigate each of such reported vulnerabilities. Examples of the retrieved actions are shown in Table 10-1. Using these two lists (vulnerable entities and mitigation actions), the vulnerability mitigation manager (Figure 10-4-3) decides the patching level (component level, class level, or method level) using e.g. HttpModules, object interceptor using dependency injection, or method level interception using dynamic weaving AOP respectively. These details are maintained in a security specification document for each application (Figure 10-4). Moreover, the mitigation manager uses the registered security services' properties to decide which security service realizes what security control type specified in the mitigation action – e.g. the identity and access management control is currently (on this platform) realized by identity manager. Finally, the vulnerability mitigation manager updates the security specification document (Figure 10-4-5) with the list of actual security services to be triggered whenever the application receives request to every vulnerable resource. The application wrapper (Figure 10-4-6) is responsible for intercepting requests to entities specified in the application interceptors' document – i.e. vulnerable entities. These requests will be redirected to the security kernel (Figure 10-4-7). The security kernel queries the security specification document to get the security controls/services to be enforced to patch the requested resource. Then, it generates calls/requests to these security services (Figure 10-4-8). When these services return, the security kernel returns the control back to the called resource. This is a bit modified version of MDSE@R to replace secure-system model that is developed by service provider and tenants with vulnerability list and reference vulnerability definition repository.

10.1.3 Experimental Evaluation

The key objectives of our evaluation experiments are to assess the soundness of our VAM-aaS in capturing different vulnerabilities' signatures, detecting these vulnerabilities in given applications, and in mitigating them. We apply the OCL-based vulnerability signatures examples and mitigation actions discussed in Chapter 8. We used the full set of benchmark applications (discussed in chapter 4) applied in the security analysis task as explained in Chapter 8**.** To assess the effectiveness of our approach we use the same evaluation metrics including precision, recall and f-measure to measure our approach soundness and completeness. The results of evaluating our analysis component applied on benchmark suite to identify four of the Top10 web applications vulnerabilities (OWSAP2010) are already presented in Chapter 8 for the security analysis part.

Table 10-2. Results of VAM-aaS vulnerability mitigation component

App	SQLI			XSS			Authn. Bypass			Improper Authz.		
	TP	FP	FN	TP	FP	FN	TP	FP	FN	TP	FP	FN
Galactic	2	1	0	4	1	0	4	0	0	2	1	0
Splendid	14	0	0	7	1	0	3	2	0	3	0	0
KOOBOO	14	2	0	10	3	0	4	1	0	12	0	0
BlogEngine	4	0	0	4	2	0	0	0	0	4	2	0
BugTracer	10	0	0	1	0	0	4	1	0	1	1	0
NopCommerce	19	0	0	5	0	0	0	0	0	1	0	0
Webgoat	9	0	0	5	1	0	4	2	0	3	1	0
Total	72	3	0	36	8	0	19	8	0	30	5	0

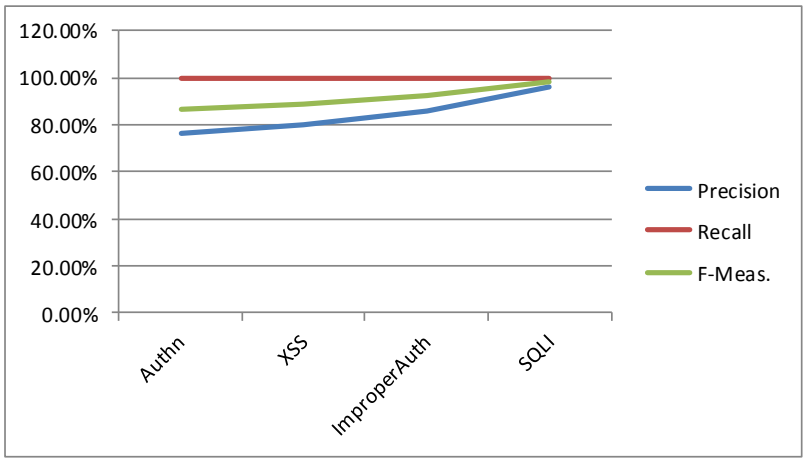


Figure 10-5 Effectiveness of the security mitigation component

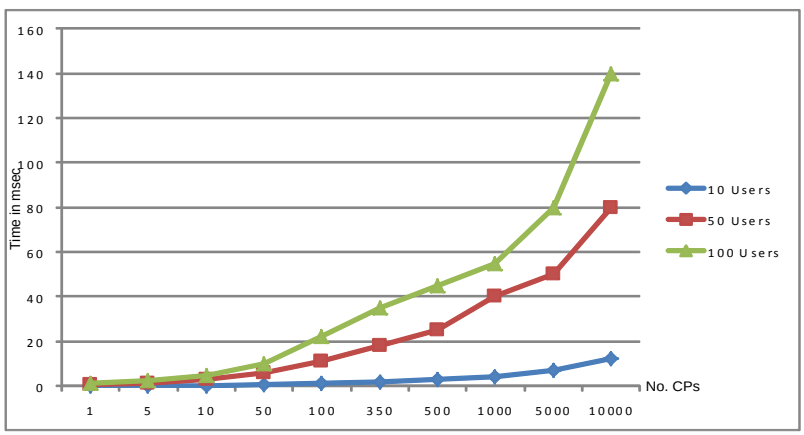


Figure 10-6. Performance overhead of the security mitigation component

Table 10-2 summarizes our experiments' results applied on benchmark suite to mitigate the vulnerabilities reported by the vulnerability analysis component. It shows the number of TP, FP, and FN. A key observation from this table is that the mitigation component does not have false negatives which means that no missing points that has not been mitigated.

Figure 10-5 shows precision, recall, and F-measure for the mitigation component, we have incorporated the results returned from the analysis component with the FN missed vulnerabilities. Although the recall rate is (100%) which means that we did not miss any of the specified mitigations, we have an average of (85%) precision – i.e. high FP - as we may secure entities that have no security problem. This depends on the accuracy of the specified mitigation actions.

Figure 10-6 shows the performance overhead of the mitigation component with different numbers of concurrent users and numbers of critical/vulnerable points (on a Core2Duo desktop PC with 4GB Memory). The performance overhead equals the time spent by the security kernel to query security specification document and get security controls to be employed in securing intercepted point, and time spent in calling these security controls. The time spent by the security controls themselves we do not factor in, as this needs to be spent whether using our approach or traditional hard-coded security. Performance can be further improved using replicas of the mitigation component with different services and platforms.

10.1.4 Discussion

We developed a formal vulnerability definition schema including vulnerability signature and mitigation actions, extensible vulnerability analyzer based on the proposed signature specification schema and applied on abstract program representation, and a vulnerability mitigation approach based on dynamic and runtime injection of security controls into vulnerable entities. Using OCL allows adoption of existing validation and query parsing tools. Using abstract representation helps generalizing and abstracting the security analysis task from specific programming languages or platform details. It also helps making the approach more scalable for larger applications. Use of a common security interface helps integrating different security controls without a need to develop new system-security control connectors.

From our experiments with mitigation actions and security controls integration, we found that although using web application firewalls is a straight forward solution, it is not always a feasible option to block all discovered vulnerabilities. The selection of the entity level to apply security controls on (application level, component level, method level, etc.) impacts the application performance – i.e. instead of securing only vulnerable methods, we intercept and secure (add more calls) the whole component requests. A key point that worth mentioning is that the administration of

security controls should be managed by the service/cloud provider administrators. Our focus is integrating controls within vulnerable entities.

Our vulnerability mitigation component works online without a need for manual integration with the applications/services under its management. The overhead added by the mitigation action can be easily saved if the service developers worked out a new service patch. In this case, the vulnerability analysis component will not report such vulnerability. Thus, the mitigation component will not inject security controls. Our experimental results show that the OCL-based analysis tool achieves (90%) precision rate and (92%) recall rate while our mitigation component achieves (100%) recall and (85%) precision rate.

10.2 Case Study No. 2: Supporting Multi-tenancy Reengineering using Re-aspects

In this case study, we address the multi-tenancy reengineering problem that obstacles service providers from adopting the cloud computing model to host their applications. One of the key issues that must be addressed in multi-tenancy reengineering is how to support security isolation between different tenants' data. To address this problem, we have applied our reengineering aspects "re-aspects" concept to help in this task. This case study is organized as follows. In Section 1, we discuss an overview of the multi-tenancy reengineering and security isolation problem. In Section 2 we introduce an analysis of the SaaS multi-tenancy reengineering requirements. Section 3 goes through usage example. Section 4 shows our experimental evaluation results and discusses implications of our approach.

10.2.1 Introduction

Multi-tenancy helps in delivering services including infrastructure, platform and software that can be shared between different tenants. In the IaaS model, multi-tenancy is achieved through using hypervisors that virtualize the server resources. Thus the Operating System itself does not need to be modified. Moreover, each customer has a separate instance (VM). However, In the SaaS model, multi-tenancy has different possible deployment models including a separate instance for each tenant up to a single instance for multiple tenants. The later deployment model is definitely the optimal model. However, it requires the SaaS application to handle multi-tenancy and tenants isolation themselves.

Supporting multi-tenancy requires the SaaS application to support capturing, processing and storing data of different tenants in the same application instance. Moreover, the SaaS application should maintain security and performance isolation between its tenants. This requires considering multi-tenancy as a key requirement from the early stages of the system development process. Many of the existing well-known, large-scale business applications that are widely used nowadays are locked-in a high cost business model. This prohibits them from targeting/servicing the "long-tail-market". Thus, it becomes a business need to migrate such applications to support multi-tenancy. Migration of such applications to support multi-tenancy is a very complicated task as it requires a deep understanding of the application. Moreover, multiple system modifications are required to be delivered. This requires revising/updating almost all system modules.

Existing multi-tenancy efforts focus either on extending applications to support multi-tenancy by wrapping a single-tenant application with a platform that manages the multi-tenancy dimension [22-24, 230, 232, 280]. The same approach has been followed in industrial efforts as well [281]. Using these approaches, applications are locked-in to cloud platforms that have such multi-tenancy

platform hosted. Moreover, features such as user interface customization, application model extension, etc. will not be available for tenants if the original applications do not support them. Limited efforts targeted conducting real reengineering of applications to support multi-tenancy [282, 283]. These efforts focus only on providing a systematic process to be followed by system engineers to support multi-tenancy. They do not provide tool support to facilitate process.

Our multi-tenancy reengineering approach is based on reengineering-aspects "Re-Aspects" concept where a given system modification (change request) details are captured as a re-aspect. A re-aspect includes a signature of code snippets to be modified; action to be applied on identified code matches (instances of these signatures) include inserting, modifying, replacing, or deleting code parts; and code to modify, replace or insert. We conduct a thorough analysis of the multi-tenancy pattern for web applications and come up with a set of key requirements/modifications that should be addressed at the database, data access layer, business logic layer, and presentation layer. Moreover, we studied the requirements for security and performance isolation.

We developed a set of modification patterns that system engineers can use when reengineering their applications to support multi-tenancy. Given these modifications specified as re-aspects, we analyse the system source code to identify code snippets that match specified re-aspect's signatures, and then it performs impact analysis to identify matched entities that need to be modified to realize the given modifications. Finally, we use the specified re-aspect actions to update the identified matches.

10.2.2 Multi-tenancy Requirements Analysis

We introduce an analysis of the potential modifications that may be required when reengineering an application to support multi-tenancy. We project our analysis to a typical architecture of a web application explaining what need to be added, modified, replaced, or deleted during the process of supporting multi-tenancy. This analysis is also helpful for service providers who plan to develop new multi-tenant SaaS application. Service providers have to make their own decisions based on their application architecture and the multi-tenancy paradigm they plan to adopt including single-instance single tenant, multiple-instance multiple-tenant, and single-instance multiple-tenant.

10.2.2.1 Multi-tenant Data Model

The multi-tenant application's database has different possible architecture models. The service provider has to select between these architecture models based on the isolation level they plan to deliver, scalability of the application, number of tables, expected sizes of the data tables, and impact on system performance. These architecture models include [13]:

- *Separate Database*: In this model, the service provider maintains a separate database for every tenant. This represents the highest level of isolation of the four models. Moreover, it is the easiest model for migration. On the other hand, database servers are usually limited in number of databases that they can host – e.g. SQL Server theoretically can support 32,767, however, practically it supports up to 2000 database instances with max number of concurrent connections up to 1000.
- *Shared Database but Separate Schema*: In this model, all tenants share the same database but different schemas. Thus each tenant has his own set of tables grouped under one separate schema. This provides a logical isolation between tenants' data. However, this approach helps mitigating limitations in the previous model; it suffers from database backup and restore problem. Moreover, it is mainly suitable for applications that have small number of tables.
- *Shared Database and Shared Schema*: In this model, all tenants share the same database and the same schema. Although this model is considered the most cost effective solution, it highlights the isolation problem between tenants' data. Developers have to make sure that every tenant cannot access other tenants' data. This may require modifying the whole application to consider filtering by tenantID in every query. This requires an intensive analysis of every system function. A simple common solution to this problem is to use database views to perform the filtering task. This in turn requires modifying all database queries to work on views-level not tables. A possible tricky solution to save such efforts is to rename all tables to be (initial + table name) – e.g. rename table Employees to sys_Employees. Then create views for all tables with the original table name – e.g.

```
EXEC sp_rename 'Employees', 'sys_Employees'
CREATE VIEW Employees AS
SELECT * FROM sys_Employees WHERE TenantID = USERID
```

  Thus all application queries will be projected automatically on views where data are already filtered by the current tenant. Of course, this requires using security impersonation (to allow the application to take the identity of the requesting user) when application connects to the database server. Another possible option is to modify the database connection in the data access layer so that all requests are redirected to a proxy where queries are validated and filtered before submitted to the actual database.

- *Mixed Model*: In this model, the service providers support different data models (of the three models discussed above) and leave it to tenants to select the model that best fits their needs in terms of scalability, security, performance and cost – e.g. Tenant T1 may decide to use shared schema model as it is less expensive and he is not worried about his data security. On the other hand, Tenant T2 may decide to use separate database model to maintain his data as he is very

keen about his data security. From the service provider perspective, this model (mixed-model) requires to support the three data models. Hence, service providers should conduct cost-benefit analysis (market share gained against cost) before delivering this model. Based on requesting user's tenant, the system (data access layer) should either connect to the shared database or to the tenant separate database.

Another issue that should be considered when architecting application data model is how to enable data model extensibility – i.e. every tenant may have special fields or data items that they need to maintain for every operation (record). This is straight forward when maintaining separate database or separate schema per tenant. However, it still has to be propagated to the next layers. There are different approaches to realize the data model extensibility including: pre-allocated fields where service providers define a set of dummy columns in every table they expect that their tenants may need to extend; Name-value pairs where the service provider defines one or more table to maintain other tables extensions. This table structure will look like (TableID, TenantID, attributeName, attributeValue); and XML extension column where every table has a predefined column of type XML where tenant extension columns can be maintained as one entity that can be saved and loaded. The selection of the database model and the model extensibility to adopt, impacts the modifications required in the next layers/tiers.

10.2.2.2 Application Layers

In data access and business logic layers we need to modify public methods' signatures to expect tenantID as a parameter. Methods' bodies should be modified as well to process the tenantID – e.g. adding tenantID to database queries, file access commands, database connection strings, loading business rules, loading and initializing workflow engine based on current tenant. TenantID is usually propagated from the presentation layer to these layers. Both the data access layer and the business logic layer should handle custom fields (data model extension) based on the model adopted in the data model. This includes handling load, store, and query of these custom fields. Business objects' classes should be modified to include tenant's specific data members.

In the presentation layer we have a set of potential modifications including user interface customization and branding (e.g. company logo, styles, themes, etc.), adding TenantID to session state, modifying calls to business logic layer functions to pass tenantID, modifying used business objects to set/get tenantID. Moreover, the presentation layer should support displaying different custom fields based on the current requesting user's tenant

```
using (DbCommand command = db.GetStoredProcCommand("dbo.GetEntityDefFields")) {
        db.AddInParameter(command, "tenantId", DbType.Guid, tenantId);
        db.AddInParameter(command, "entityDefName", DbType.String, entityDefName);
        using (IDataReader reader = db.ExecuteReader(command))
}
```

Figure 10-7. Example of modifications in the data access layer

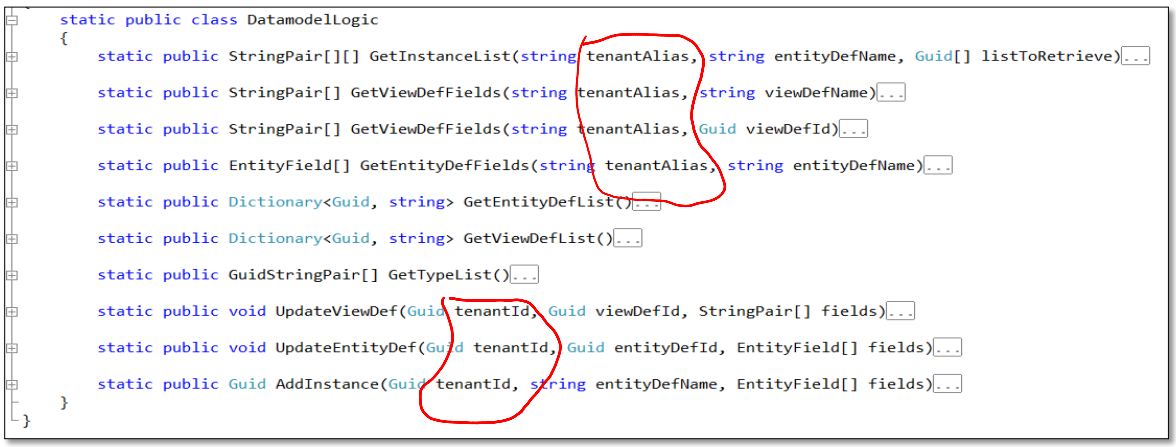


Figure 10-8. Examples of required modifications in application logic layers

10.2.2.3 Non-Functional Requirements

A multi-tenant application has to be scalable to support the potential number of tenants and their workloads. This requires the service providers to deploy their application on web farms and clusters. SaaS SLAs usually capture tenants' security, performance, availability, and reliability objectives requirements that should be satisfied by the SaaS application. This resulted in issues related to how to maintain performance isolation where the execution flow of a given tenant should not be impacted by other tenants'. Load balancers with performance controllers can help in solving this problem. However, it requires applications to be stateless. SaaS applications should maintain session information either on client side or on a shared server that is accessible to all other servers in this cluster.

Security is another nonfunctional requirement that should be addressed. A SaaS application should support customizing applications to support tenants' security "tenant-oriented security". This can be achieved by externalizing the security from the multi-tenant system by calling a standard library that performs authentication, authorization, etc. based on tenants' requirements and security controls. This enables every tenant to use his security controls – e.g. to use his LDAP server to authenticate and authorize users.

Table 10-3. Multi-tenancy change requests organized by architecture layer

Layer	Change Request
Presentation Layer	1. All web pages should load layout, localization and menus based on requesting tenant. 2. Entity extension fields should be loaded based on current tenant. 3. Every page grid-view column, user control should be enabled based on user security customization for current user's tenant. 4. All business functions should receive tenantID param. 5. Set tenantID field for every business entity created in the presentation or the business logic layer. 6. All entities display pages should include the tenant defined custom fields. 7. All entity insert/edit pages should include the tenants' defined custom fields.
Business Layer	8. All workflow definitions should filter by tenantID. 9. Update web services to have tenantID param. 10. Update all business functions to have tenantID param.
Data Access	11. All SQL queries should filter by tenantID. 12. All Linq queries should filter by tenantID. 13. All stored procedures should have parameter tenantID. 14. All business entities should have extra attribute of tenantID.
Database	15. Update all database tables with tenantID column. 16. Add new table for tenants' data.
QOS	17. User Authentication and Authorization should be done through the customer security controls, if any. 18. Support Load balancing and meet tenants' SLA.

10.2.2.4 Tenant On-boarding and Metadata service

The registration of a new tenant should be managed by a separate tenant administration service (may be an extension of an existing system administration module). This includes batches to restore a new database instance of the system template if the "separate DB" model is applied, or create a new schema with necessary tables. This module should also enable specifying security permissions for users, roles, screens and controls. It may also include screens' customization and localization.

The metadata service is a key module in a multi-tenant application. It helps tenants and service providers to customize (branding) the application to match tenants' business needs. This includes

customizing the user interface text, fields, visibility, and security capabilities, customizing the business workflow, business rules, and custom fields. Table 10-3 shows a summary of the modifications required in reengineering a given system to support multi-tenancy grouped by the application layer where each modification applied. Table 10-4 shows the re-aspects' signatures required to located entities to be modified in relation to the modifications specified in Table 10-3.

Table 10-4. List of re-aspects signatures for modifications in Table 10-3

CR	Change Request Signature
1	**Context** Method **inv** loadMethods: self.Class.GetBaseType() = "Page" **AND** self.Name = "Page_Load"
2	**Context** Method **inv** fieldExtension: self.Class.GetBaseType() = "Page" **AND** self.Name = "Page_Load" **AND** self.Contains(s : IfElseStatement | s.condition = "Page.IsPostBack"
3	**Context** Method **inv** fieldSecurity: self.Class.GetBaseType() = "Page" **AND** self.Name = "Page_Load" **AND** self.Contains(s : IfElseStatement | s.condition = "Page.IsPostBack")
4	**Context** Method **inv** businessfns: self.Contains(s : InvocationExpression | s.fnName.Contains("BusinessLayer"))
5	**Context** Method **inv** businessentity: self.contains(s : newObjectStatement | s.ClassName = "businessentity")
6	**Context** Method **inv** fieldExtension: self.Class.GetBaseType() = "Page" **AND** self.Name = "Page_Load" **AND** self.Contains(s : IfElseStatement | s.condition = "Page.IsPostBack")
7	**Context** Method **inv** fieldExtension: self.Class.GetBaseType() = "Page" **AND** self.Name = "Page_Load" **AND** self.Contains(s : IfElseStatement | s.condition = "Page.IsPostBack")
8	**Context** Method **inv** wrkflwfns: self.Class.Component = "Workflow"
9	**Context** Method **inv** webservicemethods: self.Class.GetBaseType() = "Webservice"
10	**Context** Method **inv** businesfns: self.Class.Component = "BusinessLayer"
11	**Context** Method **inv** sqlqueries: self.Contains(s: InvocationExpression | s.fnName = "ExecuteScalar" OR "ExecuteQuery")
12	**Context** Method **inv** Linqqueries: self.Contains(s: QueryExpression)
13	**Context** Method **inv** sqlqueries: self.Contains(s: InvocationExpression | s.fnName = "ExecuteScalar" OR "ExecuteQuery"
14	**Context** Class **inv** businessentityDef: self.ClassName = "businessentity"
15, 16	DB script
17	**Context** Method **inv** sqlqueries: self.Contains(s: InvocationExpression | s.fnName = "Redirect" AND TargetObject = "Response" AND Arguments.Contains("Login.aspx")
18	**Context** Class **inv** sessionmgmt: self.GetBaseClassType() = "IHttpModule"

Table 10-5. Evaluation results of our approach on the benchmark applications

CR	Galactic	PetShop	SplendidCRM	NopCommerce	BlogEngine
1	√	√	√	√	√
2	√	√	●	√	×
3	√	√	√	√	√
4	√	√	√	√	
5	√	○	○	√	√
6	√	√	√	×	√
7	√	√	√	×	√
8	√	○	×	√	○
9	√	○	○	√	○
10	√	√	○	√	●
11	√	√	√	√	√
12	√	○	○	√	√
13	○	○	√	√	○
14	√	√	○	√	√
Time	8	5	90	205	15

(√) CR successfully implemented, (●) CR Partially succeeded. (×) CR modification failed, (○) CR is not required

10.2.3 Experimental Results

To evaluate our approach, we have selected a set of our benchmark applications and tried to apply the set of change requests we identified from our analysis in the previous sections using signature developed and summarized in Table 10-4.

Table 10-5 shows that we have successfully applied our approach to migrate the benchmark applications. Some of these applications do not have features that we look for to change (○) – e.g. an application that does not provide workflow. Our approach failed to apply some changes on a set of given applications (×). This is specific for BlogEngine as code is mixed with html in the same file or use MVC pattern as in NopCommerce. Our approach has successfully implemented other remaining changes (√). We have evaluated our approach performance in locating instances to be updated for the given changes. Table 10-5 shows the total time taken by our approach to locate possible matches of the specified signatures.

10.2.4 Discussion

We introduced a new multi-tenancy reengineering approach that helps software engineers in migrating their applications to support multi-tenancy. Our re-aspects concept helps automating the program analysis and system updating (change propagation) phases using re-aspects. Software engineers model their modifications to be applied on the target application in terms of reengineering aspects. A re-aspect capture the signature of system entities to be modified in terms of OCL constraints; actions to be applied including insert, replace, modify, and delete; and code to apply. Our approach then uses these re-aspects' signatures to locate system entities to be modified and applying the actions specified for each re-aspect. We have developed a set of modifications that may be required to reengineer a given application to multi-tenancy. We used these modifications' set in validating our approach against a set of five benchmark applications. Our approach successfully helped in upgrading these applications to support multi-tenancy.

10.3 Case Study No.3: Supporting Multi-tenancy Reengineering using Re-aspects

We conclude this thesis with a case study that illustrates how the full platform components integrate together to deliver model-driven, multi-tenant, adaptive security management for cloud computing at runtime. To explain how our platform works, we start with an open source multi-tenant SaaS application, LitwareHR, developed by Microsoft to be used as a sample multi-tenant application. LitwareHR is a single instance multi-tenant SaaS Human Resources Recruiting SaaS application. This case study is organized as follows. In Section 1, we introduce the details of this case study and what scenario we are going to follow during our case study. In Section 2, we give details of the LitwareHR as our example SaaS application. In Section 3, we discuss the system description and security specification models that we will depend on through the whole case study. In Section 4, we introduce details and outcomes of the security analysis task. In Section 5, we explain how we reengineer LitwareHR to disable the built-in security capabilities of the system. In Section 6, we introduce different security models developed by different tenants of the service and how we integrate them using MDSE@R. In Section 7, we introduce a set of security metrics we want to follow up to conform the security status of our service assets and key mitigation actions.

10.3.1 Case Study Flow

Figure 10-9 shows the main steps, and possible relationships, that we are going to go throw in this case study. We possibly have two cycles: (1) security analysis, retrofitting, and patching, and (2) security management process. The first cycle starts with a deep security analysis task. This task should be a recurring and online task. The identified/reported vulnerabilities could be patched by modifying the system to patch such vulnerabilities using re-aspects engine, or could be patched using the MDSE@R "virtual patching". The reengineering task could be applied as well whenever we apply our approach on an existing system with built-in security capabilities.

The security management process (2) starts with defining security by service tenants. Then, the captured security details are realized using MDSE@R. Finally, the operated tenants' security is then monitored using our security monitoring approach. The results are fed back to the security management component to report and update the specification of security to be operated. In this case study, we start with cycle (1) as a preprocessing step – i.e. to identify and patch existing vulnerabilities and also to disable the built in security capabilities. Then, we show how the normal security management process goes including capturing tenants' security requirements, enforcing tenants' security, and finally monitoring service security status.

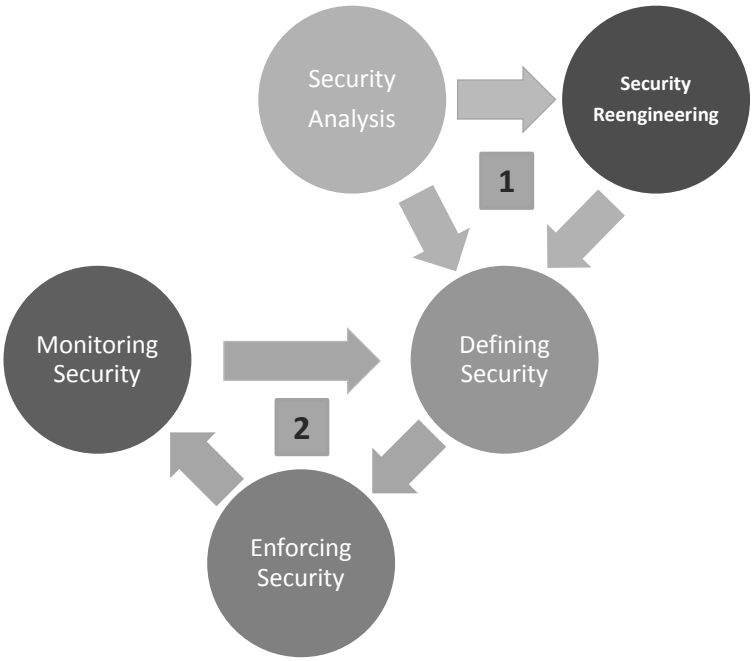


Figure 10-9. Steps and relations of case study

10.3.2 LitwareHR

LitwareHR is a sample multi-tenant SaaS application developed by Microsoft architecture strategy team to be used as guidelines for software vendors and developers who plan to develop SaaS applications. LitwareHR is based on a single-instance multi-tenant model where all tenants share the same service instance. LitwareHR uses a set of best practices in architecting and designing scalable and extensible software systems. Moreover, it uses a set of new technologies that help in developing such kind of applications. The main business delivered by LitwareHR is a recruitment management process which represents a key role of the HR department in any company. LitwareHR enables different tenants (companies) to outsource their recruitment process for third party cloud platform hosting LitwareHR to fulfill their business. LitwareHR has two key components: public site (that is used by applicants and employees to search and apply for jobs), and private site (that is used by employees to customize the application business, UI, and security).

LitwareHR comes with a usage example, Figure 10-10, where two tenants Contoso (retail shoe chain) and Fabrikam (music school) adopt the software where each tenant has their own business requirements (workflow, and data), UI (styles, logo, etc.), and security requirements (authentication, authorization). However, the LitwareHR does not enable using tenants' security controls. Those tenants are satisfied with the security requirements delivered by LitwareHR. We have added two new tenants to the usage example, Swinburne and Swine Market. Both tenants have their own security requirements and controls to be applied on their outsourced assets as we are going to discuss in the security engineering section later in this case study.

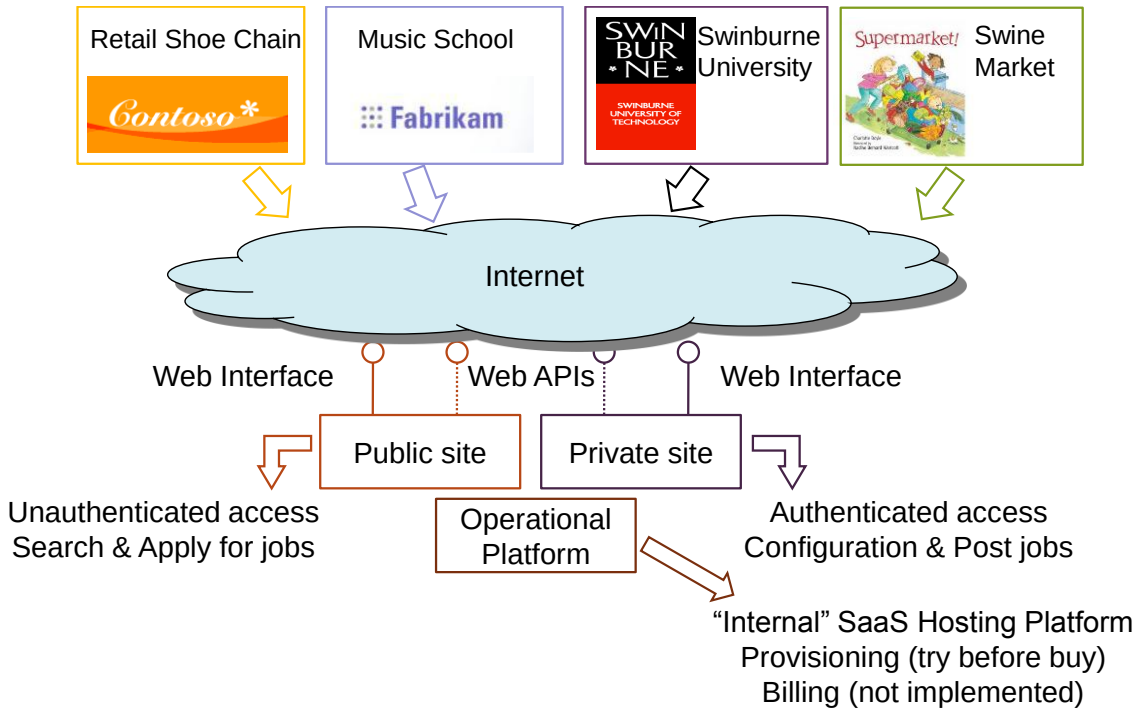


Figure 10-10. A simplified LitwareHR usage example

10.3.3 LitwareHR – SDM and SSM

Before we conduct security analysis, reengineering, or multi-tenant security engineering we need to develop system and security specification models that we can use in these tasks. However, we do not have any previous experience with LitwareHR. Thus, we had to spend some time (2 days) to understand the architecture and implementation details in order to figure out the delivered system functionalities. Fortunately, we found a set of system architecture diagrams that helped with this task. We deployed the application and used it for a couple of days in order to understand the whole set of provided LitwareHR features. Below we show and discuss the system and security details of the LitwareHR.

- *LitwareHR Features*: LitwareHR delivers a set of features that are related to HR recruitment process and a set of helping features related to the multi-tenancy concept and how to address the configurability of tenants' instances, as shown in Figure 10-11 (we developed from our understanding of LitwareHR). The main features delivered by LitwareHR includes: **manage tenant instance** (this includes customize look-and-feel, customize data-model, and customize workflow); **manage tenant security** (this includes mange roles, users and permissions); **manage tenant recruitment** (this includes posting jobs, searching for jobs, applying for jobs); and **application evaluation** (this includes interview, negotiation, acceptance, and rejection). LitwareHR is delivered with built-in security capabilities for authentication, authorization and secure communication channels for security critical capabilities.

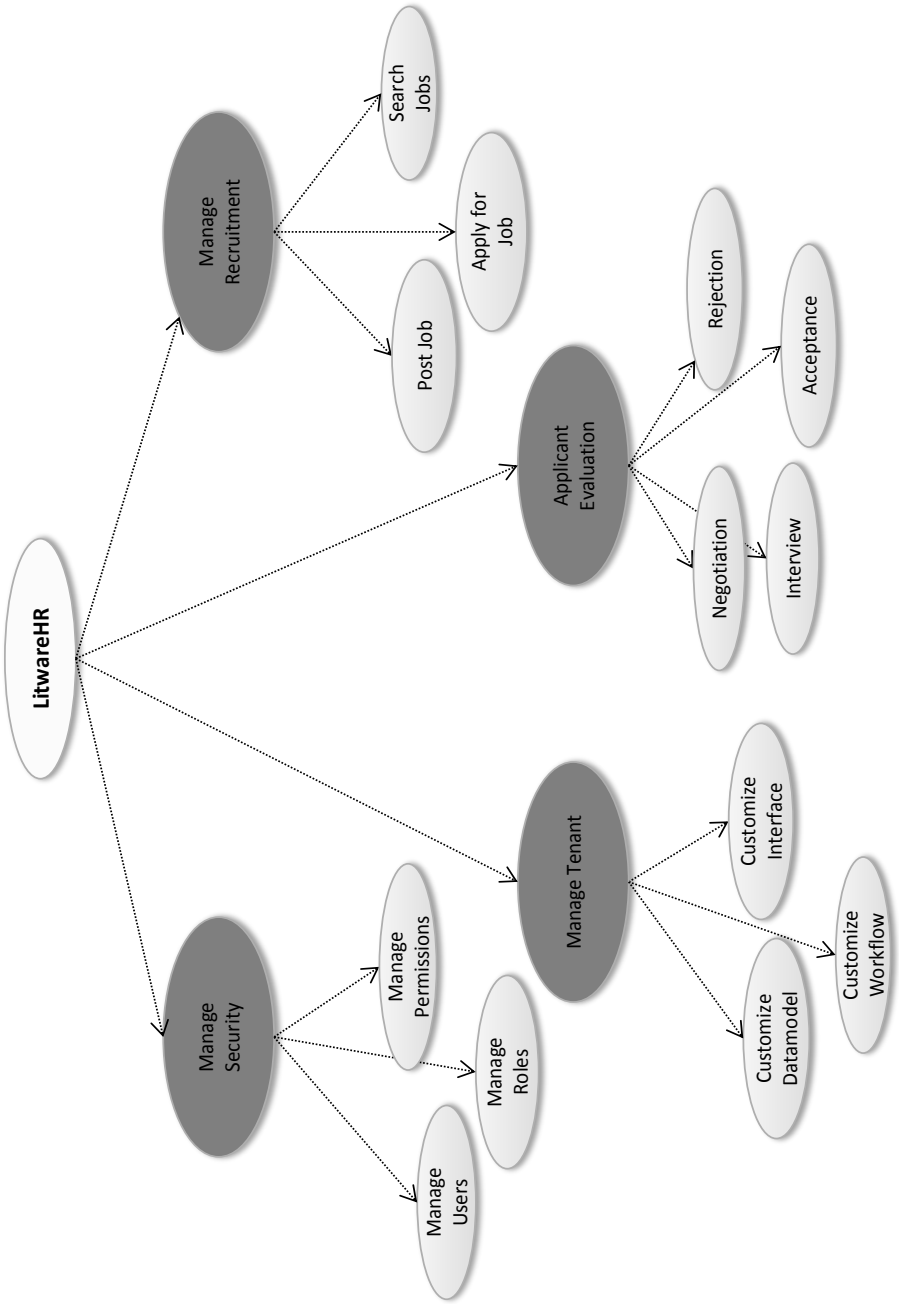


Figure 10-11. LitwareHR feature model

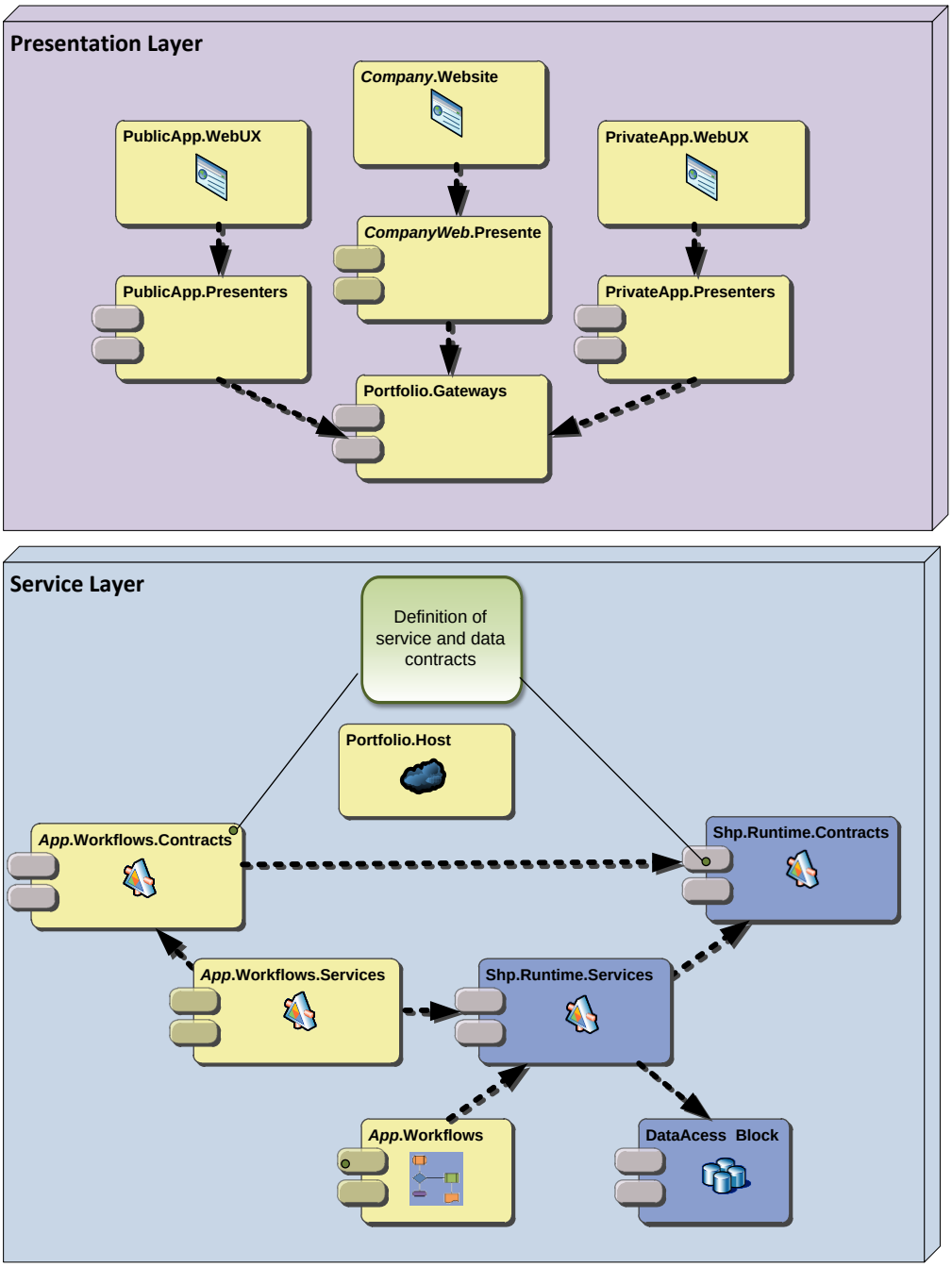


Figure 10-12. LitwareHR architecture

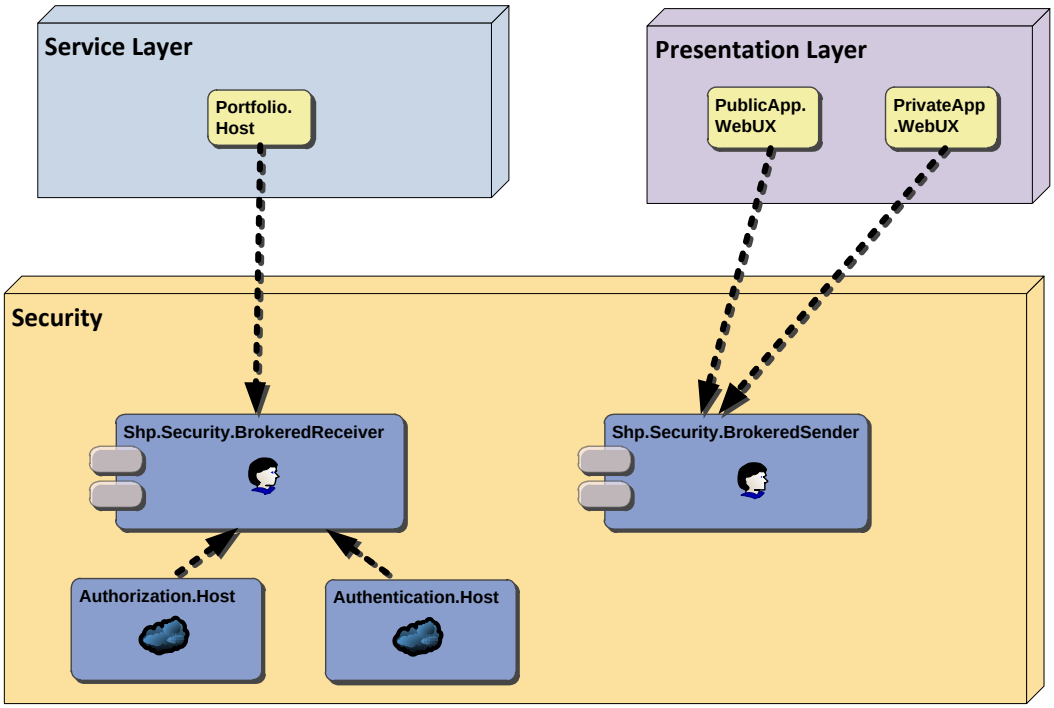


Figure 10-13. LitwareHR security architecture

- *LitwareHR Architecture and Deployment*: Figure 10-12 (provided by LitwareHR application developers) shows the LitwareHR architecture components with security components used. The ***LitwareHRWebsite*** component is the service provider website (published on the cloud platform) where tenants can register to use the LitwareHR service. This website is used to create separate copies of the public and private sites (as we will see later) and add required entries in the tenants' database and LitwareHR active directory that is used to authenticate and authorize tenants and their users. The ***publicApp*** website is used to post jobs, search and apply for jobs, and update applicants' recruitment process status according to tenant workflow. The ***privateApp*** website is used to configure the application according to tenant needs in terms of UI, security, data-model, and workflows. The ***Gateway*** component provides implementation of all functionalities used in the privateApp and publicApp components. In fact, the responsibility of the Gateway component is to delegate request from the presentation layer to the actual components/services in the business and services layer so that the presentation layer does not need to know how and who delivers the required functionality. The ***contracts*** component defines functionality interfaces that should be realized by business services. This contract is referenced by the presentation layer components to avoid being tightly coupled with the realization services (binding is done using configuration scripts). The ***services*** component delivers the realization services that implement the actual business functionalities used. The services component uses the Microsoft application blocks "Enterprise Library" to deliver the data access layer using the "DataAccess" block.

- *LitwareHR Class Diagram*: Figure 10-14 shows a part of the LitwareHR class diagram we extracted using reverse engineering of the system source code using Altova UModel toolset. We have grouped some of these classes that are related together such as classes used in the contracts component (1); classes related to workflow entities (2); classes related to authentication service (3); and classes related to the presentation view and presenter classes (4).
- *LitwareHR Security*: Figure 10-13 shows the main security components used by LitwareHR to deliver secure communication channels and interactions between LitwareHR components/layers and these security components. The main security components of LitwareHR are: BrokeredSender; BrokeredReceiver; authenticationHost; AuthorizationHost. These components are used to generate security tokens (BrokeredSender – in this case the presentation layer) and validate security token (BrokeredReceiver – services layer). Actually, the LitwareHR has other security components that are developed as part of the LitwareHR including ASP.NET custom membership feature that is used in authenticating and authorizing users in the ***publicApp*** component; and authentication and authorization services that are delivered by ***services*** component.

10.3.4 Security Analysis

The first step in our case study is to conduct a security analysis of the LitwareHR application to pinpoint the existing system security threats and vulnerabilities that we should mitigate. The objective of this task is to mitigate as much vulnerabilities as possible before publishing LitwareHR. Later on, the security analysis service will work online with the cloud services to report the existence of any new vulnerability. To fulfill this task we studied the LitwareHR system and security details covered in the last section. The list of vulnerabilities to test LitwareHR against is the list of threats and vulnerabilities we discussed in the security analysis chapter. **Table** 10-6 summarizes the list of threats and vulnerabilities we found in LitwareHR.

10.3.5 LitwareHR – Security Re-engineering

The objective of this security reengineering task is twofold: (i) to reengineer LitwareHR in order to disable the built-in security capabilities to start using MDSE@R in managing LitwareHR multi-tenant security; and (ii) to mitigate the reported vulnerabilities and threats from the previous task. To disable the LitwareHR developed security we have figured out three security properties that we need to address: secure communication, authentication, and authorization. For the secure communication, we have come up with two possible solutions: the first one requires modifying different parts of the system by adding new methods to contracts (interfaces) used in the unsecure communication and their realizations. At the same time, removing these methods from the interfaces used in secure communication channels.

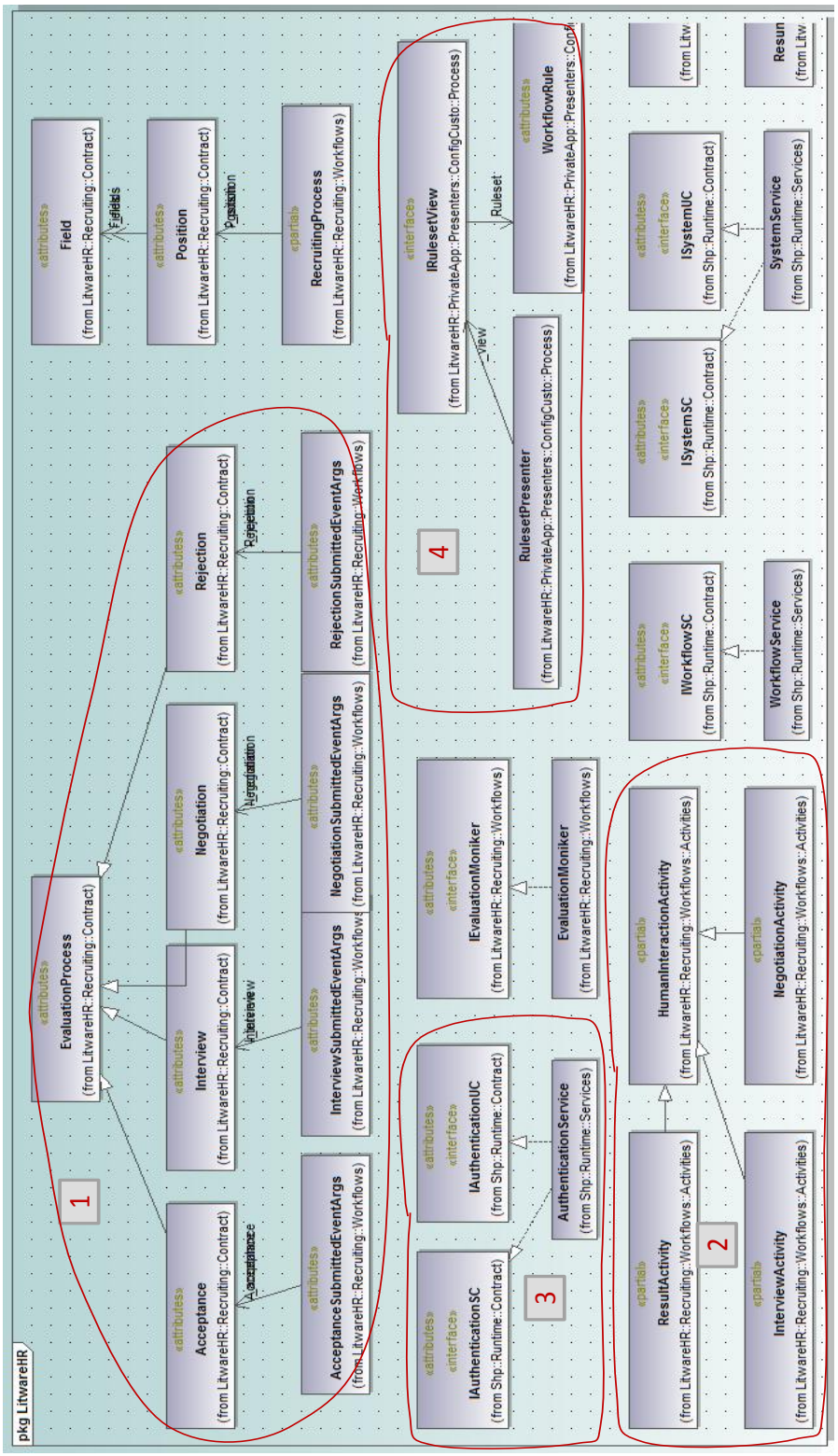


Figure 10-14. A part of LitwareHR class diagram

Table 10-6. LitwareHR found vulnerabilities and threats

Type	Name	Number/value
Attack scenarios and metrics	Man-in-The-Middle (↓)	0
	Denial of Service (↓)	2
	Data Tampering (↓)	2
	Injection Attack (↓)	3
	Attack Surface (↓)	12
	Compartmentalization (↑)	3
	Fail Securely (↓)	11
Security Vulnerabilities	SQLI	3
	Authentication Bypass	0
	Improper Authorization	3
	XSS	3
	CSRF	6

Table 10-7. LitwareHR security reengineering re-aspects

Re-aspect Signature	Re-aspect Action	Re-aspect Advice
AuthenticationGateway.GetUsers	Replace	Session[“TenantUsers”]
AuthenticationGateway.GetRoles	Replace	Session[“TenantRoles”]

Table 10-8. Tenants' security control

Security Attribute	Contoso	Fabrikam	Swinburne	Swine
Authentication	LitwareHR	LitwareHR	Forms-based	LDAP
Authorization	LitwareHR	LitwareHR	Forms-based	LDAP
I/P santization	–	–	–	Private Sanitization
Audit	–	–	Private Auditor	Private Auditor
Cryptography	LitwareHR	LitwareHR	DES	AES

The second solution, which we applied, is modifying the system configurations by removing the details of security controls configurations used in the encrypted communication. For the authentication and authorization properties, we have figured out that these properties are based on security authentication and authorization controls. Again modifying websites configurations helped to get rid of these security controls. We also found that authentication and authorization controls are used in internal business functions such as workflow roles and users. To address these problems, we have developed re-aspects to modify the LitwareHR source code to replace calls to these authentication/authorization functions with access to session variables that maintain list of roles and permissions that are set when the user login or requested from the source of security controls. We found 14 functions in the authentication service and 5 functions in the authorization service. We have categorized changes required to update system authentication and authorization into three categories as follows. **Table** 10-7 summarizes re-aspects' details required to update LitwareHR with modifications we just explained now.

- Functions that are used in managing tenants' accounts including adding, removing, updating, deleting tenants, users and roles. We do not need to modify this part. It could still be used for tenants who do not have new security requirements as we will see in the MDSE@R step.
- Functions used to authenticate and authorize users for certain actions (calls to these functions should be left out). If the tenant does not want to change the system security capabilities, we will inject system security controls using MDSE@R. A good point of the LitwareHR is that it is mostly based on configurations. Authentication and authorization functions are integrated with the system using configuration functions. Thus, we removed these configurations and will use MDSE@R to integrate them at runtime whenever needed.
- Functions used in business functions. These functions should be replaced with session-based. To do this task, we have used our re-aspects approach to modify the system source code. Here we depend on MDSE@R to fill in these session variables.

10.3.6 LitwareHR - Security Engineering

Now we come to the runtime multi-tenant security engineering task. The first step here is to deliver a system description model (SDM) that capture system features, architecture, deployment, and design details. Figure 10-11, Figure 10-12, Figure 10-13, and Figure 10-14 show the SDM and SSM models of the LitwareHR application. These models should have been delivered by LitwareHR service providers. However, in our case study, we could not have all these models because the system was developed beforehand. Thus, we developed some of these models manually by analyzing the system source code. The other part was developed using reverse engineering techniques. Next, service tenants (in this case study we have Contoso and Fabrikam) start developing (and updating whenever needed) their security specification models to define their

security objectives, requirements, architecture, and controls. As a future work of our approach, we plan to develop a client extension of MDSE@R where tenants can download the service SDM model locally – i.e. inside their network perimeter – where they can develop their security model and perform security-to-system mappings. These mapping are then refined locally – i.e. refining mapping of high-level security concepts, such as security objectives, or high-level system entities, such as system components, into security controls and system methods - and sent back to the MDSE@R platform to update the live system and security specification documents. Thus tenants can keep their security specification models confidential from hosting on the cloud platform.

In the security engineering chapter 6, we have validated in details the flexibility of MDSE@R to manage traceability of security details from high-level to detailed-level security (security objectives to security controls), managing traceability of system details using our UML profile (features to methods), and the many-to-many mappings between tenants' SSMs and system SDM. Here we focus mainly on the key (mandatory) security diagrams required to realize tenants' security (the tenant security controls model).

Table 10-8 shows LitwareHR tenants' security controls models. We consider in our usage example including Contoso, Fabrikam, Swinburne, and Swin Market. From the usage example, both Contoso and Fabrikam would like to apply the same set of security controls, while Swinburne and Swin Market would like to apply different security requirements. The key problem with the selection of these security controls to apply in our case study is that we have to develop adaptors for these controls that implement our common security interface introduced in MDSE@R chapter and integrates with these security controls. Thus, we reused the security controls we applied in the MDSE@R Chapter. Table 10-9 summarizes mappings done by each tenant between the selected security controls and system entities on the architecture level.

Table 10-9. Tenants' security-system mappings

Security Attribute	Contoso	Fabrikam	Swinburne	Swin Market
Authentication	Presentation layer	Presentation layer	Presentation layer	Presentation + Services layer
Authorization	Presentation layer	Presentation layer	Presentation + Services layer	Presentation + Services layer
I/P santization	–	–	–	Presentation
Audit	–	–	Presentation + Services layer	Presentation + Services layer
Cryptography	Communication channels	Communication channels	Presentation + Services layer	Presentation + Services layer

10.3.7 LitwareHR - Security Monitoring

We reuse the set of security metrics we defined in the security metrics and monitoring chapter (such as Authenticated Requests, Authentic Requests, Last(10) Requests to Authorization Control, Top(10) Request to Authentication Control By Admin Account, Mean Time Between Unauthentic Request, etc.) as the set of security metrics to be applied on the LitwareHR instance in this case study. For each tenant we use random number generator to control number of concurrent users per tenant, number of requests per tenant(s), number of malicious requests. As a further evaluation of the security management platform, we have defined a set of mitigation actions to be applied in case of security metrics' violations detected as shown in Table 10-10. The possible set of actions to be taken could range from simple alerts up to getting system offline or even analyzing collected measures and trying to detect root causes. However, our delivered platform capabilities, so far, is limited to mitigation actions that could be applied by the MDSE@R enforcement component. A future work in this point is to develop mitigation actions specification language with the associated mitigation actions realization components. Table 10-11shows the behavior (values of different metrics) of the LitwareHR when applying randomly generated requests (experiment attributes) at different time steps. Figure 10-15 and Figure 10-16 show the trend of the security metrics we have been monitoring.

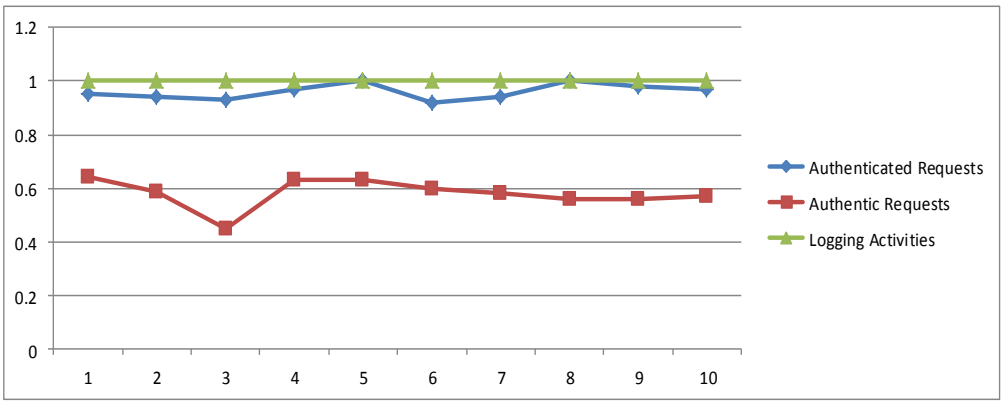


Figure 10-15. Base security metrics' status and trend overtime

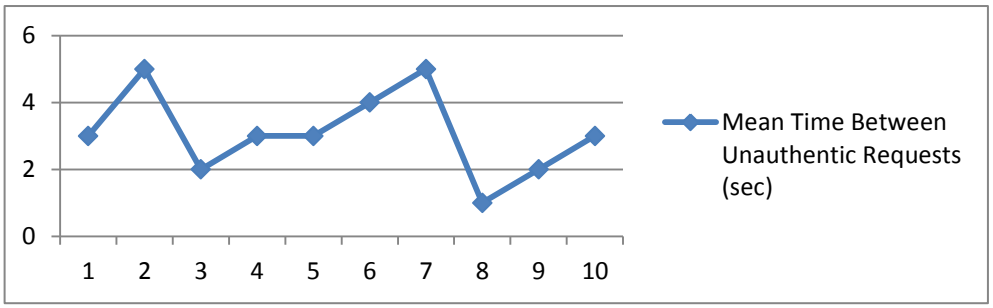


Figure 10-16. Derived security metrics' status and trend overtime

Table 10-10. Security metrics' mitigation actions

Metric	Conditions	Mitigation Actions
Authenticated Requests	M < 100%	Alert
Authentic Requests	M < 50%	Add, AuthenticationControl, LDAP
	M < 80%	Replace, AuthenticationControl, LDAP
Mean Time Between Unauthentic Requests	M < 1	Add, AuthenticationControl, LDAP
	M < 5	Replace, AuthenticationControl, LDAP
Logging Activities	M < 100%	Alert

Table 10-11. Security metrics' status

Time Step		1	2	3	4	5	6	7	8	9	10
Experiment Attributes	#Users	67	84	13	60	73	89	23	46	78	98
	#Requests	3423	4268	793	3297	4278	4977	1481	1376	4364	5154
	#Malicious Requests	2178	2535	356	2071	2697	2995	862	771	2461	2936
Security Metrics	Authenticated Requests	95%	94%	93%	97%	100%	92%	94%	100%	98%	97%
	Authentic Requests	64%	59%	45%	63%	63%	60%	58%	56%	56%	57%
	Mean Time Between Unauthentic Requests(sec)	3	5	2	3	3	4	5	1	2	3
	Logging Activities	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

10.4 Chapter Summary

In this chapter, we introduced three case studies we conducted to assess our platform components and integrations between platform components. The first case study addresses the automated virtual patching of reported vulnerabilities by our online vulnerability analysis and MDSE@R security enforcement component. Thus, this case study addresses integration between security analysis and mitigation components. The second case study addresses application of our reengineering aspects component in migrating applications to support multi-tenancy as a key task, beside the security reengineering, in the preprocessing phase before adopting the cloud computing model. The third case study shows the whole security management process for different tenants applied on a SaaS application developed as a sample multi-tenant application. One of the key areas that still need to improve is the mitigation actions that could be applied with the current metrics' values. Currently we support only mitigation actions that are linked to the security enforcement component which may be adding extra security control, replacing existing security control, or removing an existing security control to a new or already secured system entity at runtime. Further actions could be updating operated security controls' configurations, analyzing root causes of the reported problem (deviation from the expected behavior), or even taking system offline until further administrative actions are taken. This may require developing an extension of our OCL-based language to capture such invariants and metrics.

Chapter 11
Conclusions and Future Work

In this chapter we summarize the key problems we addressed in our research project; key observations we found throughout the project; key contributions we achieved; key limitations we figured out in our approach and solutions; and key future work tasks that we plan to work on as extension of the work introduced in this project and explained throughout this thesis.

11.1 Key Addressed Security Problems

In this research project we addressed a set of important security problems in the cloud computing domain. This set of problems was identified from our initial cloud computing security problem analysis that we completed in our first milestone [4]. Below we summarize this set of problems that we addressed in our research project.

We addressed the Loss-of-Control Security Problem. This is one of the top ranked cloud consumers' security concerns about the cloud computing model. This problem arises from three key factors: Outsourcing IT assets for hosting on third-party cloud platform; The new responsibility matrix of the cloud computing model that puts cloud consumers out of control over their assets (e.g. SaaS model); And lack of support to integrate cloud consumers' security controls' with cloud services taking into consideration those different tenants may be sharing the same service instance.

We addressed the Lack-of-Trust Problem. This is one of the top ranked cloud consumers' security concerns about the adoption of the cloud computing model. This problem arises from: The lack of feedback about the operated security, security breaches, and any relevant security status; Cloud consumers do not trust that the cloud providers really enforce the specified security controls; lack of security terms in the service level agreements between the cloud provider, service provider, and cloud consumers; and cloud consumers do not trust that the cloud provider administrators do not breach their assets security at rest, at processing, or at transmission.

We addressed the tenants' Security Integration Problem. Different tenants have their own security requirements, policies and controls that they operate internally in their network perimeter. These security controls should be integrated with their cloud-hosted assets as well. Currently this is not supported by default. Service providers have to prepare a certain interface or connectors to enable tenants in integrating their controls. Moreover, these tenants' security

requirements could be easily changed at runtime to address new security risks and threats. New service tenants can register to use the service and apply their security requirements. Existing tenants can unregister from the service. Those tenants should not be able to access or use the service anymore.

We addressed the security problems arise from the public accessibility of cloud services. Cloud-hosted services are publicly accessible to end users who may be malicious users. Moreover, the cloud services are shared among different tenants. One of those tenants may be malicious tenant or a competitor who wants to breach other tenants' security. The key problem of service sharing is that malicious users are granted high privilege and permissions to perform more administrative actions. This increases the possibility to exploit more complicated vulnerabilities and to perform planned attacks. On the other hand, depending on traditional service patching approaches (through the use of service maintenance) takes a long time that increases the probability of being under attack by exploiting the reported service vulnerabilities.

We addressed the tenants' data isolation problem. Supporting multi-tenancy requires cloud applications to support capturing, processing and storing data of different tenants on the same application instance. Thus these applications must maintain isolation between different tenants' data. Many of the existing well-known business applications that are widely used nowadays are locked-in a high cost business model. This prohibits them from targeting/servicing.

11.2 Key Contributions

In this research project we have introduced a set of solutions to address security problems arise from the adoption of the cloud computing model summarized in the previous section. Bellow we summarize the key contributions we did in the cloud computing and security management area.

We introduced a novel alignment of the NIST-FISMA standard to fit with the cloud computing model. The existing security management standards are not developed taking into consideration the multi-tenancy, sharing of cloud services, and outsourcing of the tenants' assets out of their network perimeter. Our proposed alignment is based on the joint-collaboration between different cloud stakeholders (cloud providers, service providers, and cloud consumers) in securing cloud platforms and services. To deliver this new alignment, we studied the standard activities and tasks. Then, we developed a new responsibility matrix that shows who is responsible to fulfill a given task and who are informed with these results. We also introduced a web-based security management prototype to help in assessing our proposed alignment.

We introduced a novel security management platform for the cloud computing model based on the use of model-based management concept to overcome the problem of manual

customization and engineering efforts required to manage the target cloud-hosted services. The model-based management is based on automating realization and configuration of the software systems and security controls based on abstract system and security models. This approach best fits with the cloud model as we cannot grant service consumers admin privileges to customize or modify shared cloud services. Our security management model enables realization of both manual security adaptation through updating system and security models as well as automated security adaptation through specification of recovery and mitigation actions in case of reported security vulnerabilities or deviations from the expected behaviors. The proposed model is based on one of the key security management standards (NIST-FISMA standard) after aligning it to fit with the cloud computing model. This helps in getting tenants and providers to keep their security management processes including their cloud hosted assets easily aligned with the security management standards using our cloud computing security management model.

We introduced a novel security modelling domain-specific visual language SecDSVL to be used in capturing and modelling their security details. SecDSVL is based on a deep analysis of the main entities and tasks existing in security management standards (mainly NIST-FISMA standard). SecDSVL is made of 5 main models including security objectives model, security requirements, security risks ad threats, security architecture and design, and security controls model. SecDSVL is designed with the loosely coupling concept where each model addresses specific perspective of the security management process that usually done by certain process stakeholders.

We invented a novel, model-driven, tenant-oriented security engineering model compared with the existing traditional design time, service-oriented, security engineering efforts. We introduced multi-tenant, model-driven security engineering at runtime approach (MDSE@R). Our approach enables different cloud and service tenants to manage (define, enforce, and monitor) their service instances' security at runtime without a need for service customizations. MDSE@R introduces a comprehensive system description model (SDM) that captures all system details (this model is developed by service providers using UML) and security specification model (SSM) that captures each tenant's security details (this model is developed by service tenants using SecDSVL). MDSE@R introduces a common security interface that helps in integrating third-party security controls with the target IT assets at runtime. Security vendors need to develop their security services' adaptor to comply with this security interface. Thus, they do not need to develop different adaptors for different services.

We developed an extensible online security analysis service. We introduced a security analysis service that can analyze service architecture, design, source code, and binaries to identify the existing security design flaws and bugs. The key contributions of the security analysis service are: integrated security analysis throughout different service artifacts including

architecture, design and code; the security analysis service is extensible, thus we can add different security analysis mechanisms without a need to modify the underlying platform; and security analysis is signature-based, thus any vulnerability, threat, or system design security metric could be easily specified and verified against the system without a need for new plugins. This helps to support online analysis for known and unknown vulnerabilities that arise at runtime as far as a signature of such vulnerability exists.

We invented a new, extensible security monitoring service. The main contribution of this security monitoring service is that we did not develop a predefined set of security metrics. Service users can define their own security metrics they wanted to use in diagnosing the security status of their cloud assets. The security monitoring service uses these metrics signatures (definitions) to generate and deploy required security probes that will be responsible for collecting required measurements from the target cloud assets. Moreover, it uses these signatures in generating metric evaluation expressions that will be used in analysing the collected measurements and generating metric values.

We invented a new pre-processing tool to help migrating legacy applications to the cloud and disabling pre-existing, hardcoded security functionalities. In order to help managing services security using MDSE@R we need to disable the existing security APIs and functions. We introduce a novel system and security reengineering approach using a new concept called reengineering aspects "Re-aspects". This new concept helps in capturing system modification details including signature of system entities to modify, actions to apply, advice(s) or code to use in realizing this change. The re-aspects engine uses these details to realize the captured change request details. This approach is supported with two signature specification approaches including code-snippets signatures and OCL-based signatures. We used re-aspects in two problems: the patching/mitigation of reported vulnerabilities and in migrating legacy applications that are not designed with multi-tenancy in mind to support cloud multi-tenancy.

We invented a new, automated vulnerability virtual patching approach. This is an integration of the MDSE@R and vulnerability analysis service. This approach provides an automated virtual patching where reported vulnerabilities are fed in MDSE@R to inject specified security controls (as specified in the vulnerability mitigation actions) at the critical (vulnerable) system entities at runtime without waiting for patches that usually take several weeks.

11.3 Key Limitations

In this section we summarize the key limitations that we determined out in our proposed solutions and contributions we explained throughout this thesis. Below we summarize these limitations grouped by the corresponding approach or contribution.

MDSE@R does not help in realizing security requirements that should be enforced on the cloud services' underlying platforms (e.g. webservers) and operating systems (in case of separate VMs). Moreover, MDSE@R currently does not support security engineering of applications developed by languages other than .NET languages because of the currently used system wrapper. We plan to develop further wrappers for systems developed with Java and scripting languages.

The current signature locator implements static signature analysis of the software source code and system architecture. This helps in identifying certain types of security vulnerabilities that have strong signatures in source code. Other vulnerabilities related to dynamic analysis such as cross site reference forgery (CSRF) could not be addressed with high accuracy using the static analysis. It is worth mentioning here that our security analysis platform is already developed with such possible extensions in mind.

Another problem with our security analysis approach is that applications using dynamic integration of security controls using aspect-oriented programming will result in high false positives as we cannot trace the existence of security controls' calls in the system source code. The same applies with applications that depend on the hosting platform (webserver) deployed security controls. Furthermore, applications with obfuscated binaries are hard to analyze (given that we do not have access to the source code) because we cannot reflect source code from system binaries using the existing reflection techniques.

The accuracy of the security analysis results depends on the specified vulnerabilities, attacks, and metrics' signatures. This justifies our assumption that such signatures should be developed by security experts. As a possible improvement to this problem, we plan to develop an artificial intelligent extension that can analyze reported vulnerabilities in the National Vulnerabilities Database (NVD) and come up with the security vulnerabilities' signatures that represent such vulnerabilities.

The current implementation of the security monitoring approach supports only security metrics but not security properties (policies). Moreover, the current approach is limited in terms of the mitigation actions that could be applied to the capabilities provided by the security enforcement component (MDSE@R). Thus any further analysis or mitigation actions still not supported.

The currently used probe generator technology (Roslyn Scripting APIs) result in security probes with high performance overhead because we compile and run security probe code at runtime. We are currently investigating in how to integrate newly generated security probes with the system wrapper without a need to perform online compilation.

Our security reengineering approach does not help with system modifications that have hierarchical impact on system entities – i.e. modifying entity A requires modifying B and C, modifying B and C requires modifying D, E, and F. our reengineering approach (re-aspects) supports only one level of the impacted entities. This can be addressed by extending impact re-aspect to be a complete re-aspect. But this will increase developers' involvement.

The accuracy of the located entities to be modified, entities that will be impacted, and validity of the applied modification actions by a given system modification depends on the signature specified by the re-aspects developer.

Applications with obfuscated binaries are hard to reengineer because we cannot reverse engineer source code from system binaries using existing reflection techniques.

11.4 Future Work

In this thesis we have introduced an adaptive, model-based cloud computing security management approach. Our proposed approach focused on delivering a platform that helps enforcing different sets of security requirements for different tenants that arise at runtime. We take the single-instance multi-tenant Software-as-a-Service service delivery model as the main model to be addressed by our approach. This is because it represents the most complicated service delivery model. The work we did with the software-as-a-service service delivery model can easily be applied on the platform-as-a-service service delivery model. Below we summarize future extensions in the proposed approach in general and in specific components of the delivered platform:

We plan to extend our security management platform to include managing security of the Infrastructure-as-a-service service delivery model. This helps tenants to extend their security management capabilities to manage security of their cloud virtual infrastructure (mainly virtual machines). This enables our security management platform to deliver comprehensive cloud computing security management platform that could be used to manage cloud platform security whatever the service delivery model(s) delivered by the cloud platform. It enables mitigating the cloud consumers' lack-of-trust problems completely. Moreover, it enables cloud providers to integrate their security management platforms (used to manage the cloud platform security) with our platform in one comprehensive and integrated model. A further key point is the adoption of homo-morphic encryption where tenants' data are not even decrypted while being processed on the cloud platform. This helps in addressing concerns related to malicious insiders – i.e. cloud platform administrators who are expected to have access to the hosting server memory, storage, and network.

We plan to extend our vulnerability analysis platform to support not only static analysis but also dynamic analysis. This dynamic analysis will be mostly dependent on the security monitoring platform with a test case generation service. The analysis of application responses should be automated according to vulnerability specified signature. The security vulnerability analysis platform is designed with extensibility in mind. Thus, we will not need to modify its design. We will need to develop the dynamic analysis component as a plugin to be registered and triggered by the vulnerability analysis platform according to the type of the vulnerability signature (static or dynamic signature).

We plan to extend the security monitoring platform with mitigation action and analysis specification language. The objective of this extension is to provide a formal and familiar language to help in developing expressions that could be used in identifying root causes of possible system deviations from the normal behavior specified by service tenants. Moreover, this could help in specifying and applying more complicated mitigation actions on the service or its underlying platform such as replacing one of the service components with a more secure one, using components from another service provider in case of mash up applications, or extending the operated security with more complicated controls.

We plan to conduct multiple large scale industrial case studies with different industrial cloud platform providers, service providers and a set of SaaS applications hosted on different cloud platforms and shared among different tenants. We also plan to contact different security vendors who deliver cloud-based security services (authentication, authorization, etc.) to get involved in developing a common security interface that facilitates integrating security controls with the target cloud services.

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