Self-Reconfigurable, Intrusion-Tolerant, Web-Service Composition Framework

by

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List of Abbreviations

API	Application Programming Interface
AOP	Aspect Oriented Programming
BP	Business Process
BPEL	Business Process Engineering Language
BPEL4WS	Business Process Execution Language for Web services
BPML	Business Process Modelling Language
CA	Cluster Analysis
DII	Dynamic Invocation Interface
DOM	Document Object Model
DoS	Denial of Service
FRR	Failure Records Repository
GPTRR	Groups Penetration Tests Results Repository
HashDoS	Hash Collision
ID	Intrusion Detection
IP	Intrusion Prevention
ITWS	Intrusion-Tolerant Web Service
NVD	National Vulnerability Database
OSVDB	Open Source Vulnerability Database
OTSC	Off-The-Shelf Components
OTSWSs	Off-The-Shelf Web Services
OWASP	Open Web Application Security Project
PCA	Principal Component Analysis
PCs	Principal Components
PTR	Penetration Tests Repository
QoS	Quality-of-Service
RPCs	Remote Procedure Calls
SAML	Security Assertion Markup Language
SAX	Simple API for XML
SB-WS	Stock Broker *WS*
SGM	Service-Groups Manager
SGR	Service-Groups Repository
SM	Services Manager
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
SPTRR	Services Penetration Tests Results Repository
SQ-WS	Stock Quote *WS*
SR	Services Repository
UDDI	Universal Description, Discovery and Integration
WA	Web Application
WASC	Web Application Security Consortium
WSCI	Web Service Choreography Interface
WSDL	Web Service Description Language
WSFL	Web Services Flow Language
WSs	Web Services
XACML	Extensible Access Control Markup Language
XML	Extensible Markup Language
XSD	*XML* Schema Definitions

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Abstract

The *Internet* has provided an opportunity for businesses to offer their services as Web Services (*WSs*). WSs are used to implement Service Oriented Architecture (*SOA*). They enable composition of independent services with complementary functionalities to produce value-added services, which results in less development effort, time consumption and cost, enabling companies and organizations to implement their core business only and outsource other service components over the *Internet*, either pre-selected or on-the-fly.

Simple Object Access Protocol (*SOAP*) based *WSs* are at risk of security vulnerabilities related to their specific implementation technologies such as Extensible Markup Language (*XML*) as well as those of their underlying platforms (e.g., operating systems and frameworks) and their applications (e.g., vulnerability to *SQL Injection* attacks). Cyber-attacks on *WSs* may cause unavailability, loss of confidentiality and/or integrity as well as significant monetary penalties. Security issues become more challenging when Off-The-Shelf Web Services (*OTSWSs*) are used since they are beyond the control of their clients.

The central question underlying this work is:

Can a self-reconfigurable Intrusion-Tolerant Web Service, implemented using N-version programming and diversity formed by composing Off-The-Shelf Web Services that are selected through penetration testing, Principal Component Analysis, and Cluster Analysis processes mitigate XML-related security vulnerabilities?

While aiming to answer the above question, this dissertation presents a novel framework to increase dependability by constructing an Intrusion-Tolerant Web Service (*ITWS*) in which *N-version programming* and *diversity*, formed by composing *SOAP-OTSWSs*, is used. It describes how penetration testing can be used as a measure of security vulnerabilities of available *SOAP-OTSWSs* (that offer the required functionality) and the resultant *ITWS*,

how Principal Component Analysis (*PCA*) and Cluster Analysis (*CA*) and be utilized to group the *SOAP-OTSWSs* based on their security vulnerabilities diversity and how a further penetration testing on each group of diverse *SOAP-OTSWSs* can be used to select the optimal set (most secure among the groups) for construction of *ITWS*.

This dissertation also demonstrates how the dynamic reconfiguration of *ITWS*, created in Business Process Engineering Language (*BPEL*), can be enabled using a combination of *BPEL* constructs and Java as *BPEL* extension approach and using only Java as *BPEL* extension approach.

The novelty of the work presented in this dissertation is twofold. On the one hand, it is security informed and on the other hand, it demonstrates the use of *Java* (as *BPEL* 2.0 extension) to implement self-reconfigurable composite *WS*. It has the advantage of, at the same time, facilitating a dependable service to users and exploiting existing standard technologies. This work also assesses the effectiveness of the proposed solutions through various case studies and discusses the implications of the proposed framework.

CHAPTER

1

Introduction

This dissertation is concerned with improving the dependability of Simple Object Access Protocol (*SOAP*) based Web Services (*WSs*) when Off-The-Shelf Web Services (*OTSWSs*[1]) are employed. Its focus is on the security vulnerabilities related to *WSs'* implementation technologies. It introduces a novel framework to increase dependability by constructing Intrusion-Tolerant Web Service (*ITWS*) in which *N-version programming* and *diversity*, formed by composing *OTSWSs*, is used. It also demonstrates how dynamic reconfiguration of *ITWS* can be enabled by using a combination of Business Process Engineering Language (*BPEL*) constructs and *Java* as *BPEL* extension approach and using only *Java* as *BPEL* extension approach.

This chapter starts by describing the motivation for the problem addressed by this dissertation (Section1.1). It then presents the context of (Section1.2) and the central question underlying (Section1.3) this work. Afterward, it enumerates the contributions (Section1.4) and lists the research distinctions (Section1.5). Finally, it outlines the remaining chapters of this dissertation (Section1.6) and presents its publication (Sec-tion1.7).

[1] The focus of this dissertation is on the *SOAP*-based *WSs* and the term "**WS*", wherever used in this dissertation, refers to this type of services.

1.1 Motivation

Service Oriented Architecture (*SOA*) is a popular paradigm for system integration and interoperation. It employs services as fundamental elements for developing applications. A service is a self-contained unit of software that provides a particular function. *WSs* are an implementation of the *SOA*. A *WS* can be as simple as a logging service or as complex as an organization's business logic that is decided to be exposed to the outside world [1]. *WSs* can advertise their services (e.g., *OTSWSs*) through a registry. Hence, desirable *WSs* can be looked up (via their description) and used individually or integrated into a composite *WS*.

In *WSs,* all documents and data are in Extensible Markup Language (*XML*) format. This property has simplified the interoperability of the various technologies employed in the development of *WSs* [1]. It has also provided other attractive features such as simple request-response service exchange architecture (ease of use), platform independence, the ability to transport lots of information over the *Internet* and capability to compose loosely coupled components [1]. Because of these features, *WSs* are being employed in the development of various critical applications, such as banking, booking, e-business, e-science, etc. [2], [3]. Hence, ensuring their security has received considerable attention from researchers: security standards [4], authorization [5], access control [6], [7], anomaly detection [8], etc.

In addition to the above attractive features, *XML* has also introduced its specific security vulnerabilities that cannot be detected by Intrusion Detection and Intrusion Prevention systems. For example, a malformed message that does not comply with expected message structure can make the server unavailable or cause unintended operations. Use of *WS*-* security standards [4] and message validation (before they reach the business logic) are often cited as sufficient countermeasures to safeguard against attacks exploiting this type of security vulnerabilities [9]–[11].

The *WS*-* security standards are members of *WSs* specifications and apply integrity and confidentiality through *SOAP* extensions (e.g., *XML* Signature and *XML* Encryption). They also provide communication of several security token formats (e.g., Security Assertion Markup Language, Kerberos, and X.509). However, they have the following limitations:

- Equipping a SOAP message with these standards may require changes to the message's structure since their use may introduce additional elements which did not exist previously.
- If their use is revoked, the message structure may require significant changes.
- They may cause security vulnerabilities themselves. For example, McIntosh and Austel [12] have shown that the content of a *SOAP* message, which is protected by an *XML* Signature (as specified in *WS-Security* standard) can get changed without invalidating the signature.

A *SOAP* message validator checks whether the message adheres to the specified schema and discards the message if it does not. However, this approach also has various limitations such as:

- Often such validators rely on XML Schema Definitions derived from Web Service Description Language document or hand-coded by programmers, which may make them prone to cyber-attacks.
- Similarly to the previous limitation, manual unguided schema updates that rely entirely on the skills of a programmer may also make the validator prone to cyber-attacks.
- If the schema used by the validator is loosely defined, it may allow malicious messages to pass through.
- They cannot safeguard against some cyber-attacks exploiting *XML-related* security vulnerabilities. For example, Jenson *et al*. [13] have shown that even the most restrictive *XML* Schema validators may fail to defend against *XML* Signature Wrapping attacks.

The security issue gets more challenging when *OTSWSs* are employed since they are ready-made black boxes of unknown quality and their security is out of the control of their clients. However, any attacks exploiting their security vulnerabilities will also affect the services offered by their clients. Also, *OTSWSs* may be updated (which may increase or decrease their security) or more secure *OTSWSs* (offering the same required functionality) may become available. Therefore, their clients should be able to replace them to maintain or even improve the overall security, if they wish to. The replacing to a more secure *OTSWS* may need to be done dynamically as switching off the client's system might not be acceptable.

To address these challenges, a self-reconfigurable, intrusion-tolerant *WS* remains an interesting choice, which is the motivation for the work presented in this dissertation and one of its key benefits is the possibility of ensuring correct behaviour in the presence of attacks.

This dissertation presents a novel framework to increase dependability by constructing *ITWSs* in which *N-version programming* and *diversity*, formed by composing *OTSWSs*, is used. It uses penetration testing as a measure of security vulnerabilities (*XML-related*) of available *OTSWSs* (that offer the required functionality) and the resultant *ITWS*. It employs Principal Component Analysis (*PCA*) and Cluster Analysis (*CA*) to group the *OTSWSs* based on their security vulnerabilities diversity then performs further penetration testing on each group to select the optimal set (most secure among the groups) for construction of *ITWS*. It also investigates the dynamic reconfiguration of *ITWS*, created in Business Process Engineering Language (*BPEL*), using a combination of *BPEL* constructs and *Java* as *BPEL* extension approach and using only *Java* as *BPEL* extension approach.

1.2 Context

This section discusses how the current work can be used.

Assume a Stock Broker WS (*SB-WS*), which uses a third-party Stock Quote WS (*SQ-WS*). If this *SQ-WS* becomes unavailable for any reason or returns incorrect stock prices, it will affect the *SD-WS* business and reputation. These problems can be diminished through redundancy approaches. For example, through *SD-WS* using *SQ-WSs* (offered by various vendors) simultaneously to get the stock price then performing majority voting on the returned stock prices. In this way, *SD-WS* can continue to provide reliable service as long as the majority of the employed *SQ-WSs* return the correct stock price. This approach (redundancy) can also improve the overall security of the *SD-WS* if the utilized services have security vulnerabilities diversity. Otherwise, any common security vulnerabilities will be a window of opportunity for compromising all the *SQ-WSs,* having the targeted security vulnerability, at the same time that will also affect the *SD-WS's* business and reputation. Also, *SQ-WSs* may become upgraded (which may increase or decrease their security) or more secure *SQ-WSs* may become available. Therefore, *SD-WS* should be able to perform dynamic (since switching off *SD-WS* will cause significant monetary penalties) self-reconfiguration to use the optimal set of *SQ-WSs* (set of *SQ-WSs* with most security vulnerabilities diversity).

The framework presented in this dissertation addresses the above needs of *SD-WS* as follows:

1. Redundancy: through a composite *WS* constructed using *BPEL* (a de facto language for *WSs* composition).
2. Security vulnerabilities diversity: by identifying the security vulnerabilities of each available *SQ-WS* through penetration testing then grouping these services based on their security vulnerabilities diversity using *PCA* and *CA* approaches and finally selecting the optimal set (most secure) through a further penetration testing.
3. Dynamic reconfiguration: through a combination of *BPEL* constructs and *Java* as *BPEL* 2.0 extension approach or using only *Java* as *BPEL* extension approach.

1.3 Research Questions

The central question underlying this work is:

Can a self-reconfigurable ITWS, implemented using N-version programming and diversity formed by composing OTSWSs that are selected *through penetration testing, PCA, and CA processes mitigate XML-related security vulnerabilities?*

1.4 Contributions

In particular, this dissertation makes the following contributions:

1. A general architecture for an *ITWS* (formed by composing *OTSWSs*) that mitigates *XML*-related security vulnerabilities.
2. The integration of penetration testing, *PCA,* and *CA* to group *OTSWSs* based on their overall *XML*-related security vulnerabilities for *ITWS* implementation.
3. An approach to reconfiguring the *ITWS* (implemented in *BPEL*) using a combination of *BPEL* constructs and *Java* snippets (as *BPEL* 2.0 extension).
4. A method for reconfiguring the *ITWS* (implemented in *BPEL*) using only *Java* as *BPEL* 2.0 extension.

1.5 Research Distinctions

The major novelties of this work are as follows:

1. Consideration of *XML*-related security vulnerabilities in selecting *OTSWSs* and implementing *ITWS*.
2. Use of *PCA* and *CA* analysis on penetration tests results of *OTSWSs* in choosing a diverse group of services regarding their security vulnerabilities to implement *ITWS*.

1.6 Outline

The rest of this dissertation is organised as follows:

Chapter 2 further explains the motivation for the work of this thesis and describes its background. In particular, it elaborates on main areas that constitute the current context, namely, *WSs'* architecture and characteristics, their security issues, their composition and self-reconfiguration capabilities and penetration testing them as well as dependability (*N-version programming* and *diversity*), *PCA* and *CA* approaches.

Chapter 3 explains the architecture of proposed framework and the assumptions made.

This dissertation demonstrates the proposed framework through some case studies. Chapter 4 introduces the penetration testing tool, utilized in the case studies presenting the proposed service selection framework. It then demonstrates the feasibility of *ITWS* implementation based on penetration test results of the candidate *WSs*.

Chapter 5 shows that *BPEL* could affect the *XML*-related security vulnerabilities of the candidate (for *ITWS* implementation) *WSs* and argues that these effects should be considered in service selection process.

Chapter 6 shows, how penetration test results of the candidate *WSs, PCA,* and *CA* could be used to group *WSs* based on their *XML*-related security vulnerabilities and how these groups could be sorted using further penetration testing.

Chapter 7 demonstrates the implementation of self-reconfigurable *WS* using a combination of *BPEL* constructs and *Java* as *BPEL* 2.0 extension approach and utilizing only *Java* as *BPEL* extension approach through two case studies.

Chapter 8 evaluates the work presented in this dissertation using the outcomes of the case studies covered in Chapters 4-7.

Chapter 9 reviews recent related work.

Finally, Chapter 10 provides a summary, conclusions, and discusses future work.

1.7 Publication

The following publication is based on this dissertation:

S. Khani, C. Gacek, and P. Popov, “Security-aware selection of Web Services for Reliable Composition,” *ArXiv151002391 Cs Math*, Oct. 2015.

CHAPTER

2

Background and Motivation

Simple Object Access Protocol (*SOAP*) based Web Services (*WSs*) have attractive features such as simplified interoperability of the various technologies employed in their development. However, they may also have Extensible Markup Language (*XML*) related security vulnerabilities that can be mitigated through appropriate countermeasures such as the use of *WS*-* security standards and message validation (before a message reaches the business logic). But each of these approaches has its limitations especially when Off-The-Shelf Web Services (*OTSWSs*) are employed.

This chapter presents the background and motivation for this dissertation and identifies Intrusion-Tolerant Web Service (*ITWS*), created using *N-version programming* and *diversity* (formed by composing *OTSWSs* with security vulnerabilities diversity), as an interesting choice to safeguard against cyber-attacks exploiting *WSs'* security vulnerabilities (including *XML-related* security vulnerabilities). In this work, a combination of penetration testing, Principal Component Analysis (*PCA*), and Cluster Analysis (*CA*) approaches are employed to select a set of most diverse *OTSWSs* regarding their security vulnerabilities and its motivation is given throughout this chapter.

In particular, this chapter is divided into the following sections, each corresponding to a different dimension that shapes this dissertation:

Section 2.1 provides an overview of the architecture and the characteristics of the *WSs*.

Section 2.2 provides an overview of security issues concerning *WSs* including their *XML-related* security vulnerabilities, the existing countermeasures to safeguard against cyber-attacks exploiting this type of security vulnerabilities and the limitations of such countermeasures. It then concludes that an *ITWS* remains an interesting choice to protect against cyber-attacks threatening *WSs* including those exploiting *XML-related* security vulnerabilities especially when *OTSWSs* are employed.

Section 2.3 presents a concise overview of the concepts and techniques of dependability and how intrusion-tolerance can be achieved using such methods.

Sections 2.4 and 2.5 briefly discusses penetration testing, *PCA,* and *CA* approaches and explains how they can be employed to achieve diversity (regarding security vulnerabilities) for *ITWS* purpose.

Section 2.6 provides an overview of *WSs'* composition and how it can be used to implement *ITWS*. It then argues the usefulness of self-reconfigurable *ITWS* for security and reviews the capabilities and limitations of Business Process Engineering Language (*BPEL*) 2.0 in this matter.

Finally, Section 2.7 summarizes the discussions provided in this chapter and the motivations for the work presented in this dissertation.

2.1 Web Services Overview

A publically available service is a self-contained process (deployed over standard middleware such as *J2EE*) that can be described, published, discovered and invoked over a network [14]. It can be as simple as a logging service or as complex as an organization's business logic (e.g., holiday booking service).

Service Oriented Architecture (*SOA*) is an architectural style for implementing software systems out of loosely coupled, interoperable services

[15]. This approach supports the development of rapid, low-cost and easy to compose distributed applications [14]. An *SOA* typically consists of the following roles (the operational architecture of the *SOA* roles is shown in Figure 2.1):

- **Provider:** is the owner of the service that hosts its implementation, defines its description and publishes it to a registry [1].
- **Requester:** it can be either a person or another *WS*. It uses the service registry to identify its desirable service(s) through its (their) description then binds to it (them) using the binding information provided in its (their) description [1].
- **Registry:** it is a searchable registry of service descriptions (published by their owners) [16].

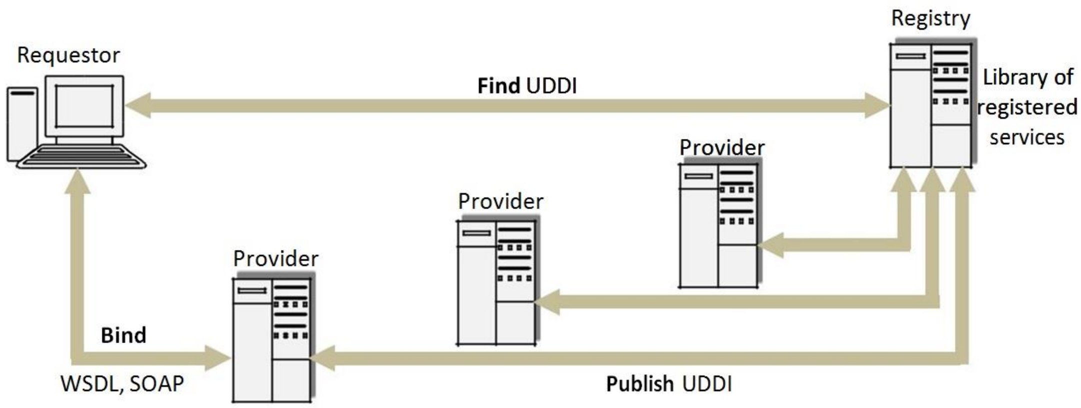


Figure 2.1: The Service Oriented Operational Architecture [1]

WSs are the standards-based realization of *SOA* [17]. They are modular, self-describing, self-contained software components, which are network accessible (e.g., they are accessible through *HTTP*) [14]. Each service consists of an implementation (which is accessible over a network) and an interface (which is based on *XML*). The interface contains the service's description including its datatypes, operations, protocol bindings and the network location for its implementation (e.g., the *URL* for the service's implementation) [1]. The characteristics of *WSs* include:

- **They are *XML*-based:** *XML* is a specification language and can be used to transmit or store data. In *WSs, XML* is used for invoking the services and representing the data. Forasmuch as it can accommodate any data type and structure, it enables interoperability of the technologies adopted in the development of *WSs* [1], [18].

- **They are loosely coupled:** in *WSs*, the client and the server logics are loosely coupled. Therefore, any changes in either of these interfaces do not require an update in the other interface [1].
- **They are coarse-grained:** unlike object-oriented technologies that expose the services through several fine-grained methods, *WSs* only expose coarse-grained services [1].
- **They can be synchronous or asynchronous:** *WSs* can be either synchronous (the client should wait until the last service invocation is completed before invoking the next service) or asynchronous (the client can invoke different services concurrently) [1].
- **They support *RPCs*:** clients of the *WSs* can invoke procedures, functions, and methods on remote objects through an *XML*-based protocol [1].
- **They support document exchange:** in *WSs,* complex documents can be represented in *XML* format, which enables *WSs* to exchange them [1].

2.1.1 Web Services' Core Technologies

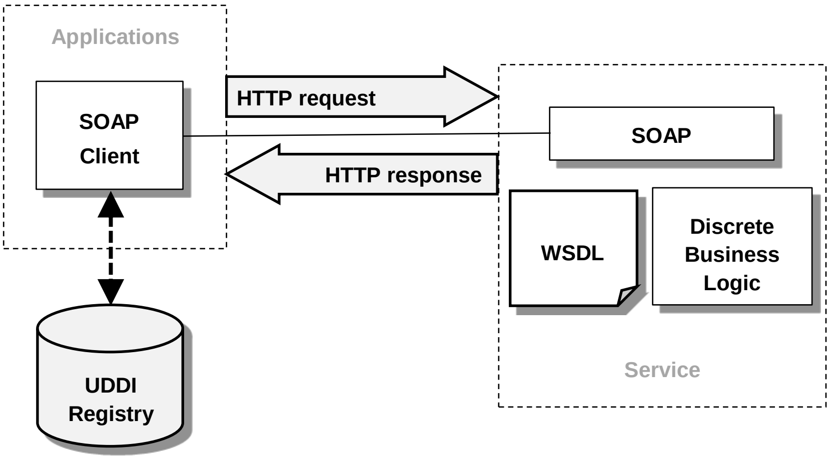


Figure 2.2: Simple *WS* Interaction [1]

SOAP [19], Web Service Description Language (*WSDL*) [20] and Universal Description, Discovery and Integration (*UDDI*) [21] are *WSs'* major technologies [22], whose interaction is demonstrated in Figure 2.2.

SOAP

SOAP is a simple and lightweight protocol for exchanging the *XML* data over the *Web* [22]. It enables interoperability among the *WSs'* heterogeneous clients and servers [1]. A *SOAP* message contains an *Envelope* (identifies the *XML* document as a *SOAP* message), a *Header* (contains *Metadata* such as timestamps) and a *Body* (contains call and response information) elements [1].

WSDL

WSDL is an *XML* language for describing a *WS* including its data type definitions, the operations it offers, its input/output message format, its network address, its protocol binding, etc. [22]. It assists the clients to understand how the interaction with the *WS* can be set.

UDDI

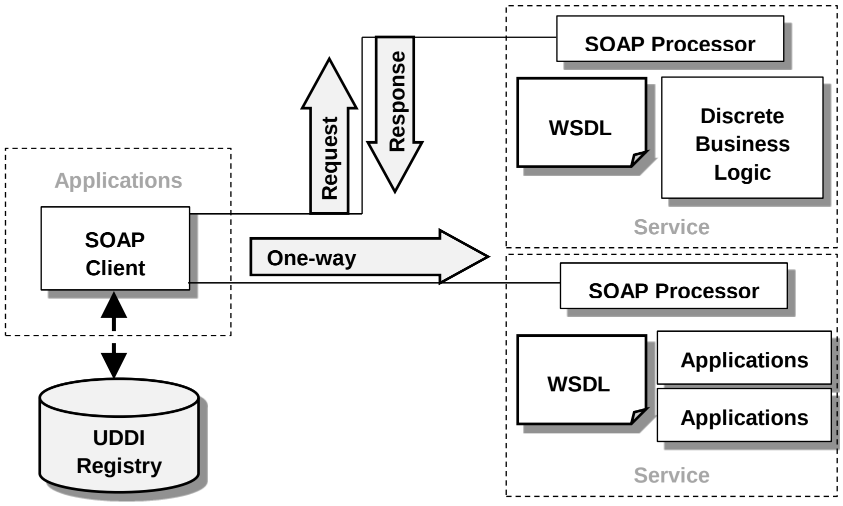


Figure 2.3: Discrete Components in a *WS* Architecture [1]

UDDI provides a registry where the *WSs* can be advertised and discovered by their names, specifications, etc. [1]. In the example presented in Figure 2.3, an application is acting as a client, which has submitted the information (e.g., specification) about its desirable services to a *UDDI*. The *UDDI* has identified the suitable services, based on the client's requirements, and has returned the location of their *WSDL* to the client. The client is then communicating with the identified services through *SOAP* messages and contact information provided in their *WSDL* files.

Sometimes the client may need to communicate with another client, which itself is communicating with a number of other *WSs* (see Figure 2.4) to perform a task. In this case, the target client and the *WSs* that it communicates with can be combined and encapsulated to form a composite service [1].

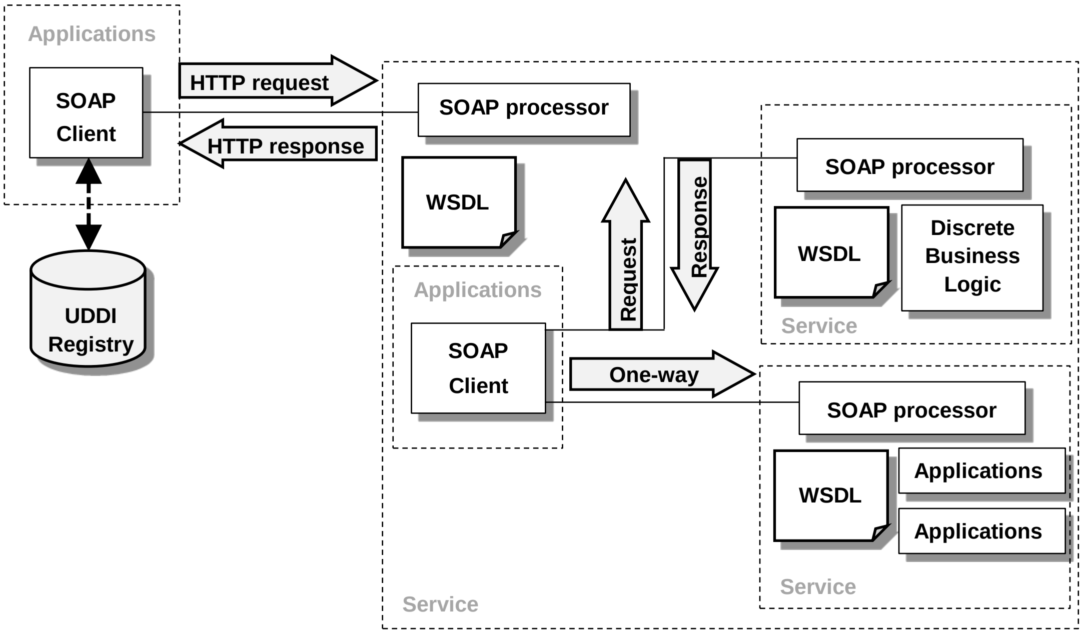


Figure 2.4: Composite *WS* [1]

2.1.2 Summary

This section briefly presented the architecture of the *WSs* and showed that they are modular, self-describing, self-contained software components, which are accessible through *HTTP*. These features allow companies to save on their costs by speeding the application(s) implementation and integration processes [23]. On the other hand, *WSs* also have security issues that have to be addressed. The next section first explains the concept of security properties, vulnerabilities, and attacks as well as security in distributed software systems. It then presents security vulnerabilities concerning *WSs* followed by an overview of a number of existing countermeasures against cyber-attacks exploiting *WSs' XML-related* security vulnerabilities (as the focus of the work in this dissertation is on this type of security vulnerabilities). It then explains some of the limitations of these countermeasures and concludes that an *ITWS* is a suitable countermeasure to safeguard against cyber-attacks threatening *WSs* including those exploiting *XML-related* security vulnerabilities, especially when *OTSWSs* are employed.

2.2 Web Services' Security Challenges and Issues

Security Properties

The security objective of computer systems is to protect the stored information and the data that should be transferred over the networked devices. To achieve these objectives, the following main security properties should be satisfied [24]:

- **Authorization:** to ensure that users do not take action or access the resources and information beyond their specified rights.
- **Authenticity:** to ensure that the people or systems taking part in the communication are who they claim to be.
- **Confidentiality:** to ensure that the information will only be disclosed to the authorised people.
- **Integrity:** to ensure that the information will only be altered by the authorized people.
- **Non-repudiation:** to ensure that the involvement of the legitimate people or systems in a transaction cannot be denied.
- **Availability:** to ensure that authorized parties can access the information when needed.

Cyber-attacks and Vulnerabilities

Any action violating any of the above properties is an attack and any possibility (loophole in the security architecture of the computer system) enabling an attacker to harm the resources is a vulnerability [24]. Cyber-attacks can be divided into *Passive* and *Active* groups.

- **Passive attacks:** eavesdropping or accessing unauthorised data are the objectives of *Passive* attacks [23].

- **Active attacks:** this type of attacks attempt to change the unauthorised data by making a modification or adding false data [23]. *Active* attacks can be further divided into the following groups:
  - **Masquerade:** one entity tries to gain access to unauthorised data or resources by pretending to be an entity with this access right [23].
  - **Replay:** replaying the message back to the sender as if it was the reply from the receiver [23].
  - **Unauthorised access:** getting access and using unauthorised data/resources [23].
  - **Unauthorised alteration:** illegitimate modification, removal or alteration of the data [23].
  - **Repudiation of action:** a party denies an action it has performed [23].
  - **Unauthorised *DoS*:** one party denies other entities authorised access to the resources [23].

Security in Distributed Software Systems

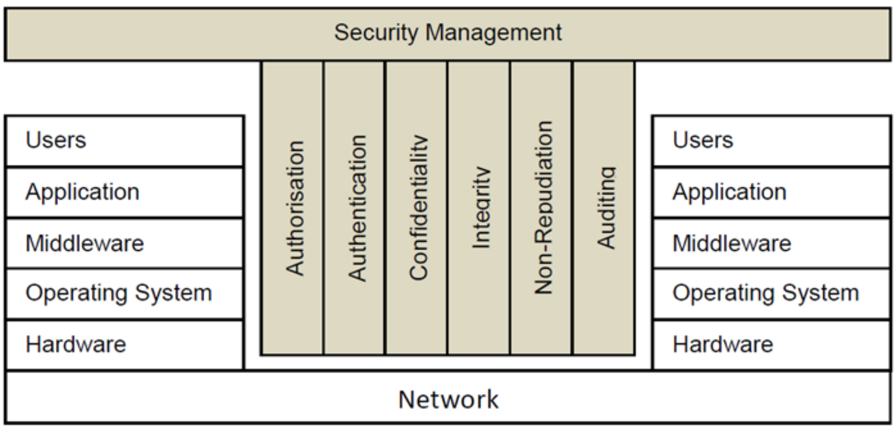


Figure 2.5: UT Model [23]

Figure 2.5 illustrates the association between the security properties (explained previously) and a distributed software system such as *SOA*, implemented using *WS* technology. It is known as *UT* model [23], because it resembles the shape of the alphabet letters *U* and *T*. the legs of the *U* represent various layers of the distributed system and the *T* demonstrates the security properties and their management that may be required across the layers of the distributed system [23].

2.2.1 Security Vulnerabilities Concerning WSs

SOA Security Vulnerabilities

Security vulnerabilities affecting *SOA* implemented using *WS* technology can be divided into four major groups (see Figure 2.6); Classical Vulnerabilities in hardware, operating systems and software used to build *SOA* middleware; Web Application (*WA*) vulnerabilities as *SOA* is commonly built on top of the *Web* protocols; and vulnerabilities due to the nature of *SOA* design, and new protocols and message formats supporting an *SOA* (the grey layers in Figure 2.6) [23]. All these security vulnerabilities are briefly discussed in the remainder of this section.

Business Process Layer Vulnerabilities
Web Services Layer Vulnerabilities
Web Application Vulnerabilities
Classical Vulnerabilities in Hardware, Operating Systems and Software

Figure 2.6: Security Vulnerabilities Affecting *SOA* (implemented using *WSs* technology) Layers [23]

Classical Security Vulnerabilities

Classical security vulnerabilities refer to security vulnerabilities in the existing operating systems, software and hardware infrastructure that could be exploited without the use of more recent web technologies (e.g., buffer overflow) [23]. These vulnerabilities are listed and updated in the U.S. *NVD* [25], *OSVDB* [26], *US-CERT* Vulnerability Notes Database [27], *MITRE* Common Vulnerabilities and Exposure [28] and *SecurityFocus* [29].

The existing operating systems, software and hardware infrastructure are employed to implement and deploy *WSs* hence, their related security vulnerabilities (listed in the above databases) also affect *WSs*.

Web Application Vulnerabilities

Web Application security vulnerabilities are related to the middleware and application layer of *WSs*. These vulnerabilities are classified in *WASC* [30], and a list of their most critical types is maintained by the *OWASP* [31].

WSs' Specific Security Vulnerabilities

This type of security vulnerabilities is due to the *WSs'* specific implementation technologies. Jensen *et al*. [9], [32] have presented a list of such security vulnerabilities, which are identified through exemplary attacks on widespread *WS* implementations. According to them, some of these vulnerabilities are due to implementation weaknesses, but the majority of them are due to protocol flaws. Similarly, Suriadi *et al*. [33] have investigated *WSs'* specific security vulnerabilities to *DoS* attacks in well-known *WS* platforms including *Java Metro*, *Apache Axis*, and *Microsoft .NET*. The results from their experiments indicate that the majority of the *WS* platforms cope well with attacks targeting memory exhaustion. However, they are still vulnerable to attacks that target the *CPU*-time exhaustion. A number of *WSs'* specific security vulnerabilities are as follows:

WSDL Scanning

As explained in Section 2.1, *WSDL* is an interface of a *WS* and advertises its operations, parameters, data types and network bindings. A *WS* may contain operations that should be accessed from the local network only, as well as operations that are intended to be offered to the outer network. In this case, separate *WSDL*, advertising the information about the external operations only, could be provided to the external clients to avoid these clients to get access to the internal operations. However, to invoke the external operations, the external clients should have access to the *WS's* endpoint [32]. Therefore, an attacker can still try to guess the omitted operations and try to invoke them, which is called *WSDL Scanning* [32].

Metadata Spoofing

The metadata document of a *WS* contains all information, necessary for its invocation (e.g., message format, network location, and security requirements). This document is published by the *WS's* owner and is available to its clients. It is usually distributed using *HTTP* or mail communication protocols, which brings a *Metadata Spoofing* possibility. *WSDL Spoofing* and *Security Policy Spoofing* are two examples of attacks that exploit these vulnerabilities. For example, a *WSDL Spoofing* attacker may modify the network endpoint to perform man-in-the-middle attack for eavesdropping or modifying data [32].

Attack Obfuscation

As it will be introduced later, *WS-Security* [34] is a very flexible security standard that allows signing and encrypting only parts of the message, which contain sensitive data. However, an attacker may use an encrypted part to conceal malicious code for cyber-attacks such as *Oversize Payload*, *Coercive Parsing*, etc. [32]. Hence, the encrypted parts of the message should be inspected for the existence of such attacks. To enable examining the encrypted parts, they should first be decrypted, which is a disadvantage of using this standard. This type of attack may affect the availability of the *WS* in two ways [32]:

- **If the message is decrypted after the schema validation**: its malicious contents may pass the validation.
- **If the message is decrypted before schema validation**: the required *XML* and cryptographic processing may cause a long delay since decryption can be a performance-intensive process especially if the message contains malicious contents.

Oversized Cryptography

In *WS-Security*, there is no limit for the parts of the message that can be encrypted and for the size of the encrypted content. The flexibility of this standard allows a variety of security elements to be used in the *WS-Security* header, which prevents strict schema validation and gives the possibility of the *Oversized Cryptography* attack [32]. This type of attack may affect the availability of the *WS* in three ways [32]:

- **If an oversized security header is used and the target system processes the entire security header:** the attack can have a similar effect on the targeted *WS* as an *Oversized Payload* attack.
- **If chained encrypted keys are used within the security header:** each encrypted key is used to encrypt the next key. Hence, the decryption process produces a very high *CPU* load.
- **If the *SOAP* message contains a large number of nested encrypted blocks:** a large number of cryptographic operations produce a very high *CPU* load.

BPEL Scanning

As it will be explained later, *BPEL* [35] is a de-facto standard and an executable business process modelling language enabling the modelling of the behaviour of a composite *WS*. Hence, it contains important information that can be used by an adversary to plot *BPEL Scanning* attacks (similar to *WSDL* scanning) on the business processes [23].

BPEL State Deviation

Many instances of a *BPEL* process may run concurrently, and their communication endpoints will be open for incoming messages at any time, which can be used by an attacker to plot *BPEL State Deviation* attack [32]. Two examples of such attack are as follows [32]:

- An attacker may flood a *BPEL* engine with messages that are correct in terms of their message structure but have no meaningful content (no correct instance identifier). These messages will eventually be discarded by the *BPEL* engine but after a significant amount of redundant work (reading and searching all existing process instances for a process matching the message). This redundant work can exhaust the computational resources of the *BPEL*.

- An attacker may use messages which contain correct instance identifiers but target a *receive* activity that is not enabled in the running business process instance.

<u>SOAPAction Spoofing</u>

As described in Section 2.1, a *SOAP* message package consists of a transport protocol header and an envelope (which itself consists of a header and a body). The first child element of the body contains the operation addressed by the *SOAP* request [32]. If *HTTP* transport protocol is used, an additional operation identifier element called *SOAPAction* can be added to the request's header [32]. However, it gives the possibility of *SOAPAction Spoofing* attack in the following cases [32]:

- **When the requested operation is solely identified based on the *SOAPAction* value:** a man-in-the-middle attacker may try to invoke a different operation than the one specified in the *SOAP* body by adding the malicious operation to the *SOAPAction* header (*HTTP* header is not protected by *WS-Security* so it can be easily modified).
- **When the requested operation is solely identified based on the first child element of the *SOAP* body:** an attacker may bypass the *HTTP* gateway if it is configured only to accept the value added to the *SOAPAction* header. Then the *WS's* logic will execute the operation in the first child element of the *SOAP* body regardless of the *SOAPAction* value.

<u>XML Injection</u>

An *XML Injection* attacker targets the integrity of the *XML* stream (e.g., *SOAP* message) by overwriting its static portions (e.g., by adding some contents containing *XML* tags) [32]. Using this method, an attacker may get access to restricted data.

<u>XML Denial of Service</u>

Early steps in processing a request *SOAP* message include parsing and transforming the contents of the message to be usable for the *WS's* backend applications. Therefore, an *XML* parser is an essential part of the *WS's* application logic. *SAX* [36] and *DOM* [37] are two typical *XML* parsers.

DOM parsers read the whole *XML* stream into memory then create hierarchical objects for each node (an element, an attribute, etc.) that is referenced by the application logic. An attacker can plot a *DoS* attack on a *DOM*-based *WS* by inputting a large *XML* file [38]. Such attacks (e.g., *Oversize Payload* and *Coercive Parsing*) affect the availability of the *WS* by exhausting its resources and eliminate the legitimate user's access [39].

On the other hand, *SAX* parsers perform *XML* parsing at the start or end of a node without loading the whole *XML* stream into memory (they load a maximum of two elements into memory at a time) [38]. Whenever the parser reaches a node, it triggers an event, and the program's event handler starts processing the data [38].

StAX is another event-based *XML* parsing approach. However, instead of triggering an event, it waits for a method call to parse its corresponding operation [40].

DoS attacks are one of the most popular attacks, which can be performed through a variety of techniques. This type of attacks exploit the vulnerabilities in *XML*-based documents (e.g., *SOAP* messages) targeting the parsing mechanisms and other resources, affecting the availability of the *WS*. A large number of these attacks, targeting well-known companies such as *VISA* and *PayPal* suggests that they can be a serious threat to today's *IT* infrastructure [41]. Some *XML DoS* attacks include:

- ***HashDoS***: hash tables can be employed within a *SOAP* message to store values and their references (e.g., attributes and their corresponding namespace). Ideally, each key should represent a unique value. If different keys represent the same value, a collision will happen, which results in resource-intensive computation. An attacker can exploit the weak hash function to perform a *DoS* attack [42], [43].
- ***Oversize Payload*****:** according to Meiko Jenson *et al*. [32], the majority of *WS* frameworks employ *DOM*-based *XML* processing models.

These parsers consume a memory much bigger than the size of the message (factor 2 to 30) [32]. Therefore, one easy way to perform *DoS* attack on *WSs* would be to query the service using a very large request message (*Oversize Payload*).

- ***Coercive Parsing*:** making *XML* parsing as complex as possible using a large number of namespace declarations, oversized prefix names/namespace *URIs* or very deeply nested *XML* structures are other ways to perform *DoS* attack on *WSs* and is called *Coercive Parsing* [9], [32].
- ***SOAP Array* Attack:** an attacker may add a *SOAP* array (with a large number of elements) into the *SOAP* message, forcing the *WS* to reserve a large space in memory for these elements before parsing the message [44].
- ***XML Attribute Count* Attack:** *XML* does not limit the size of the contents (elements, attributes and attributes' value) between the *XML* tags. Hence, an attacker may add a large number of attributes into the *SOAP* message and perform *XML Attribute Count* attack if no such limit is enforced by the developers of the *WS* [45].
- ***XML Element Count* Attack:** similarly to *XML Attribute Count* attack, an attacker may add a large number of non-nested elements into the *SOAP* message and perform *XML Element Count* attack if no limit is enforced to the size of the contents between the *XML* tags by the developers of the *WS* [45].

2.2.2 Existing Countermeasures and their Limitations

The previous subsection (2.2.1) introduced a number of security vulnerabilities, specific to *WSs*. Here, we present a number of existing countermeasures against these security vulnerabilities followed by a number of their limitations.

Countermeasures

Some of the existing countermeasures against previously introduced *WSs'* specific security vulnerabilities are as follows:

WSs Security Standards

As described in Section 2.1, the communication between *WSs* is supported by *XML*-based protocols (e.g., *SOAP* messages) that are vulnerable to *XML* attacks [32]. As a result, organizations such as the *OASIS* and *W3C* consortia have developed various security standards, an overview of which is presented in Figure 2.7. The most commonly implemented security standards are described below [46]:

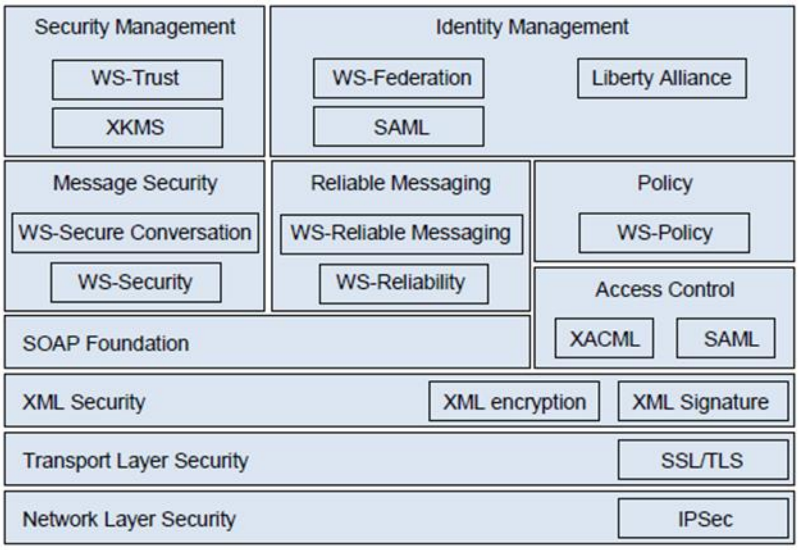


Figure 2.7: Web services Security Standards – National Reference Model [46]

- ***WS-Security***: it describes how to use *XML* to sign, verify, encrypt and decrypt *SOAP* message exchanges [18]. It defines a *SOAP* extension within the security header of the *SOAP* message, enabling the association of the security tokens (*UsernameToken*, *BinarySecureToken,* and *XML Tokens*) with the message. In addition to message authentication, it provides message integrity and confidentiality through *XML Signature* and *XML Encryption* in conjunction with security tokens, respectively. *WS-Security* is very flexible and allows signing and encrypting only parts of the message that contain sensitive data.
- ***WS-Security Policy***: the characteristic of the *WS-Security*, which allows parts of the *XML* document to be signed and encrypted, requires *WS* servers and clients to negotiate a security policy. This security policy allows defining the *WS-Security* elements that can be used (e.g., the algorithms and the required security tokens) and requires the

SOAP message to contain all the defined security tokens as a minimum. The *WS-Security Policy* standard provides the *XML* syntax for such security policy [47].

- ***SAML*:** it defines how authentication should be securely exchanged among the services [48].
- ***XACML*:** it is an *XML*-based technology for writing access control polices enabling developers to determine the resources that are allowed to be accessed by a user [49].
- ***XML Encryption*:** this standard provides data confidentiality by enabling the encryption of fragments of an *XML*. The encrypted fragment will be replaced with an *EncryptedData* element containing the ciphertext for the encrypted fragment. This standard also enables the creation of an *EncryptedKey* element, inside the security header, for hybrid encryption [50].
- ***XML Signature*:** this standard provides data integrity and authenticity by enabling the digital signature of fragments of an *XML*. The result of the signing operation will be added to the signature element of the security header [12].

Schema Validation and Schema Hardening

- **Schema Validation:** this approach is effective in defending against attacks that use messages not conforming to the *WS's* description. It validates the incoming message against the *XML* schema generated from the *WSDL* of the *WS* [32].
- **Schema Hardening:** this approach is about restricting the *WS's* description constructs to finite boundaries, removal of non-public operations from the *WS* description, etc. For example, Nils Gruschka and Norbert Luttenberger [51] proposed a system that generates *XML* schemas from the *WSDL* file of a *WS*, hardens it (e.g., converts the unbounded elements, maxOccurs="unbounded" to a finite number of elements, maxOccurs=" finite number"), then advertises the modified description to the *WS's* clients. It also validates the incoming messages against this hardened description.

Possible usages of schema-hardening and schema validation to defend against cyber-attacks exploiting *WSs'* specific security vulnerabilities are as follows:

- ***Attack obfuscation*****:** validating the decrypted message [32].
- ***XML Injection*****:** a strict schema validation on *SOAP* messages, including data type validation, to eliminate the possibility of an attacker getting access to restricted data [32].
- ***Oversized Cryptography*****:** to only accept the security elements that are explicitly defined in the security policy (this approach is called Strict *WS-SecurityPolicy Enforcement*) [32]. However, more security tokens may be added to the *SOAP* message than those defined in the *WS-Security Policy,* making the system vulnerable to unbounded number of additional tokens that an attacker may add to a *SOAP* message, which may cause costly cryptographic computations. This side effect can be mitigated by putting a limit on the number of security tokens that the *SOAP* message may contain and rejecting messages exceeding this limit [32], [52].
- ***Oversize Payload:*** restricting the message size to a pre-defined limit and rejecting any larger messages. Currently, *.NET* 2.0 framework employs this method and rejects any message larger than 4MB, by default [32]. A more appropriate approach is to modify the *XML* schema used in the *WS's* description then validate incoming *SOAP* messages against this schema [51].
- ***Coercive Parsing*****:** using schema validation to defend against deeply nested *XML* [32].
- ***SOAP Array*****:** enforcing strict schema validation on the maximum number of array elements. If it is not possible to put a limit on the number of array elements, comparing and validating the declared and existing number of elements in a *SOAP* array thereafter dropping the *SOAP* packet at the *WS* layer if the validation is failed [44].
- ***XML Attribute Count*** **and** ***XML Element Count*****:** to put a limit on the size of the components (e.g., elements and attributes) within an *XML*

tag by the developers of the *WS* since the *XML* standard doesn't impose such limit [45], [53].

- ***SOAPAction Spoofing*****:** identifying the requested operation based on the first child element of the *SOAP* message. Additionally, the identified operation should be compared with the *SOAPAction* value and get rejected if it does not match [32].
- ***Metadata Spoofing*****:** checking all metadata documents for authenticity [32].

Firewall

Sometimes an *XML* firewall is a more appropriate countermeasure against the attacks exploiting the WSs' *XML-related* security vulnerabilities, such as:

- ***WSDL Scanning***: all request messages (internal and external) have the same destination *IP* address, *TCP* port, and *HTTP URL*. Therefore, to reject invocation of the internal operation by the external clients, only a *WS*-aware *XML* firewall can distinguish whether an operation should be accessed by an external client [32].
- ***BPEL State Deviation***: Gruschka *et al*. [54] proposed a firewall for processing and rejecting the invalid messages using as few computational resources as possible.
- ***BPEL Scanning***: enforcing appropriate access control mechanisms on the internal operations [23].

Other countermeasure approaches

- Establishment of trust relationship prior to the communication (countermeasure against ***Metadata Spoofing***) [32].
- Deploying internal and external operations on separate *WSs*, preferably on different servers (countermeasure against ***WSDL Scanning* and *BPEL Scanning***) [32]

Limitations of the Introduced Countermeasures

Here, we present a number of the limitations related to the counter-measure approaches introduced previously:

- Equipping a *SOAP* message with *WS*-* security standards may require changes to the structure of the message since their use may introduce additional elements which did not exist previously.
- If the employed standard is revoked, the message structure may require significant changes.
- The difficulty, variety, and limitations of the *WS*-* standards as well as unfamiliarity of the developers with all of these standards have resulted in the development of *WSs* that are still vulnerable to cyber-attacks [18]. For example:
  - McIntosh and Austel [12] have shown that the content of a *SOAP* message, which is protected by an *XML Signature* (as specified in *WS-Security*) can be changed without invalidating the signature. The authors have shown that a signed element can be replaced with a fake element so that the signature remains valid.
  - The *WS-Security* standard is an important defence against the *WSs'* specific cyber-attacks but only when its corresponding *WS-SecurityPolicy* is defined correctly. Otherwise, it may cause integrity and confidentiality vulnerabilities, for example, it may no longer require the *SOAP* message to contain all the security tokens as a minimum (see Section 2.2.2 for more details) [12], [55].
  - *WS-SecurityPolicy* header schema allows any kind and amount of security tokens and the encrypted blocks are allowed nearly everywhere within the *SOAP* message, which may cause costly cryptographic computations [32].
  - Improper use of *SOAPAction* standard opens a window to *SOAPAction Spoofing* attack.

- Schema validation may cause high *CPU* load and large memory consumption [32].
- In *XML* specifications, there is no limit specified for the number of namespace declarations per *XML* element and for the length of the namespace *URIs* (which enables *Coercive Parsing* attack). Arbitrary restrictions can be enforced on the number and length of the namespaces to defend *WSs* against the attacks misusing namespace declarations. However, it can result in unpredictable rejection of the messages [32].
- Often validators rely on *XSD* derived from *WSDL* document or hand-coded by programmers, which may make them prone to cyber-attacks.
- Similar to the previous limitation, manual unguided schema updates that rely entirely on the skills of a programmer may also make the validator prone to cyber-attacks.
- If the schema used by the validator is loosely defined, it may allow malicious messages to pass through.
- Schema restriction and validation cannot safeguard against some cyber-attacks exploiting *XML-related* security vulnerabilities. For example, Jenson *et al*. [13] have shown that even the most restrictive *XML* Schema validators may fail to defend against *XML Signature Wrapping* attacks.
- The approaches explained above will be effective only when event-based message processing (e.g., *SAX*) is employed [32]. Otherwise, these protection systems themselves will be vulnerable to similar attacks [32].
- Each countermeasure only defends against specific cyber-attacks.

2.2.3 Summary

This section presented the security issues related to the *WSs* and a number of the existing countermeasures against *WSs'* specific security vulnerabilities (since the focus of the work presented in this dissertation is on the *WSs' XML-related* security vulnerabilities). It then explained a number of limitations related to the presented approaches.

In addition to all the discussions presented in this section, the security issue gets more challenging when *OTSWSs* are employed since they are ready-made black boxes of unknown quality and their security is out of the control of their clients. Hence, *ITWS* is a more appropriate approach to tolerating the security issues when *OTSWSs* are used, which is about making the system to live with the security vulnerabilities of its constituent *OTSWSs* to ensure delivery of sufficiently dependable service. This approach is the motivation for the work presented in this dissertation, and one of its key benefits is the possibility of ensuring correct behaviour in the presence of attacks. The next section gives a concise overview of the concepts and techniques of dependability and its relation to intrusion-tolerance.

2.3 Dependability and Intrusion-Tolerance

Dependability of a computing system is the capability to avoid failures that are more frequent or more severe, and outage durations that are longer than is acceptable to the user(s) [56]. It consists of threats to, the attributes of, and the means by which the dependability is attained (see Figure 2.8). Sections 2.3.1-2.3.4 present the dependability means.

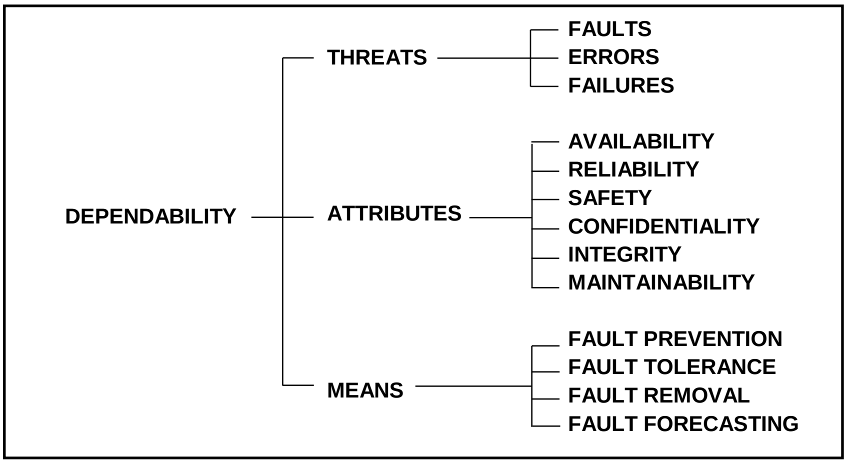


Figure 2.8: The Dependability Tree [56]

2.3.1 Fault-Prevention

Faults may be prevented through utilization of quality control techniques during the process of design and manufacturing hardware and software. These approaches may prevent operational physical faults, interaction faults and malicious faults [56].

2.3.2 Fault-Tolerance

Initially, practical techniques (e.g., error control code, diagnostics to locate failed components, etc.) were used to improve the reliability of the early computers [56]. At the same time Neumann, Moore, Shannon, and their successors developed theories of using redundant less reliable components to create reliable logics and structures [56]. Then Pierce unified these theories to the concept of failure tolerance and Avizienis [57] integrated redundancy with practical techniques (e.g., error detection and recovery) into the concept of *Fault-Tolerance* systems. Thereafter, Randell [58] introduced software *Fault-Tolerance*, which was later complemented by *N-version programming* [59].

The objective of *Fault-Tolerance* is to retain the delivery of correct service in the presence of active faults (faults that cause an error). It is generally implemented using error detection and subsequent system recovery approaches [56]:

- **Error detection:** it generates error signals or messages (within the system) and is divided into concurrent and preemptive error detection techniques, which operate at the run time and while service delivery is suspended, respectively.
- **Recovery:** it transforms the system state containing error(s) and/or fault(s) into a state without any discovered errors and faults. It consists of:
    - **Error handling:** eliminates errors from the system state and may have the following forms:
        - **Rollback:** returning the system back to a checkpoint state (the state saved prior to error detection).
        - **Compensation:** eliminating error through redundancies within an erroneous state.

        - **Roll-Forward:** transforming the system state to a new state with no detected errors.
    - **Fault handling:** prevents determined faults from being activated again in four steps:
        - **Fault diagnosis:** identifying and recording the location and type of the cause(s) of error(s).
        - **Fault isolation:** excluding the faulty component(s), physically or logically, from further participation in service delivery.
        - **System reconfiguration:** switching to use spare component(s) or appointing the task(s) to fit component(s).
        - **System re-initialization:** checking, updating and recording the new configuration and updating system data and records.

The classes of faults that can be tolerated and the choice of *Fault-Tolerance* implementation are directly related to the underlying fault assumption [56]. However, redundancy is widely employed to implement *Fault-Tolerance* and is surveyed in the various literature [60]–[62]. Assuming that hardware components have an independent failure, channels with identical design may be used to tolerate operational physical faults. Whereas, to tolerate solid design faults, channels providing the same functionalities via separate designs and implementations (design diversity) should be used [56].

Redundancy

Antonio Carzaniga and his colleagues [63] describe redundancy as a system's capability of executing the same functionality in several execution environments or various ways (e.g., using different execution paths). Redundancy is believed to be a valid defence against physical faults. Running multiple replicas of the system and switching to the functioning one when a failure occurs is an example of using redundancy to overcome hardware faults [64]–[66]. Redundancy can also be applied to the code, data, and environment of a software system to overcome its non-physical faults (e.g., partial or complete replication of the code, input data or execution environment, including the execution processes themselves) [67].

Redundancy from Architectural Viewpoint

From a software architecture point of view, redundancy can be divided into intra-components, which only changes the structure of a single component (e.g., wrappers that filter component interactions) and inter-components groups [63]. The Figures 2.9-2.11 present three different inter-component redundancy patterns: *Sequential Alternative Pattern*, *Parallel Selection*, and *Parallel Evaluation*.

<u>Sequential Alternative Pattern</u>

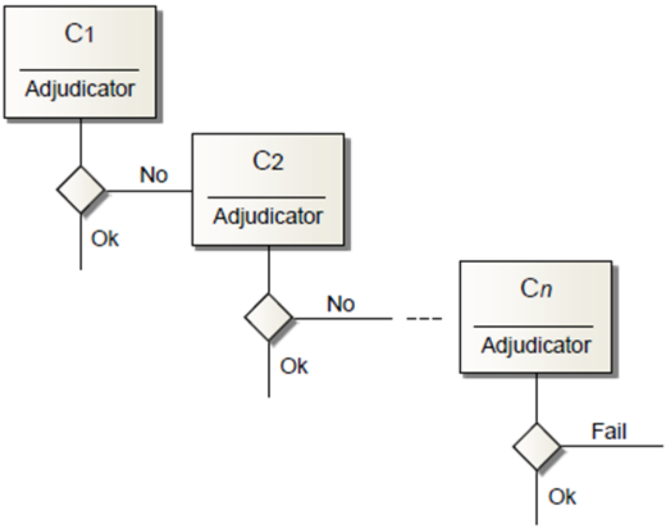


Figure 2.9: Sequential Alternative Pattern [63]

In *Sequential Alternative* pattern (see Figure 2.9), an alternative program will be executed if the execution of the current program fails. In this design, a separate *Adjudicator* (e.g., a voting system) is connected to the end of each program to detect its failure and to validate its output. This pattern is employed in recovery blocks, service substitution approaches, etc. [63].

<u>Parallel Selection Pattern</u>

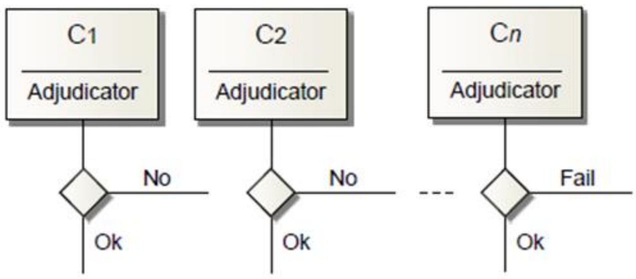


Figure 2.10: Parallel Selection Pattern [63]

Parallel Selection pattern (Figure 2.10), consists of the concurrent execution of several programs. In this pattern, a separate *Adjudicator* (e.g., a voting system) is connected to the end of each program to detect its failure and to validate its output. This pattern is employed in self-checking programming [63].

<u>Parallel Evaluation Pattern</u>

Parallel Evaluation pattern (Figure 2.11), consists of the concurrent execution of several systems/programs and an *Adjudicator* (e.g., a voting system), which evaluates the result from those parallel executions to produce a correct result. This pattern is employed in *N-version programming* [63].

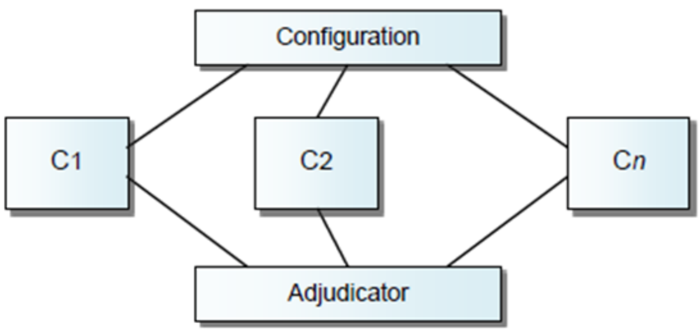


Figure 2.11: Parallel Evaluation Pattern [63]

N-version programming

N-version programming is a technique that concurrently executes *N* different systems/programs, which provide the same functionality but are implemented differently and are fed with the same input configuration, then forms a consensus on the output from all these systems/programs to produce the final output [68]. The purpose of this technique is to achieve fault tolerance, assuming that these different systems/programs will exhibit failure diversity [68].

Diversity

In 1975, Randell [58] introduced design diversity as a mechanism for software fault tolerance. He proposed using backup components (with an independent design from the main components) when main components are failed. Design diversity is now a recognised defence against design faults, and a comprehensive survey of its benefits is presented in [69].

Joseph and Avizienis [70] proposed the use of *diversity* as a means of improving security and discussed the feasibility of using diverse compilers (implemented using *N-version programming*) to detect and mask *Trojaned* compilers that infect the generated executables with viruses. Later, Forrest *et al*. [71], [72] and Littlewood and Strigini [73] argued the validity and effectiveness of using *diversity* to mitigate the effects of cyber-attacks. Classifications of *diversity* techniques for improving security are presented in [74], [75].

2.3.3 Fault-Removal

Fault-Removal may be performed during the development phase and operational life. The fault removal process during the development phase starts by checking whether the system adheres to given properties (verification phase). If it does not, the diagnosis phase starts checking for identification of the fault that is preventing the verification condition to be fulfilled. Following on identification of the fault, necessary corrections are performed (correction phase). Finally, the system goes through verification again to make sure that the correction has not caused any undesirable consequences. *Fault-Removal* during the operational life of a system can be divided into two groups of corrective maintenance and preventive maintenance. The corrective maintenance removes the faults after they have produced an error. Whereas, the preventive maintenance uncovers and removes the faults before they produce an error [56].

2.3.4 Fault-Forecasting

Fault-Forecasting is about the evaluation of the system behaviour (through modelling and testing, e.g., fault injection) with respect to fault occurrence or activation and has two aspects [56]:

- **Qualitative**, or **ordinal**, **evaluation (e.g., failure mode and effect analysis):** identification, classification, and ranking of the failure modes or the events that would lead to system failures.
- **Quantitative**, or **probabilistic**, **evaluation (e.g., Markov chains and stochastic Petri nets):** evaluation in terms of probabilities of the extent to which some of the attributes of dependability are satisfied.

2.3.5 Intrusion-Tolerance

Fault-Tolerance is not restricted to accidental faults [56]. Research on the integration of fault tolerance and the defences against deliberately malicious faults (e.g., security threats) was started in the mid-80's [70], [76], [77] and since, designs have been proposed for the tolerance of intrusions, malicious logic and viruses [56]. Hence, dependability approaches may also be employed to implement *Intrusion-Tolerance*.

2.3.6 Summary

This section presented an overview of the concepts and techniques of dependability. It briefly introduced *Fault-Prevention*, *Fault-Tolerance* (including redundancy, *N-version programming,* and *diversity*), *Fault-Removal* and *Fault-Forecasting* concepts and explained that dependability approaches could also be employed to implement *Intrusion-Tolerance*.

As discussed previously, *WSs* allow companies and organizations to implement their core business only and outsource other service components (e.g., *OTSWSs*) over the *Internet*, either pre-selected or on-the-fly. *WSs* are at risk of security vulnerabilities related to their specific implementation technologies such as *XML* as well as those of their underlying platforms (e.g., operating systems and frameworks) and their applications (e.g., vulnerability to *SQL Injection* attacks). Security issues become more challenging when *OTSWSs* are used since they are beyond the control of their clients. Hence, tolerating their security vulnerabilities through dependability techniques is a more appropriate approach.

In this work, the focus is on tolerating *XML*-related security vulnerabilities of *WSs* when *OTSWSs* are employed. It utilizes *WSs'* composability, *PCA*, *CA* and penetration testing to implement an *ITWS* formed by *N-version programming* and *diversity*, providing *Fault-Tolerance* and *Fault-Prevention*. Also, the penetration test results of the *OTSWSs* give the providers of these services an opportunity to improve their security (*Fault-Removal*) in the future releases. The following sections briefly introduce each of these concepts and explain their role in this work.

2.4 Penetration Testing

Penetration testing is an attempt to break into a system not to exploit it, but rather to identify its weaknesses [78]. According to Tran and Dang [79], penetration testing is the simulation of attacks (that could be performed by real hackers) to identify security vulnerabilities of the target system. However, penetration testing is not a measure of true security, but it enables improving security by eliminating the anticipated security vulnerabilities. Despite advantages such as identifying security vulnerabilities hence providing countermeasures for them and assisting organizations to acknowledge the effectiveness or ineffectiveness of the implemented security measures, penetration testing may cause information disruption, denial of services, and information leakage, as the individuals performing penetration tests, are usually granted access to substantial amounts of sensitive information [80]. Hence, it might not be performed on the actual operational environment, which in turn may affect the test results. It also has other limitations, such as limitations of known exploit and experiment.

There are two types of penetration testing, black-box and white-box [78]. The black-box approach is commonly employed to test *WAs*. Regarding the *WSs* these tests are performed as follows:

- **Black-box penetration testing:** the service under test is seen from the point of view of an attacker. The tester maliciously manipulates the *SOAP* messages being sent to the *WS*, then analyses the *WSs'* response and its program execution.
- **White-box penetration testing:** similar to static code analysis, this approach looks into the source code of the *WS* to identify its potential vulnerabilities.

Both black-box and white-box techniques can be used to assess the security of a *WS* [81]. However, the former approach enables the understanding of what an unknown attacker can achieve. It can be scripted and performed automatically by a penetration testing tool [18], [82]. Regarding the *WSs'*, automatic penetration testing tools can be divided into tools testing the security vulnerabilities specific (e.g., *WS-Attacker* [18]) and nonspecific (e.g., *w3af* [83]) to *WSs*. Otherwise, penetration testing can be done manually using other tools such as *SoapUI* [84].

In the work presented in this dissertation, penetration testing is used to identify the security vulnerabilities of the candidate *OTSWSs*, which enables the selection of the optimal set (set of *OTSWSs* with the most diverse security vulnerabilities) to implement the *Intrusion-Tolerance*. Diversity is particularly important because any common security vulnerabilities among *OTSWSs* (participating in *ITWS*) opens a window of opportunity for compromising all the *OTSWSs,* suffering from the targeted security vulnerability, at the same time. Hence, such effect should be diminished as much as possible.

2.5 Principal Component and Cluster Analysis

This section briefly introduces the *PCA* and *CA* and their role in the work presented in this dissertation.

2.5.1 Cluster Analysis

When dealing with large amounts of data, it is very important to be able to classify and group them according to various criteria. *CA* allows splitting a group of objects (e.g., data) into a number of homogeneous subgroups (or clusters) using various clustering algorithms [85]. Clustering is widely adopted in a variety of fields, ranging from engineering (e.g., machine learning and pattern recognition), computer sciences (e.g., web mining), medical sciences (e.g., genetics), to earth sciences (e.g., geography), social sciences (e.g., psychology), and economics (e.g., marketing) [86].

There is no universally agreed selection of features and clustering schemes [87]. Most researchers describe a cluster based on the internal homogeneity (within objects in each cluster) and the external separation (among the objects in different clusters) [88], [89]. Xu and Wunsch [86] have classified the clustering algorithms (each having various descriptions), some of which are presented below:

- **Hierarchical:** organizing data into a hierarchical structure according to the proximity matrix, which can be further divided to:
  - **Agglomerative:** starting with *n* clusters each containing only one object, followed by a series of merge operations until one cluster containing all the objects is left. Based on the different definitions for the distance between two clusters (e.g., single linkage, complete linkage), there are many agglomerative clustering algorithms.
  - **Divisive (e.g., MONA and DIANA** [90]**):** in contrast to agglomerative analysis, the divisive analysis starts with a cluster containing all the objects then follows a series of divisive operations, dividing objects among different clusters until only one object is left in each cluster.
- **Squared Error-Based (e.g., K-means** [91]**):** aims to partition *n* objects into *k* clusters so that each object belongs to the cluster with the nearest mean.
- **pdf Estimation via Mixture Densities (e.g., GMDD** [92]**):** from the probabilistic point of view, data objects are assumed to be generated according to several probability distributions. Hence, pdf Estimation

algorithm uses the probability distributions of the data objects to form clusters.

- **Graph Theory-Based (e.g., Chameleon** [93]**):** this algorithm uses graph theory to distribute objects among different clusters.
- **Combinatorial Search Techniques-Based:** aims to find the global or approximate optimum global for combinatorial optimization.
- **Fuzzy (e.g., FCM** [94]**):** in the fuzzy algorithm, there is no restriction for each object to only belong to one cluster, and an object can belong to all the clusters with certain membership degree.
- **Neural Networks-Based (e.g., SOFM** [95]**):** this algorithm uses neural networks to distribute objects among different clusters.

2.5.2 Principal Component Analysis

PCA [96], is a useful statistical technique for analysing datasets with high dimensions (when patterns are difficult to be found) by reducing their dimensions while retaining the variations among their data as much as possible [97]. Hence, it has found application in fields such as face recognition [98] and is a common technique for finding patterns in data of high dimensions [99]–[101].

Principal Components (*PCs*) are linear transformations of the original set of variables, which are uncorrelated and are ordered in a way that the first few *PCs* contain the most variation within the original dataset [97].

2.5.3 Application of PCA in Cluster Analysis

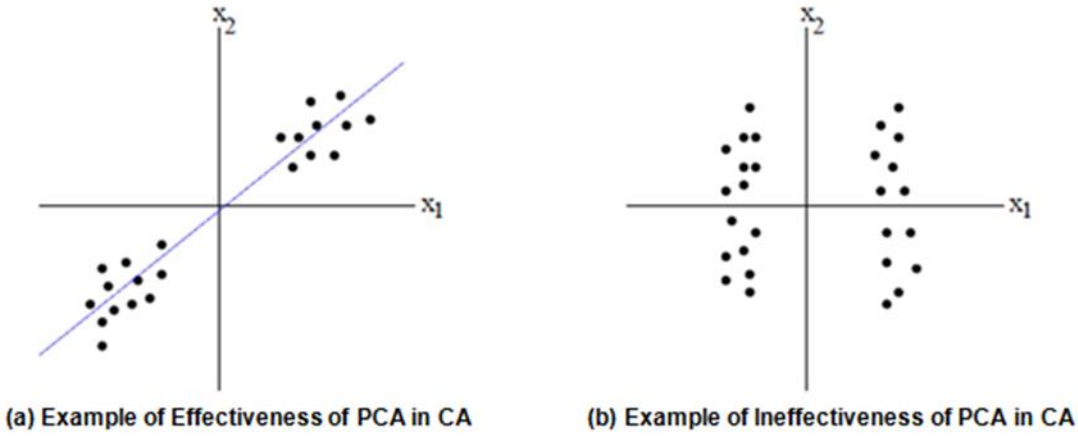


Figure 2.12: PCA in CA [102]

Sometimes (when the first few *PC's* contain cluster information) in literature, *PCA* is employed to reduce the dimensions of the dataset before *CA*, hoping to reduce the running time for *CA's* computation using a fewer number of *PCs* [102]. However, the first few *PC's* may not always contain cluster information [103]. Figures 2.12a and 2.12b illustrate two fictitious situations where the *PCA* pre-processing step before *CA* may and may not help, respectively. Figure 2.12a shows that the projection of the data points on the first *PC* (the diagonal line) clearly highlights the separation between the two clusters in the data. Whereas, in Figure 2.12b, the projection of the data points on the first *PC* (in the direction of x_2) does not preserve the separation between the two clusters in the data. Therefore, there is a need to investigate the effectiveness of *PCA* as the pre-processing step to *CA* before adopting such approach.

2.5.4 Summary

This section briefly introduced the concepts of *CA* and *PCA*. It then explained the utilization of *PCA*, prior to *CA*, as a means of extracting the structure of the clusters through reduction of dimensions of the dataset and showed (Figure 2.12) that such approach may not always be useful and its effectiveness should be investigated before being adopted. Hence, for the purpose of this work first, the effectiveness of *PCA* as a pre-processing step to *CA* on results from penetration testing candidate *OTSWSs* is investigated. Then both *PCA* and *CA* along with further penetration testing are used to identify the optimal (most diverse in terms of their security vulnerabilities) set of *OTSWSs* for implementation of *Intrusion-Tolerance*.

2.6 *WS* Orchestration and Choreography

SOA enables the composition of several services with complementary functionalities to form a single value-added composite service and offer it to the clients through a single interface. Hence, a composite *WS* may consist of various other single and/or composite *WSs*.

The constituent services of a composite *WS* may become unreachable for various reasons (e.g., becoming the victim of a DoS attack), which may impact its dependability (e.g., its integrity as it may not be able to provide the requested service). Also, more suitable (in terms of their *QoS*) services, offering similar functionality as covered by composite *WS's* constituent services, may become available. Hence, *WSs* capable of dynamic reconfiguration would be a practical solution to address such changes. In this way, composite *WSs* can react to the changes in a timely manner while using the most suitable available resources and avoiding long service disruptions due to off-line repairs. Therefore, an increasing number of today's services are developed using dynamic composition of the available resources to address the clients' complex demands.

Each building block of a composite service consists of its constitutive *WSs* (among which the tasks are divided) and a description of data, management and control flow between them [104]. Hence, a variety of specifications and standards has been introduced to support the implementation of composite *WSs*. This section reviews Web Service Choreography Interface (*WSCI*) [105], Business Process Modelling Language (*BPML*) [106], and *BPEL* [35].

2.6.1 WSCI

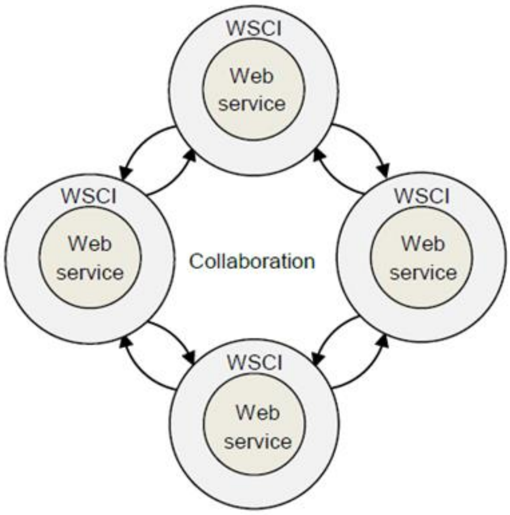


Figure 2.13: WSCI Collaboration [107]

Sun, *SAP*, *BEA,* and *Intalio* developed the *WSCI* specification, which enables the description of the message to flow between the aggregated *WSs* in *XML* format. However, it does not support the definition of executable business processes. *WSCI* choreography is an extension to *WSDL* and describes the interactions between the operations described in the *WSDL*. It requires a *WSCI* interface for each *WS* participating in the interaction. It also supports conditional looping, parallel and sequential processing, and exception handling [107]. Figure 2.13 illustrates *WSCI* collaboration.

2.6.2 BPML

BPML is developed by *Intalio*, *Sterling Commerce*, *SUN,* and *CSC*. It has the underlying process execution as *WSCI* and similar process flow constructs and activities as *BPEL*. A developer can describe the public interactions between the *WSs* and develop private implementations using *WSCI* and *BPML,* respectively [107].

2.6.3 BPEL

Initially, *Microsoft* and *IBM* developed *XLANG* [108] and Web Services Flow Language [109], respectively, to support business flow design. Later *Microsoft*, *IBM*, *Siebel Systems*, and *SAP* combined these standards and formed version 1.1 of the *BPEL4WS*, called *BPEL*. *BPEL* is a de-facto standard and an executable business process modelling language for implementing composite *WSs*. It is a workflow language used for composition, orchestration, and coordination of *WSs*. It provides an *XML*-grammar to model the behaviour of a composite *WS,* for example, sharing the tasks between the aggregated *WSs* and describing the control logic among them [107].

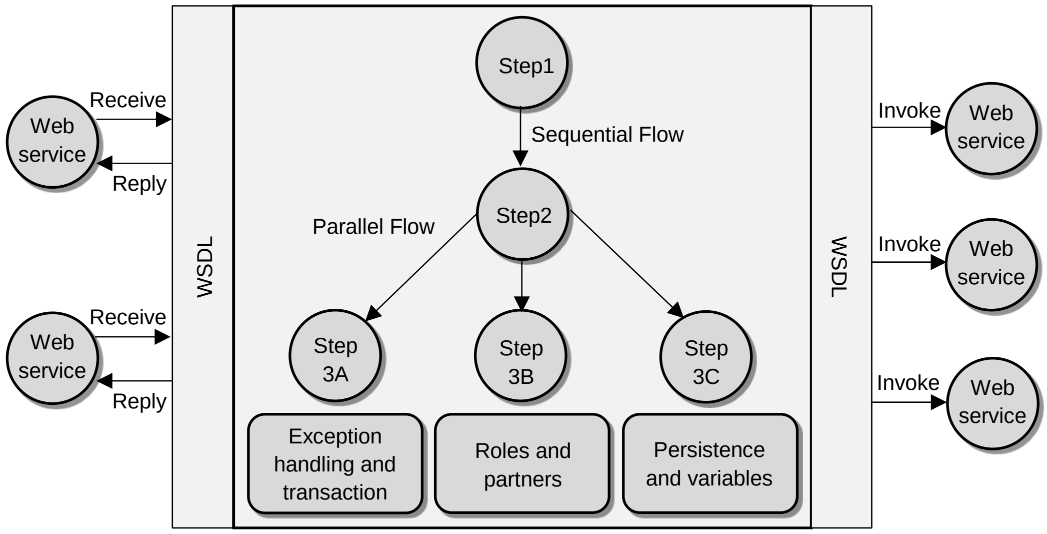


Figure 2.14: BPEL4WS Process Flow [107]

BPEL is a layer on top of *WSDL*. It communicates with other *WSs* through their *WSDL* interfaces. In standard *BPEL* processes, the interactions with other *WSs* are modelled as *PartnerLinks*, which are defined **statically.** Each *PartnerLink* has a *PartnerLinkType*, indicating two *WSDL PortTypes*, one to be used by the external *WS* (partner) to communicate with the *BPEL* and the other to be used by the *BPEL* to communicate with the external *WS*. *BPEL* only abstractly refers to other *WSs,* and it is the responsibility of the execution engine to indicate which port (and therefore binding) should be used for each *PortType* [110]. In contrast with *WSDLs*, *BPEL*-based *WSs* are stateful and may have long-running interactions with other *WSs*. Hence, *BPEL* also supports the correlation of application data to the process instances.

BPEL supports modelling of *executable*[2] and *abstract*[3] business processes and offers basic (e.g., *receive*, *reply*, *assign*, *invoke*, etc.), structural (e.g., *sequence*, *pick*, *while*, *forEach*, etc.) and exceptions-handling activities [107]. It also supports synchronous and asynchronous processes [111]. Figure 2.14 presents a *BPEL4WS* process.

BPEL Basic Activities

A *BPEL* process starts with a *receive* activity, which accepts the service request. The *reply* activity returns the response from *the BPEL* process, in the request-response processes. *BPEL's invoke* and *assign* activities, invoke a partner *WS* and copy data from one location within the *BPEL* process to another, respectively.

BPEL Structural Activities

BPEL's structural activities consist of other *BPEL* activities (basic or structural) and define the business logic among them. *BPEL* supports sequential (through *sequence* activity) and parallel (e.g., *forEach* activity) processes, which are the aggregation of activities that will be executed in an ordered sequence and simultaneously, respectively:

- ***pick* activity**: enables the selection of one of the alternative *BPEL* paths [111].
- ***if* activity**: is a conditional construct for implementing a *BPEL* branch [111].
- ***while* and *forEach* activities**: provide loop constructs [111].
- ***flow* activity**: provides concurrent execution of *BPEL* activities [111].

BPEL Variables

BPEL's variables are typed (*WSDL* message type, *XML* schema primitive type or *XML* schema element) and are used to store messages that are

[2] Behaviour of the web services in a specific business process that can be executed by an orchestration engine

[3] Message exchange between the participating web services

exchanged within the business process or to hold data that relates to the state of the process [111].

BPEL Fault and Compensation Handling

A *BPEL* process can be divided into hierarchically organized parts using *scope* activities, which provide behavioural context for other *BPEL* activities [111]. *Scope* activities allow the definition of faults, compensations, termination and event handlers for activities within their boundary. When a fault occurs within a business process (e.g., a fault is thrown by the *BPEL* process), the process may successfully complete its operation only if the fault is handled by a *scope* [111]. *BPEL* allows defining fault-handling activities (*catch* or *catchAll*) within a *faultHandler* construct. When a fault handler catches a fault, the execution of the activities within the *scope* (to which it is related) stops, and exception handling process begins. If no *catch* is selected and *catchAll* is not present, the fault will be re-thrown to the immediately enclosing *scope*, if present. Otherwise, the process will terminate abnormally [111].

In business processes, the compensation behaviour must be explicitly defined to reverse the effects of non-completed processes. A *compensationHandler* gathers all activities that have to be carried out to compensate the fault. If a *compensationHandler* is not defined for any given *scope*, the *BPEL* engine implicitly creates a default *compensationHandler*, which compensates all inner *scopes* [111].

BPEL Extensibility

BPEL is extensible and supports the inclusion of *Java* code snippets directly into the *BPEL* process. The benefits of this approach are speed and transactionality. However, the best practice is to incorporate only small segments of *Java* code (short utility-like operations rather than business code). Otherwise, the separation of the business logic from implementation will be lost [112].

BPEL Development Tool

There are different providers of *BPEL* engines (open source and commercial). Open source *BPEL* engines include *ActiveBPEL* [113], *ApacheODE* [114], *Open ESB* [115] and *jBPM* [116]. Commercial *BPEL* engines include Oracle BPEL Process Manager [117], SAP Exchange Infrastructure [118] and WebSphere Process Server [119].

2.6.4 Summary

This section briefly explained the composition of *WSs* and introduced three composition approaches (*BPEL*, *WSCI,* and *BPML*) among which *BPEL* and *BPML* support development of the executable business processes and *WSCI* provides a more choreographed approach [107]. As it is explained, *BPEL* enables concurrent invocation of *WSs*, which is used in this work to implement *Intrusion-Tolerance* (through *N-version programming* and *diversity*) in *ApacheODE BPEL*.

Also, *OTSWSs* may be updated (which may increase or decrease their security) or more secure *OTSWSs* (offering the same required functionality) may become available. Therefore, their clients should be able to replace them with more secure *OTSWS*, if they wish to. The replacement for a more secure *OTSWS* may need to be done dynamically as switching off the client's system might not be acceptable. But, *BPEL* constructs only allow invocations of *OTSWSs* that either already have a statically defined *PartnerLinks* or have exactly the same interface matching an existing *PartnerLink.* Otherwise, to perform the replacement, the *BPEL* process has to be redeployed. However, dynamic invocations may still be achieved through *Java* snippet activities that are available as *BPEL* extensions. Hence, this work also demonstrates the reconfiguration of the *ITWS* using a combination of *BPEL* constructs and *Java* as *BPEL* extension approach as well as using only *Java* as *BPEL* extension approach, in *Oracle BPEL*.

2.7 Summary

This chapter first presented the overview of *WSs'* architecture and introduced their main technologies (*SOAP*, *WSDL,* and *UDDI*). It then explained that *WSs* are at risk of security vulnerabilities related to their specific implementation technologies (e.g., *XML*) as well as those, of their underlying platforms (e.g., operating systems) and *WAs* (e.g., vulnerability to *SQL Injection* attacks).

Afterward, it presented a number of existing countermeasures against attacks targeting *XML*-related vulnerabilities followed by a list of their limitations. It then argued that the issue gets more challenging when *OTSWSs* are employed, as they are ready-made black boxes of unknown quality and their security is out of the control of their clients, thus, tolerating their security vulnerabilities through a reconfigurable *ITWS* is a more appropriate approach.

Then, it briefly introduced dependability approaches and explained that *ITWS* could be achieved using these techniques which (*Fault-Tolerance* and *Fault-Prevention*), in this work, are achieved through utilization of *WSs'* composability, *PCA*, *CA* and penetration testing. Finally, it briefly introduced each of these concepts and explained the motivation for their adoption in this work. Next chapter presents the architecture of this reconfigurable *ITWS*.

CHAPTER

3

Architecture of Reconfigurable ITWS Framework

The previous chapter briefly introduced Web Services (*WSs*) and their related security issues and discussed that a reconfigurable Intrusion-Tolerant Web Service (*ITWS)* is a suitable solution to their security issues, especially when Off-The-Shelf Web Services (*OTSWSs*) are employed.

This chapter presents the architecture of the proposed self-reconfigurable *ITWS*, which can be deployed by the clients of *OTSWSs* to diminish the impact of *WSs'* (specifically *XML*-related) security vulnerabilities. It begins by explaining the overall objective (Section 3.1) followed by assumptions made (Section 3.2), the overview of the architecture (Section 3.3) and a summary of the discussions presented in this chapter (Section 3.4).

3.1 Objective

The objective of this architecture is to enable the transformation of an ordinary *BPEL* process that employs *OTSWS(s)* into a self-reconfigurable *ITWS* as depicted in Figure 3.1.Through this architecture, every *OTSWS* can be replaced by its equivalent self-reconfigurable[4] *ITWS* (a group of *OTSWSs* from various vendors, offering the desired functionality with security vulnerabilities diversity, that majority vote on their responses is considered as the final response).

[4] If one group of *OTSWSs* fails the business process switches to an alternative group

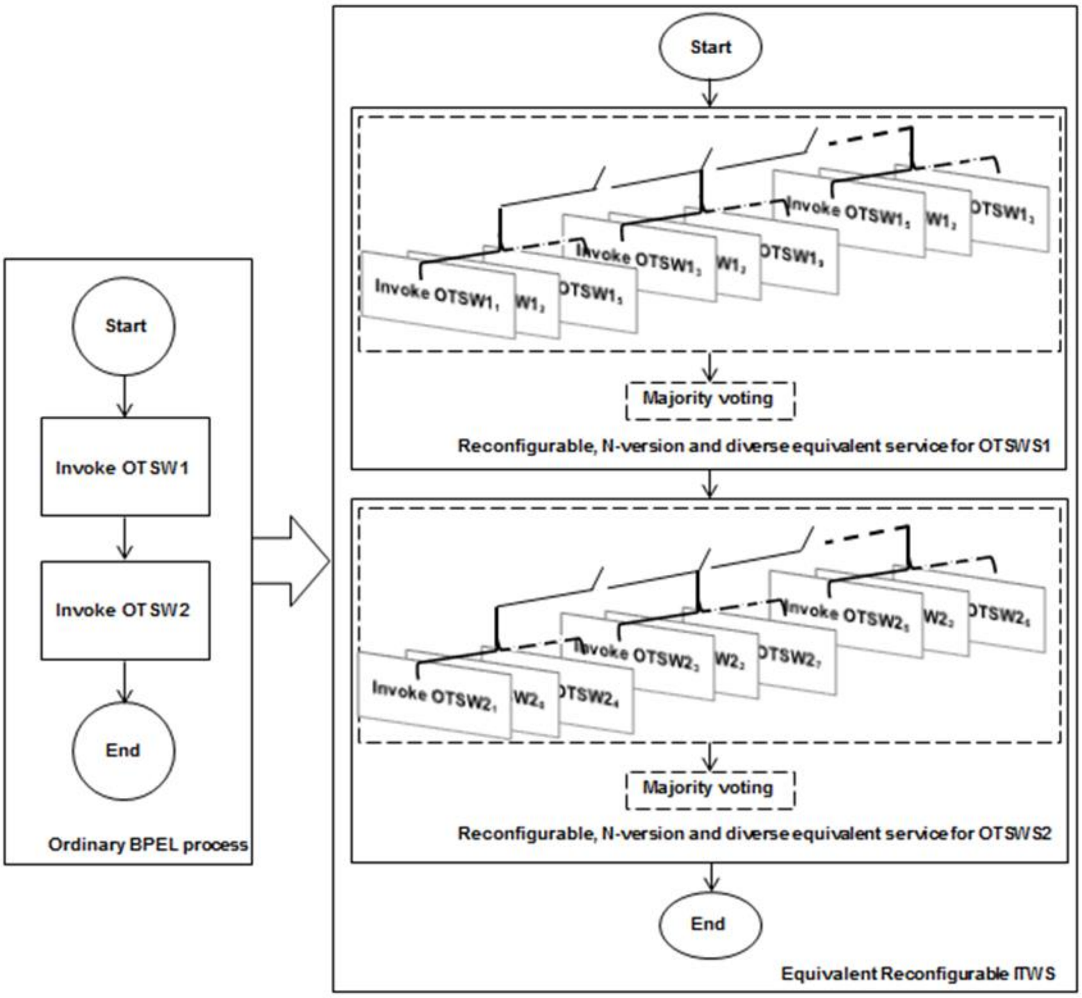


Figure 3.1: Overview of the Framework's Objective

The steps to achieve the above objective are as follows:

1. Finding as many *OTSWSs* (offering the desired functionality) as possible.
2. Penetration testing each of these services to identify their security vulnerabilities.
3. Performing statistical analysis on the penetration test results (from step 2) to form groups of 2*f*+1 services with security vulnerabilities diversity. This is because, with 2*f*+1 services, the majority of the responses remain correct even after as many as *f* failures (e.g., unavailability as a result of *DoS* attacks in the context of this work) [120], [121]. A system consisting of a number of distinct components is *f-fault-tolerant* if it satisfies its specification provided that no more than *f* of those components become faulty during some interval of interest

[120]. The *f-fault-tolerant* is a measure of the *Fault-Tolerance* supported by the system architecture [120].

4. Penetration testing each group (from step 3) to identify the optimal set (the most secure among the groups) as well as to order each group in terms of their overall security vulnerabilities (ascending order starting with the most secure group).
5. Starting the business process with the first group (most secure group) and switch to the next group if the first group fails and so on.
6. Perform majority voting on the responses from *OTSWSs* within the running group to indicate the response of the *ITWS*.

3.2 Assumptions

This section presents the assumptions made in this framework:

- There are a sufficient number of candidate *OTSWSs* (offering the desired functionality) to implement *Intrusion-Tolerance*.
- Permission is granted by the owners of *OTSWSs* to perform penetration testing on these services since it may cause information disruption, denial of services and/or information leakage.
- It is possible to integrate the external penetration testing tool into this framework.

3.3 Architecture

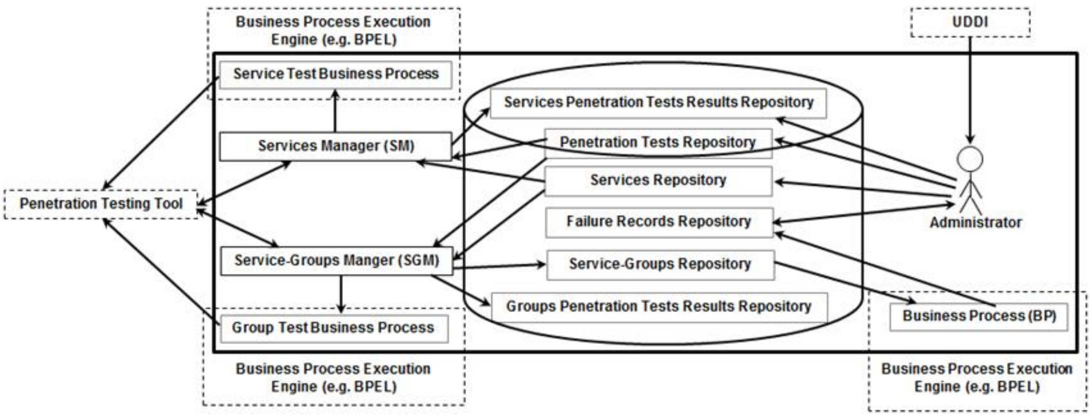


Figure 3.2: General Architecture, the dotted lines indicate the external systems

The architecture (see Figure 3.2) of this framework consists of various repositories, an *Administrator*, a Services Manager (*SM*), a Service-Groups Manager (*SGM*), a Business Process (*BP*) and two other business processes (one for testing *OTSWSs* and one for testing groups of *OTSWSs*). It is necessary to test *OTSWSs* inside a business process as they may eventually participate in the *BP*. Hence, any effect from the business process engine should be taken into account when testing *OTSWSs*. Also, separate business processes (with the exact setup as *BP*) than *BP* should be used for testing purposes to eliminate the effects of penetration testing on the operation of *BP* that executes the business logic.

Based on the case studies presented in Chapter 7, the dynamic adaptation using *Java* as *BPEL* extension only, and a combination of *Java* snippets and *BPEL* constructs can be implemented using about 400 and 260 lines of codes, respectively. The service selection is performed manually in the case studies (Chapters 4-6) aiming to evaluate the proposed service selection approach.

Repositories

This architecture consists of the following repositories:

- **Services Repository (Table 3.1):** is managed by the *Administrator* and is used by *SM*, *SGM,* and *BP*. It stores required information for invoking candidate *OTSWSs*. Each *OTSWS* may offer more than one service, which may be invoked at different stages of the *BP*, or have different versions. Hence, this repository stores each of these services separately with a unique *Id*.
    - **ID:** a unique *Id* is assigned to each service.
    - **Service Name:** stores the name of the *OTSWS*.
    - **Endpoint:** stores the web address (*URL*) of the *OTSWS* through which the operations provided by the *OTSWS* are accessible.
    - **Target Namespace:** stores the namespace of the *OTSWS*.

- **Invocation Id:** indicates at which stage of the *BP* this service may be invoked.
- **Operation Name:** each *OTSWS* may offer more than one services (operations). This column stores the name of the service that could be used in the *BP*.
- **Input:** stores the type and order of the service's inputs parameters.
- **Output:** stores the type of the service's output parameter.

➢ **Penetration Tests Repository (Table 3.2):** is managed by the *Administrator* and is used by *SM* and *SGM*. It stores information about available penetration tests and their settings (the *Administrator* makes these decisions).

- **Test Id:** each test may be performed with various settings (e.g., *Coercive Parsing* may be performed with various numbers of open tags). Hence, this repository stores each test separately with a unique *Id*.
- **Test Name:** stores the name of the test.
- **Test Setting:** stores the setting to be used for the test.

➢ **Services Penetration Tests Results Repository (Table 3.3):** is managed by *SM* and is used by *SGM*. It stores the information about penetration test results of each *OTSWS*.

- **Service Id:** stores the *Id* of the tested *OTSWS.*
- **Test Id:** stores the *Id* of the penetration test performed on the *OTSWS.*
- **Test Date:** stores the date when the penetration test is performed on the *OTSWS.*
- **Test Result:** stores the penetration test result (e.g., whether the penetration test has been successful or not).

➢ **Service-Groups Repository (Table 3.4):** is managed by *SGM* and is used by *BP*. Recall (see section 3.1) that in this framework *OTSWSs* are grouped based on their penetration test results and that the resultant groups are ordered in terms of their overall security vulnerabilities (ascending order starting with the most secure group), this repository stores information about service groups.

- **Service-Group Id:** it associates services to different service groups identified by a *Service-Group Id*.
- **Service Id:** stores the *Id* of the *OTSWSs* enabling *BP* to retrieve, from the *SR,* the required information for invoking them.
- **Invocation Id:** indicates at which stage of the *BP* the services from this group should be invoked.
- **Order Number:** indicates the order of the selection of the groups. The service group with the lowest *orderNumber* has the highest overall security among other groups, and the business process should start with that group and switch to the next group if it fails and so on.

➢ **Groups Penetration Tests Results Repository (Table 3.5):** is managed and used by *SGM*. It stores the information about penetration test results of each group of *OTSWS*.

- **Service-Group Id:** stores the *Id* of the tested service group.
- **Test Id:** stores the *Id* of the penetration test performed on the service group.
- **Test Date:** stores the date when the penetration test is performed on the service group.
- **Test Result:** stores the penetration test result (e.g., whether the penetration test has been successful or not).

➢ **Failure Records Repository (Table 3.6):** is managed by *BP* and is used by the *Administrator*. It stores information about runtime failures of each *OTSWS*.

Table 3.1: Services Repository (*SR*)

ID	Service Name	Endpoint	Target Namespace	Invocation Id	Operation Name	Input	Output
S1	Service1	http://...	a.b.c	Inv1	Op1	type in_1, … type in_n	type out
S2	Service1	http://...	a.b.c	Inv6	Op2	type in_1, … type in_n	type out
:	:	:	:	:	:	:	:
Sn	Servicen	http://...	d.e.f	Inv1	Op1	type in_1, … type in_n	type out

Table 3.2: Penetration Tests Repository (*PTR*)

Test Id	Test Name	Test Setting
T1	Coercive Parsing	1500 open tags
T2	Coercive Parsing	2000 open tags
:	:	:
Tn	Hash Collision	1000 colliding attributes

Table 3.3: Services Penetration Tests Results Repository (*SPTRR*)

Service Id	Test Id	Test Date	Test Result
S1	T1	dd/mm/yyyy	Passed
S1	T2	dd/mm/yyyy	Failed
:	:	:	:
Sn	Tn	dd/mm/yyyy	Failed

Table 3.4: Service-Groups Repository (*SGR*)

Service-Group Id	Service Id	Invocation Id	Order Number
G1	S1	Inv1	1
G1	S2	Inv1	1
:	:	:	:
Gn	Sn	Inv1	x

Table 3.5: Groups Penetration Tests Results Repository (*GPTRR*)

Service-Group Id	Test Id	Test Date	Test Result
G1	T1	dd/mm/yyyy	Passed
G1	T2	dd/mm/yyyy	Failed
:	:	:	:
Gn	Tn	dd/mm/yyyy	Failed

Table 3.6: Failure Records Repository (*FRR*)

Failure Id	Service Id	Failure Date	Failure Time
F1	S1	dd/mm/yyyy	.. : ..
:	:	:	:
Fn	S1	dd/mm/yyyy	.. : ..

Administrator

An *Administrator* is a person (the only human in this architecture) who is in charge of:

- Instantiating the framework.
- Designing the *BP.*
- Finding desired *OTSWSs* and adding their records to the *SR*.
- Recording new versions of an existing *OTSWS* as a new service into *SR* (it facilitates *N-version programming*).
- Removing the record of *OTSWSs* from *SR, FRR,* and *SPTRR*, if they should no longer be used (are no longer available or their number of failures, reported by *BP*, is very high).

➢ Recording the information about available penetration tests along with their setting (a separate record for each setting) into the *PTR*.
➢ Removing the records for penetration tests (that are no longer available) from the *PTR* and *SPTRR.*

Services Manager

The role of the *SM* is to test the services and record the test results through the following steps:

1. Retrieves the information about the service from the *SR*.
2. Adds to the 'Service Test Business Process', the information required for invoking the service.
3. Retrieves the information about penetration tests and their settings from *PTR*.
4. Uses the 'Service Test Business Process', tests information collected in step 3, and the external penetration testing tool to test the service.
5. Records the test result into *SPTRR*.

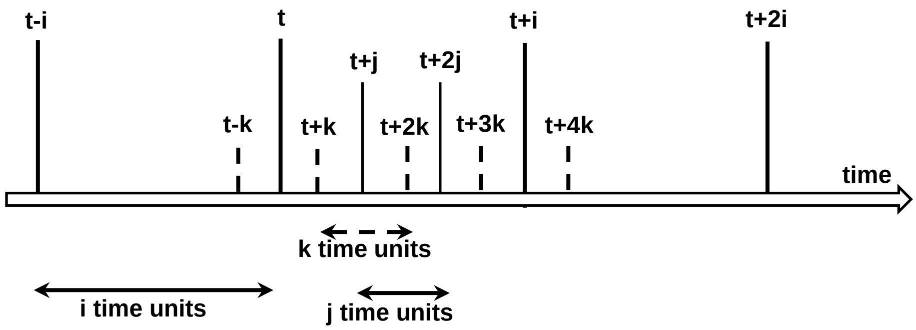


Figure 3.3: Combined SM and SGM Operation Intervals. The solid lines and dotted lines indicate SM and SGM operation intervals, respectively

SM performs steps 1-5 above in the following cases:

➢ Periodically (refer to Figure 3.3, every ***i*** time units) tests all services recorded in *SR*. *OTSWSs* may go under un-versioned updates, which may affect their security vulnerabilities, for example, switching off the schema validation through *WS's* source code: [*(BindingProvider) wsClient).getRequestContext().put("set-jaxb-validation-event-handler", "false"*]. Or services may be removed from *SR*. Hence, *SM* periodically tests all the services available in *SR* and updates *SPTRR*.

- Periodically (refer to Figure 3.3, every ***j*** time units) checks whether a new service or a new failure is recorded in *SR* and *FRR,* respectively, and if it is, it tests that particular service. The runtime failure of an *OTSWS*, reported by *BP*, might be as a result of un-versioned changes to that service. Hence, it should be tested.

Service-Groups Manager

The role of the *SGM* is to group and test services having the same *invocationId.* It fulfils this task through following steps:

1. Retrieves, from the *SPTRR*, the penetration tests results of all the *OTSWSs* having the same *invocationId*.
2. Performs statistical analysis and groups *OTSWSs* based on their security vulnerabilities diversity and record the result into *SGR*.
3. For every group:
    a. Retrieves from the *SR* the record of every *OTSWS* in that group.
    b. Adds the information required for invoking the group to the 'Group Test Business Process'.
    c. Retrieves the information about penetration tests and their settings from *PTR*.
    d. Uses the 'Group Test Business Process', tests information collected in the previous step, and external penetration testing tool to test the group.
    e. Records the test result into *GPTRR*.
    f. Assigns an *orderNumber* to each group after comparing their penetration test results.

SGM repeats the above steps for every *invocationId*. Also, every *k* time units (Refer to Figure 3.3) it checks *SPTRR* for changes related to the addition of a new penetration test record or deletion of an existing one. In the event of these changes, *SGM* repeats the above steps for all the services having the same *invocationId* as the service that the change is related to. It then performs the grouping process from scratch since addition or removal of an *OTSWS* requires the re-creation of all related groups.

Business Process

BP uses *SR* and *SGR* to add groups of *OTSWSs* into the business process. It starts with the groups having the lowest *orderNumber* (the most secure among other groups). To catch any failure, *BP* invokes each group of *OTSWSs* from inside a *scope* activity (introduced in the previous chapter) and uses its *faultHandler* facility. In the event of group's execution failure, *BP* repeats their execution one more time, and if it fails again, *BP* records the failure and switches to the group with the next *orderNumber*. *BP* adopts the same approach throughout the business process execution cycle.

3.4 Summary

This chapter presented the architecture for the proposed framework along with its objectives and the assumptions made. It then explained the role of each of its components and the interactions among them. The next chapter evaluates this framework through various case studies.

CHAPTER

4

ITWS Formed Based on Penetration Test Results of Candidate WSs

Previous chapters have presented the background and motivations, and the architecture for the proposed framework. As discussed previously, diversity is a valid and effective approach to mitigating the effects of cyber-attacks. In this work, diversity is achieved through penetration testing candidate *OTSWSs.* This chapter uses a case study to evaluate the feasibility of using penetration test results of candidate *OTSWSs* as a means of achieving diversity for implementation of *ITWS*.

In particular, Section 4.1 briefly introduces the third-party penetration testing tool that is used in the case studies presented in this work. Section 4.2 demonstrates the feasibility of *ITWS*; formed based on penetration tests results of candidate *OTSWSs*, in terms of mitigating the *XML*-related security vulnerabilities. Section 4.3 provides the summary of the discussions presented in this chapter.

4.1 Penetration Testing Tool, WS-Attacker

The proposed framework is not based on any specific penetration testing tool or method (the penetration testing tool itself is not part of the framework). Therefore, the type of penetration tests and how they should be performed depends on the selected penetration testing tool.

For evaluation of the proposed framework, a third-party penetration testing tool was required. *WS-Attacker* [18], *SoapUI* [84], *WSFuzzer* [122], and *WSFAggressor* (which is also based on *WS-Attacker*) [123] enable penetration testing *WSs* for *XML*-related security vulnerabilities, which is the focus of this work. However, except *WS-Attacker*, they either support fewer numbers of attack types and do not provide attack evaluation (in the case of *SoapUI* and *WSFuzzer*) or require access to the system under test (in the case of *WSFAggressor*) [40]. Hence, *WS-Attacker* is selected, which also enables automatic penetration testing.

WS-Attacker is an open source penetration testing tool, which enables automatic tests for *XML*-specific security vulnerabilities. It consists of a framework and plugin architecture (see Figure 4.1).

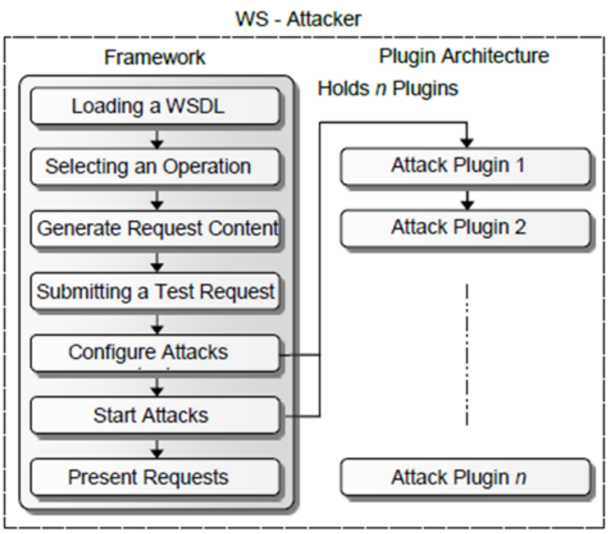


Figure 4.1: Overview of WS-Attacker and Its Processing Steps [18]

Figure 4.2 presents the component diagram for *WS-Attacker*, which shows that each plugin connects to its framework through an interface.

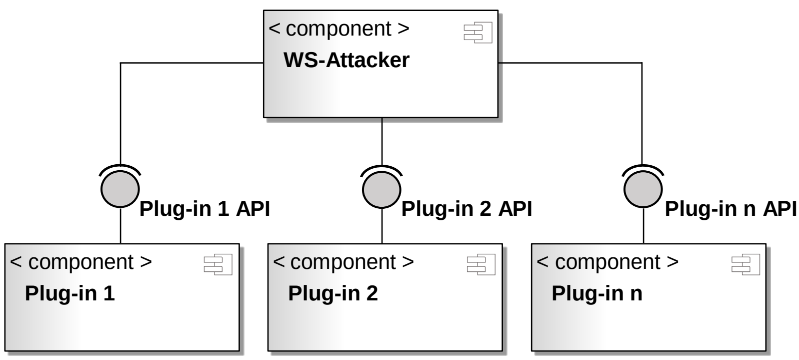


Figure 4.2: Component Diagram for WS-Attacker

4.1.1 WS-Attacker Framework

WS-Attacker's framework is based on *SoapUI* [84] and sets up an environment for attacking *WSs* to identify their *XML*-related security vulnerabilities. It requires the user to load the Web Service Description Language *(WSDL)* document of the *WS* that should be tested. It then parses the loaded *WSDL*, presents the extracted operations to the user and generates Simple Object Access Protocol (*SOAP*) requests based on the extracted information. To setup the *WS-Attacker's* environment, the user should:

1. Select the target operation
2. Send a test request to the target operation through the user interface provided by *WS*-Attacker. From the response of the *WS* to the test request, *WS*-Attacker can identify the normal state of the *WS* and analyse the attack results accordingly.
3. Select and configure the attack plugins related to the attacks against which the *WS* should be assessed.
4. Run the framework to perform the selected attacks on the *WS*.

Upon successful attack completion, *WS-Attacker* presents the attack result to the user. The attack result indicates whether the attack has been successful and its criticality score [18]. The attack‘s success (true or false) depends on whether a security vulnerability is detected. The score indicates the potential damage the attack can cause and is calculated by *WS-Attacker* in different ways for each attack plugin (for example, see *SOAPAction Spoofing* attack plugins in Section 4.1.2).

4.1.2 WS-Attacker Plugin

In *WS-Attacker*, the attacks are implemented as plugins. Each plugin is an implementation of a model of an adversary performing one type of attack and allows the user to set various parameters, such as the number of parallel attack threads, number of requests per thread, milliseconds between every test-probe request, and milliseconds between every attack request.

WS-Attacker is extendable and provides a plugin interface enabling new attack plugins to be added [18]. A number of attack plugins have been developed for *WS-Attacker* by its developers and other researchers [18], [40], [41].

SOAPAction Spoofing Attack Plugins

SOAPAction Spoofing is one of the attack plugins of *WS-Attacker* [18]. It provides automatic and manual attack options. In the automatic mode, it generates attack requests with all possible *SOAPAction* headers and sends them to the *WS* under test. However, in manual mode, the user is allowed to set the *SOAPAction* header manually. According to the developers of this attack plugin, possible responses from a *WS* to a *SOAPAction Spoofing* attack are as follows:

a) A *SOAP* fault message, which is the proper response to a *SOAPAction Spoofing* attack.
b) A server error or misconfiguration message.
c) Execution of the first operation in the body of the message, meaning that the *SOAPAction* header is only checked by the *HTTP* firewall while it is ignored by the *WS's* logic.
d) Execution of the operation defined in the *SOAPAction* header, meaning that the operation to be executed is solely selected based on the *SOAPAction* value.

This plugin interprets (b), (c) or (d) responses (listed above) as a successful attack [18]. It also rates the vulnerability to the performed attack in percentage, based on the difficulty of the execution of the attack and the impact it may have on the *WS* under test. For example, response (d) indicates a more vulnerable *WS* because the attack is easier to execute, it only requires changes to the *SOAPAction* element [18].

Mainka *et al*. [18] have tested this plugin on *Apache Axis2 v1.6.1*, *JBossWS Native 6.0*, *JBossWS CXF 7.0* and *.Net WSs 3.0*, *WS* frameworks and the results have shown the vulnerability of all these frameworks to this type of attack. Within the named frameworks, *Apache Axis2* and *.Net WSs* are identified as the most vulnerable frameworks, as they always execute the operations defined in the *SOAPAction* header.

Denial of Service Attack Plugins

Denial of Service (*DoS*) attacks are one of the most popular attacks, which can be performed through a variety of techniques [40]. History of such attacks, targeting well-known companies, such as *VISA* and *PayPal*, indicates that they can be a serious threat to today's *IT* infrastructure [40]. Other examples of this type of attacks are called *HashDoS* attacks, which exploit the weakness of a hash-mapping algorithm implementation [42], [43]. Regarding the *WSs*, *DoS* attacks can exploit the vulnerabilities in *XML*-based documents (e.g., *SOAP* messages) targeting the parsing mechanisms and other resources, affecting the availability of the *WS*.

Falkenberg *et al*. [40] have developed a number of fully automatic *DoS* attack plugins for *WS-Attacker* enabling the identification of the *WSs'* vulnerability to *Coercive Parsing*, *SOAP Array*, *XML Attribute Count*, *XML Element Count*, *XML Entity Expansion*, *XML External Entity*, *XML Overlong Names* and *HashDoS* attacks. In implementing these plugins, they have assumed that the tester does not have direct access to the *WS* under attack, and can only examine its vulnerability by sending payloads to its server then evaluating its response time. They have defined the response time as the time when the last byte of the request is sent to the server until the first byte of the response is received from the server. These attack plugins test a *WS* for vulnerability to *DoS* attacks as follows [40]:

1. They send the user-defined untampered requests (extended to the size of the tampered requests) to the *WS* then log the response times. According to the developers of these attack plugins, the extension to the size of the untampered requests does not cause *DoS* attack and if it does it will be clearly indicated in the result to eliminate false positive.

2. After a user-defined elapsed time, they send the tampered requests (with the same load patterns as the untampered ones) to the *WS* then log the response times.
3. They calculate the ratio of the median of the response times of the last 10 (or the maximum number of requests if less than 10 requests are sent) tampered requests to the median of the last 10 (or the maximum number of requests if less than 10 requests are sent) untampered requests (see Equation 4.1). The attack success is decided according to the threshold values (see Table 4.1) that are chosen based on pre-tests on vulnerable and non-vulnerable *WSs*.

$$ARTR = \frac{median\ response\ time\ of\ the\ last\ 10\ tampered\ requests}{median\ response\ time\ of\ the\ last\ 10\ untampered\ requests} \qquad \textbf{(4.1)}$$

Table 4.1: WS-Attacker's DoS Attack Success Metrics [40]

Metric Value	Rating
ARTR < 3	Payload ineffective
3 ≤ ARTR < 6	Payload effective
6 ≤ ARTR	Payload highly effective

In designing these attack plugins, all major errors, such as the increase in response time because of various message sizes or various network loads, are eliminated [40].

These plugins also test for *DoS* attack's effect on third-party users (who visit the *WS* under attack) by continuously sending test requests to the target *WS* at constant user-defined intervals and in parallel to testing the *WS* for vulnerability to *DoS* attack. The attack's effect on the third-party users is decided by comparing the median of the response times of all simulated third-party requests (*MRTTPR*), after starting to send first tampered request, with the threshold values (see Table 4.2) that are considered an acceptable response time by the developers of these attack plugins. They believe that longer response times than these thresholds exponentially increases the users' annoyance level [40].

Table 4.2: WS-Attacker's DoS Attack's Effect Metrics on Third-Party Users [40]

Metric Value	Rating
MRTTPR < 2 sec	no or small effect on third-party users
2 ≤ *MRTTPR* < 5	third-party users are affected
5 ≤ *MRTTPR*	third-party users are highly affected

Falkenberg *et al*. [40] have tested a number of these attack plugins on *Apache Axis2*, *Apache CXF*, *Metro,* and *ASP .Net* frameworks as well as the *IBM DataPower XI50 XML Security Gateway*. The results of these tests (see Table 4.3) show that *ASP .Net and IBM XI50* are not vulnerable to any of these *DoS* attacks while *Apache Axis2*, *Apache CXF*, and *Metro* frameworks are vulnerable to at least one of these *DoS* attack.

Table 4.3: Results of Testing DoS Attack Plugins on a Number of Web service Frameworks [40]

Attack Name	Axis2	CXF	Metro	ASP .Net	IBM XI50
Coercive Parsing	Yes	Yes	x	x	x
DJBX31A Hash Collision	Yes	Yes	Yes	x	x
DJBX33A Hash Collision	x	x	x	x	x
DJBX33X Hash Collision	x	x	x	x	x
XML Attribute Count	Yes	Yes	Yes	x	x
XML Element Count	x	Yes	x	x	x
XML Entity Expansion	x	x	x	x	x
XML External Entity	x	x	x	x	x
XML Overlong Names	x	x	x	x	x

4.2 Case Study: Feasibility of ITWS Formed Based on Penetration Test Results of Candidate WSs

This section uses a case study (the author's work published in [124]), to demonstrate the feasibility of using penetration test results of candidate *OTSWSs* as a means of achieving diversity for implementation of *ITWS.*

The objective of this case study is to exemplify the implementation of an *ITWS* using *WSs* selected based on their security vulnerabilities identified through penetration testing, and testing its effectiveness as a defence against *XML*-related *DoS* attacks. The remainder of this section presents the procedure of this case study.

4.2.1 WSs Preparation

For this case study the following stock purchase *WSs* is developed:

- Two *WSs* developed using *Apache Axis2* 1.5.1 framework and were deployed on *Apache Tomcat* 6.0.18 running on *Intel*® *Core*™ i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System.
- Two *WSs* developed using .*NET* 4.0 framework and were deployed on *Intel*® *Core*™ 2 *Duo CPU* P8400@ 2.26GHz system with 3.00GB *RAM* and 32-bit Operating System.

Also, one third-party *ASP*.*NET WS* [125], which provides similar stock purchase functionality, is employed.

4.2.2 Penetration Tests Settings

In this study, *Coercive Parsing* attack is performed on these services with *WS-Attacker's* settings presented in Table 4.4.

Table 4.4: *WS-Attacker's* Settings

Test Message Settings	*WS-Attacker's* other Settings
Coercive Parsing with 75,000 open tags plotted in the body of the SOAP message	2 parallel attack threads, 4 requests per thread, 500 milliseconds between every testprobe request, 750 milliseconds between every attack request, 4 seconds server recovery time, 5 seconds stop after the last tampered request

4.2.3 WSs' Penetration Test Results

Each *WS* is tested individually for security vulnerability to *Coercive Parsing* attack, using *WS-Attacker's* settings shown in Table 4.4. The penetration test results of these *WSs* are presented in Table 4.5. In this table, 100% indicates that the *WS* is vulnerable to *Coercive Parsing* attack and 1% shows that it does not have this security vulnerability.

4.2.4 ITWS Implementation

The *ITWS* is implemented through the composition of the three *ASP.NET* services and one of the *Axis2* services (four highlighted services in Table 4.5), using *BPEL* 2.0 plugin for *Eclipse* 3.4. It is then deployed on *Apache Ode* 1.2 runtime (on top of *Apache Tomcat* 6.0.18 server) on the same machine that is hosting the *Axis2 WSs* (*Intel® Core™* i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System). Figure 4.3 presents the overview of this *BPEL* process.

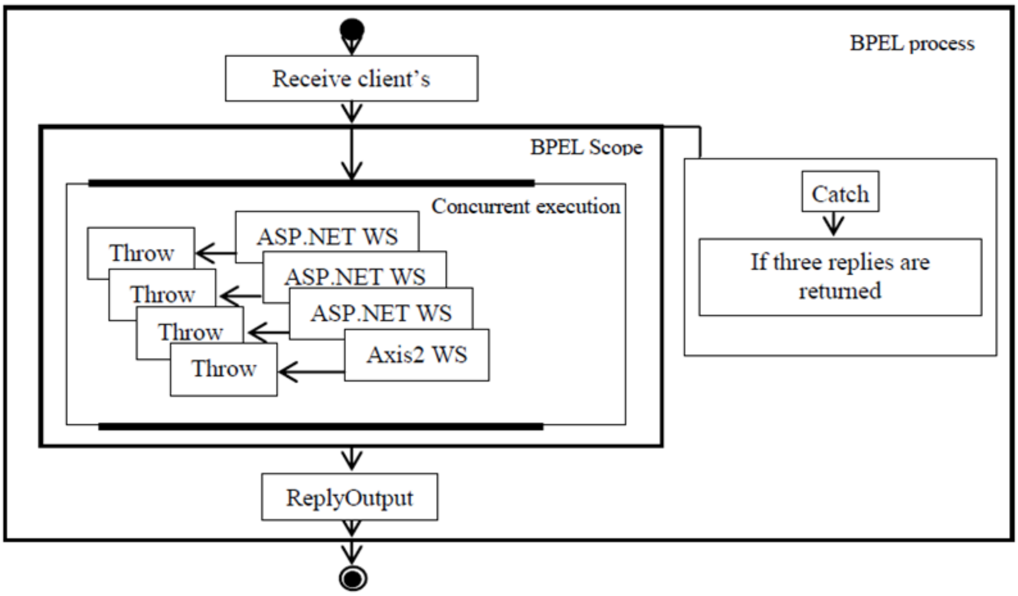


Figure 4.3: BPEL Diagram of the ITWS

The operation of this *ITWS* is as follows:

1. Receives client's request.
2. Initializes variable associated to each concurrent invocation process (each invocation process is responsible for invoking one of the *ITWS's* four constituent services) to 0.
3. Passes the client's request to each of the parallel invocation processes.
4. Each concurrent invocation process invokes its associated *WS*.
5. Each concurrent invocation process sets its associated variable to 1 upon receiving a response from its associated *WS*.

6. Once three responses are returned by three of the constituent services (three of the variables associated to the invocation processes are having the value of 1), the *BPEL* scope (the concurrent invocation processes are wrapped within a *BPEL* scope which provides exception handling, see Section 2.6 for further details) throws an exception.
7. The exception handler terminates the concurrent invocation processes.
8. The business process replies to the client.

4.2.5 ITWS's Penetration Test Results

The *ITWS* is tested for security vulnerability to *Coercive Parsing* attack using *WS-Attacker* with the same settings that were used to test individual services (see Table 4.4).

Table 4.5: Penetration Tests Results

WS Framework	Axis2 WS	Axis2 WS	ASP.Net WS	ASP.Net WS	ASP.Net WS	ITWS
Penetration test result for Coercive Parsing attack	100%	100%	1%	1%	1%	1%

The last column of Table 4.5 presents the penetration test result for this *ITWS* and indicates that it is not vulnerable to *Coercive Parsing DoS* attack (1% denotes that the *WS* under test does not have this security vulnerability).

4.3 Summary

This chapter briefly introduced the penetration testing tool that is used in the case studies presented in this work. It then demonstrated the feasibility of *ITWS* formed using *WSs* with security vulnerabilities diversity (identified through penetration testing) using a case study. Chapter 8 uses the outcome of this case study to evaluate the proposed framework.

CHAPTER

5

Effects of BPEL on WSs' XML-Related Security Vulnerabilities

In this work, *Intrusion-Tolerance* is implemented using Business Process Engineering Language (*BPEL*). Hence, the effect of *BPEL* on the security vulnerabilities of Off-The-Shelf Web Services (*OTSWSs*) should be considered in the selection of these services. This chapter uses a case study to demonstrate that *BPEL* could affect the security vulnerabilities of *WSs.* Hence, penetration testing for service selection should be performed while *OTSWSs* are wrapped in a *BPEL* process.

Sections 5.1 and 5.2 demonstrate the case study and the summary of the discussions presented in this chapter, respectively.

5.1 Case Study: Effects of BPEL on WSs' XML-Related Security Vulnerabilities

This section uses a case study to demonstrate (from the point of view of *WS-Attacker*) that *BPEL* could affect the *XML*-related security vulnerabilities of *WSs*. The remainder of this section presents the procedure of this case study.

5.1.1 WS Preparation

For this case study, a simple *WS* is developed using the source code presented in Code 5.1 and *Axis2* 1.6.1 *WS* framework. This service is deployed on *Apache Tomcat* 6.0.18 server running on *Intel*® *Core*™ i5-3320M

CPU @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System. This *WS* provides two simple *sum* and *factorial* services (see Code 5.1).

Code 5.1: Source Code for the Developed WSs

```
package Axis_Tom_6;
public class Axis_Tom_6_sum {
    public int addIntegers (int firstNum, int secondNum) {
        return firstNum + secondNum;
    }
    public int factorial(int n) {
        int result = 1;
        for (int i = 1; i <= n; i++) {
            result = result * i;
        }
        return result;
    }
}
```

5.1.2 WS Wrapped within BPEL process

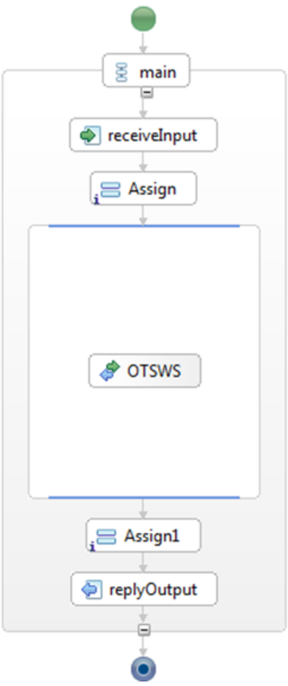


Figure 5.1: BPEL Process for Wrapping the Developed WSs.

The service from Section 5.1.1 is wrapped in a *BPEL* process (see Figure 5.1) developed using *BPEL* 2.0 plugin for *Eclipse Neon*.2 4.6.2. And was deployed on *Apache* 1.3.4 runtime (on top of *Tomcat* 5.5.26 server) running on *Intel*® *Core*™ i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System. The operation of this *BPEL* process is as follows:

1. Receives client's request.
2. Assigns the client's request to the invocation process that invokes the *WS* (from Section 5.1.1).
3. Invokes the *WS*.
4. Assigns the response from the *WS* to the output of the *BPEL* process.
5. Replies the response from the *WS* to the client.

5.1.3 Penetration Tests Settings

In this study, *Coercive Parsing, DJBX31A Hash Collision, and XML Attribute Count* attacks are performed on these services (*WSs* from Sections 5.1.1 and 5.1.2). Table 5.1 presents the *WS-Attacker's* settings for each of these tests.

Table 5.1: WS-Attacker's Settings

Test ID	Test Message Settings	***WS-Attacker's* other Settings**
Test 1	Coercive Parsing attack with 3,000 open tags plotted in the header of the SOAP message	2 parallel attack threads, 4 requests per thread, 500 milliseconds between every testprobe request, 750 milliseconds between every attack request, 4 seconds server recovery time, 5 seconds stop after the last tampered request
Test 2	Coercive Parsing attack with 11,000 open tags plotted in the body of the SOAP message	
Test 3	DJBX31A Hash Collision attack with 2,000 paired keys/values plotted in the header of the SOAP message	
Test 4	XML Attribute Count attacks with 50,000 paired keys/values plotted in the header of the SOAP message	

5.1.4 Attack Elements for Test SOAP Messages

In the penetration tests performed on these services, the attack element is either plotted in the header or the body of the test *SOAP* message as presented in Message 5.1 and Message 5.2, respectively.

Message 5.1: Test SOAP Message with Attack Element Plotted in its Header

```
<soapenv:Envelope xmlns:soapenv="http://schemas.xmlsoap.org/soap/envelope/"
xmlns:axis="http://Axis_Tom_6">
  <soapenv:Header> AttackElement </soapenv:Header>
  <soapenv:Body>
    <axis:addIntegers>
      <axis:firstNum>1</axis:firstNum>
      <axis:secondNum>2</axis:secondNum>
    </axis:addIntegers>
  </soapenv:Body>
</soapenv:Envelope>
```

Message 5.2: Test SOAP Message with Attack Element Plotted in its Body.

```
<soapenv:Envelope xmlns:soapenv="http://schemas.xmlsoap.org/soap/envelope/"
xmlns:axis="http://Axis_Tom_6">
  <soapenv:Header></soapenv:Header>
  <soapenv:Body>
     AttackElement
    <axis:addIntegers>
      <axis:firstNum>1</axis:firstNum>
      <axis:secondNum>2</axis:secondNum>
    </axis:addIntegers>
  </soapenv:Body>
</soapenv:Envelope>
```

In each type of attack, the attack element is replaced as follows:

- **Coercive Parsing Attack:** *AttackElement* is replaced with various number of open tags (e.g., <X><X>…</X></X>).
- **DJBX31A Hash Collision Attack:** *AttackElement* is replaced with *<attackElement $$PAYLOADATTR$$> test </attackElement>* and *$$PAYLOADATTR$$* element is replaced with various number paired keys/values (e.g., tttttt="0" ttttuU="1" ttttv6="2").
- **XML Attribute Count Attack:** *AttackElement* is replaced with *<attackElement $$PAYLOADATTR$$> test </attackElement>* and

$$PAYLOADATTR$$ element is replaced with various number paired keys/values (e.g., a0="0" a1="1" a2="2").

5.1.5 Penetration Tests Results

The services developed in Sections 5.1.1 and 5.1.2 are tested using *WS-Attacker's* settings shown in Table 5.1. Figures 5.2 and 5.3 show the component diagram for direct penetration testing the *Axis2 WS* (*WS* from Section 5.1.1) and for penetration testing this *WS* while it is wrapped in a *BPEL* process (*WS* from Section 5.1.2), respectively.

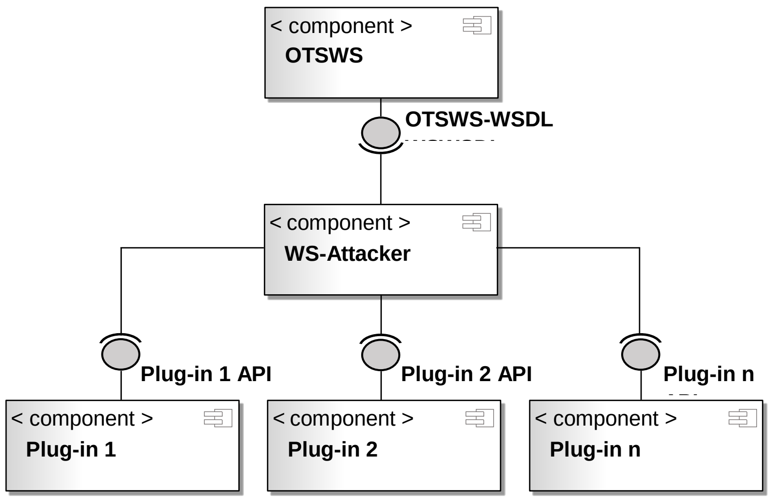


Figure 5.2: The Component Diagram for Direct Penetration Testing of the WS in this Case Study

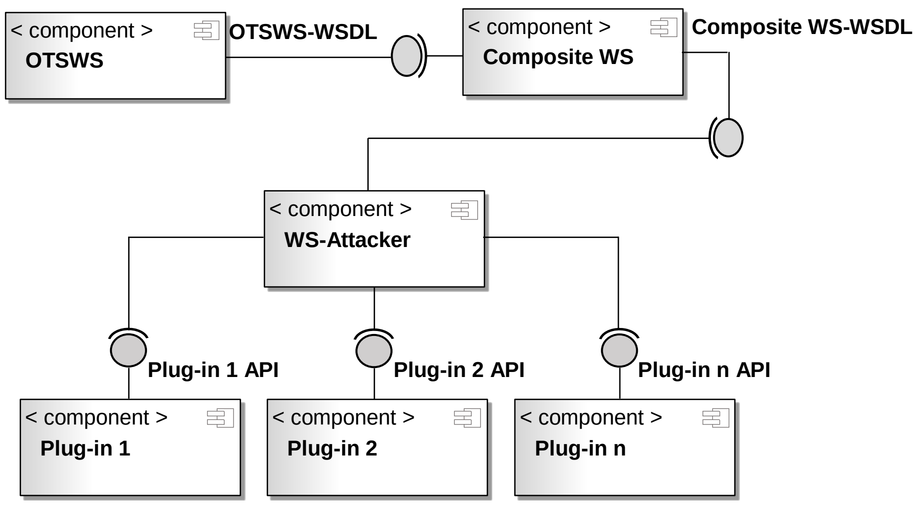


Figure 5.3: The Component Diagram for Penetration Testing of the WS in this Case Study while it is wrapped in a BPEL Process.

Figures 5.4a-5.4d and 5.5a-5.5d show the penetration test results for each test attack performed on *A*xis2 *WS* (*WS* from Section 5.1.1) when it is tested directly and when it is tested while wrapped in a *BPEL* process (*WS* from Section 5.1.2), respectively. The penetration test results show the vulnerability of these *WSs* to the performed attacks in percentage so that 100% indicates that the *WS* is very vulnerable to the attack and 1% shows that it does not have this security vulnerability.

Each test is repeated ten times (to increase the confidence of the outcome of these tests) and the average of the results is considered. Because, these test plugins decide on the security vulnerability of the *WSs* based on their response times that slightly differs every time the same test is performed. The vertical and horizontal lines in these graphs (Figures 5.4a-5.4d and 5.5a-5.5d) show the result of the penetration test every time the same test is performed and the average of the penetration test results for each test, respectively.

These results demonstrate that *BPEL* affects the *XM*-related security vulnerabilities of *WSs* (from the point of view of *WS-Attacker*). In some cases (*Coercive Parsing* plotted in the header, *DJBX31A Hash Collision,* and *XML Attribute Count* attacks) it has improved the vulnerability, and in other cases, it has worsen it (*Coercive Parsing* plotted in the body attack). Hence, it is a better approach to perform penetration testing while *OTSWSs* are wrapped in a *BPEL* process, as in this framework the *ITWS* is implemented using *BPEL* so its effects on the security vulnerabilities of the *OTSWSs* should also be taken into account.

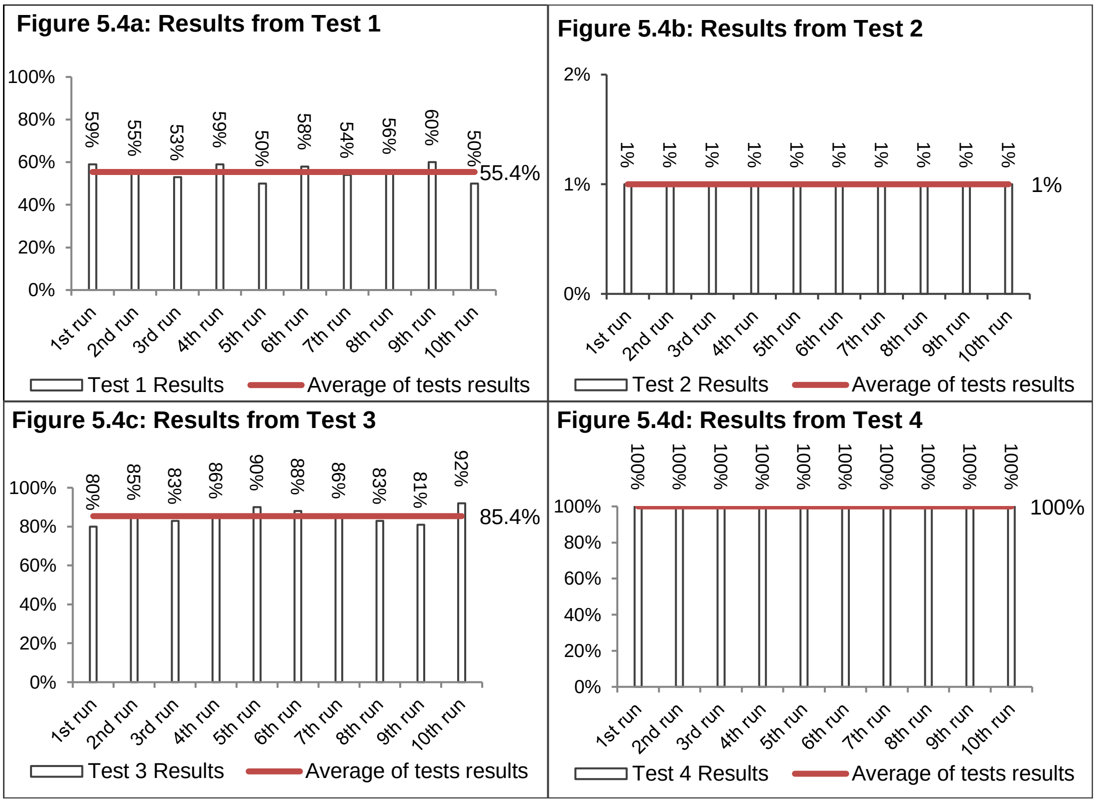


Figure 5.4: Results from Direct Penetration Testing Axis2-1.6.1 WS(for information about each test see Table 5.1)

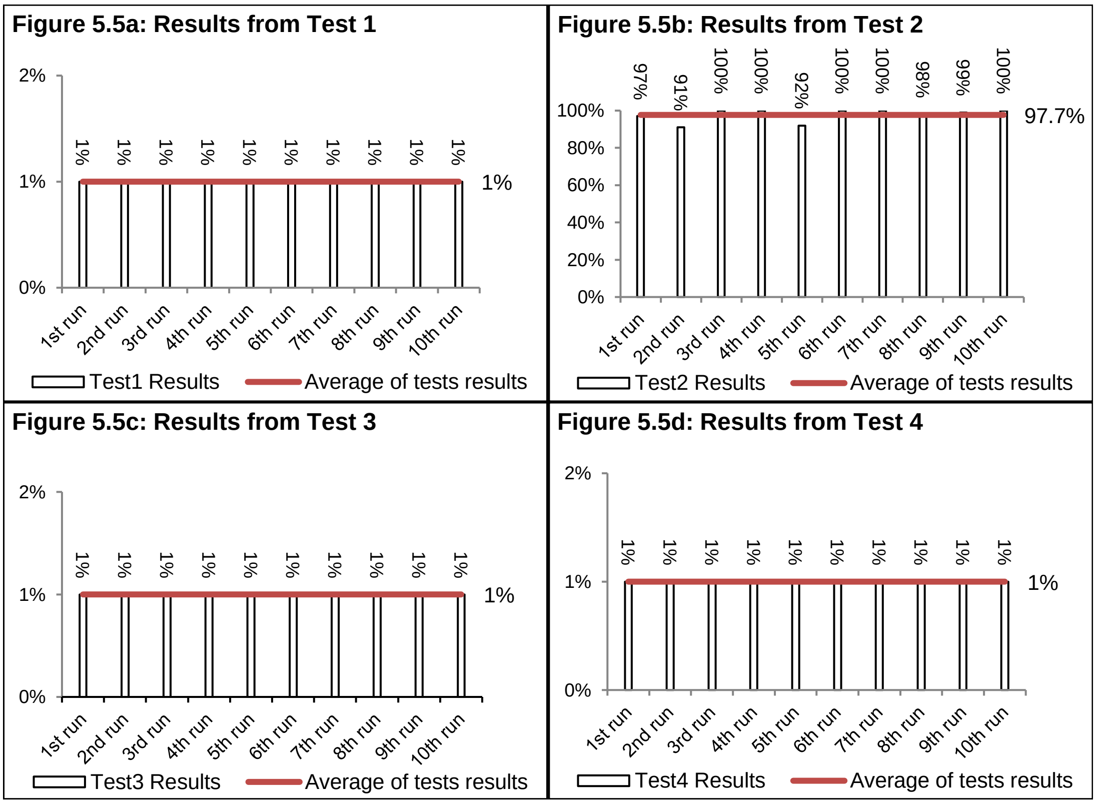


Figure 5.5: Penetration Test Results for Axis2-1.6.1WS while it was wrapped in a BPEL Process (for information about each test see Table 5.1)

5.2 Summary

This chapter used a case study to demonstrate (from the point of view of *WS-Attacker*) that *BPEL* could affect the *XML*-related security vulnerabilities of *WSs*. It improved the security vulnerabilities to *Coercive Parsing* (plotted in the header), *DJBX31A Hash Collision* and *XML Attribute Count* attacks while increasing security vulnerability to *Coercive Parsing* (plotted in the body) attack. The outcome of this case study is used in the service selection case study, presented in the next chapter.

CHAPTER

6

Security-Aware Selection of Optimal Group WSs using PCA and CA, for Implementation of ITWS

In this work, *ITWS* is achieved through penetration testing candidate *OTSWSs,* grouping these services based on their security vulnerabilities diversity (using *PCA* and *CA*), ordering the groups according to their overall security vulnerabilities (identified through penetration testing), and starting the *ITWS* with services from the most secure group and switch to the next group if it fails and so on.

This chapter uses a case study to explain and exemplify the proposed service selection framework. Sections 6.1 and 6.2 demonstrate the case study and the summary of the discussions presented in this chapter, respectively.

6.1 Case Study: Security-Aware Selection of Optimal Group of WSs using PCA and CA, for Implementation of ITWS

This section uses a case study to evaluate the effectiveness of *PCA* and *CA* utilization in security-aware service selection based on penetration tests results of the candidate *OTSWSs*. The objective of this case study is to explain and exemplify the proposed service selection framework. The remainder of this section presents the procedure of this case study.

6.1.1 WS Preparation

As previously discussed, this framework is based on diverse *OTSWSs* (open source *WSs*). However, *OTSWSs* could not be used for this case study because

1. There was not an adequate number of third-party *WSs* offering similar services (e.g., third-party *WSs* offering stock purchasing service).
2. We did not have permission to perform penetration testing on the available third-party *WSs*.

Hence, for this case study, six *WSs* are developed using the source code presented in Code 5.1 (Chapter 5) and various *WSs'* frameworks. These services are deployed on either *Apache Tomcat* 6.0.18 or *Apache Tomcat* 7.0.72 servers running on *Intel*® *Core*™ i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System. However, in the utilization of this framework if more in-house *WSs* should be used (e.g., lack of adequate number of *OTSWSs*), these *WSs* can be run on different servers (other than the one running the *ITWS*) to avoid scalability issues.

The details of the six services developed for this case study are as follows:

- S1: *Axis1* 4 deployed on *Apache Tomcat* 6.0.18 server
- S2: *Axis2* 1.5.1 deployed on *Apache Tomcat* 6.0.18 server
- S3: *Axis2* 1.6.1 deployed on *Apache Tomcat* 6.0.18 server
- S4: *CXF* 2.3.10 deployed on *Apache Tomcat* 6.0.18 server
- S5: *CXF* 2.5.11 deployed on *Apache Tomcat* 7.0.72 server
- S6: *CXF* 2.6.3 deployed on *Apache Tomcat* 7.0.72 server

The Web Service Description Language (*WSDL*) files of these services are presented in *Appendices* A-F.

6.1.2 WSs Wrapped within BPEL processes

Recall from the result of the case study presented in Chapter 5 that penetration testing should be performed on the services while they are wrapped in a *BPEL* process (to also take into account the effects of the *BPEL* on the security vulnerabilities of the *WSs*), each of the *WSs* developed in the previous section are wrapped in the *BPEL* process as presented in Section 5.1.2 (see Chapter 5).

These business processes are developed using *BPEL* 2.0 plugin for *Eclipse Neon*.2 4.6.2 and are deployed on *Apache* 1.3.4 runtime (on top of *Tomcat* 5.5.26 server) running on *Intel® Core™* i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System.

6.1.3 Penetration Tests Settings

Table 6.1: WS-Attacker's Settings

Test ID	Test Message Settings	*WS-Attacker's* other Settings
Test 1	Coercive Parsing attack with 8,000 open tags plotted in the header of the SOAP message	2 parallel attack threads, 4 requests per thread, 500 milliseconds between every testprobe request, 750 milliseconds between every attack request, 4 seconds server recovery time, 5 seconds stop after the last tampered request
Test 2	Coercive Parsing attack with 9,000 open tags plotted in the header of the SOAP message	
Test 3	Coercive Parsing attack with 10,000 open tags plotted in the header of the SOAP message	
Test 4	Coercive Parsing attack with 11,000 open tags plotted in the header of the SOAP message	
Test 5	Coercive Parsing attack with 12,000 open tags plotted in the header of the SOAP message	
Test 6	Coercive Parsing attack with 13,000 open tags plotted in the header of the SOAP message	
Test 7	Coercive Parsing attack with 8,000 open tags plotted in the body of the SOAP message	
Test 8	Coercive Parsing attack with 9,000 open tags plotted in the body of the SOAP message	
Test 9	Coercive Parsing attack with 10,000 open tags plotted in the body of the SOAP message	
Test 10	Coercive Parsing attack with 11,000 open tags plotted in the body of the SOAP message	
Test 11	Coercive Parsing attack with 12,000 open tags plotted in the body of the SOAP message	
Test 12	DJBX31A Hash Collision attack with 2,000 paired keys/values plotted in the body of the SOAP message	
Test 13	DJBX31A Hash Collision attack with 3,000 paired keys/values plotted in the body of the SOAP message	
Test 14	XML Attribute Count attack with 40,000 paired keys/values plotted in the body of the SOAP message	
Test 15	XML Attribute Count attack with 50,000 paired keys/values plotted in the body of the SOAP message	
Test 16	XML Attribute Count attack with 60,000 paired keys/values plotted in the body of the SOAP message	

In this study, *Coercive Parsing*, *DJBX31A Hash Collision,* and *XML Attribute Count* attacks are performed on these services. Table 6.1 presents the *WS-Attacker's* settings for each of these tests. In the remainder of this section, these tests are referenced by their *Id* as presented in Table 6.1.

6.1.4 Attack Elements for Test SOAP Messages

In the penetration tests performed on these services, the test *SOAP* messages and their attack elements were set as it is explained in Section 5.1.4.

6.1.5 Penetration Test Results of Candidate WSs

The services developed in Sections 6.1.2 are tested using *WS-Attacker's* settings shown in Table 6.1. Figures 6.1-6.12 show the penetration test results for test attacks performed on these services (every two figures show the tests results related to one of these services). Due to the space limitation, the *Id* of the penetration tests are used in these graphs, for information about each test, see Table 6.1.

The penetration test results show the vulnerability of these *WSs* to the performed attacks in percentage so that 100% indicates that the *WS* is very vulnerable to the attack and 1% shows that it does not have this security vulnerability.

Each test is repeated ten times (to increase the confidence of the outcome of these tests) and the average of the results is considered. Because, these test plugins decide on the security vulnerability of the *WSs* based on their response times that slightly differs every time the same test is performed. The vertical and horizontal lines in these graphs (Figures 6.1-6.12) show the result of the penetration test every time the same test is performed and the average of the penetration test results for each test, respectively.

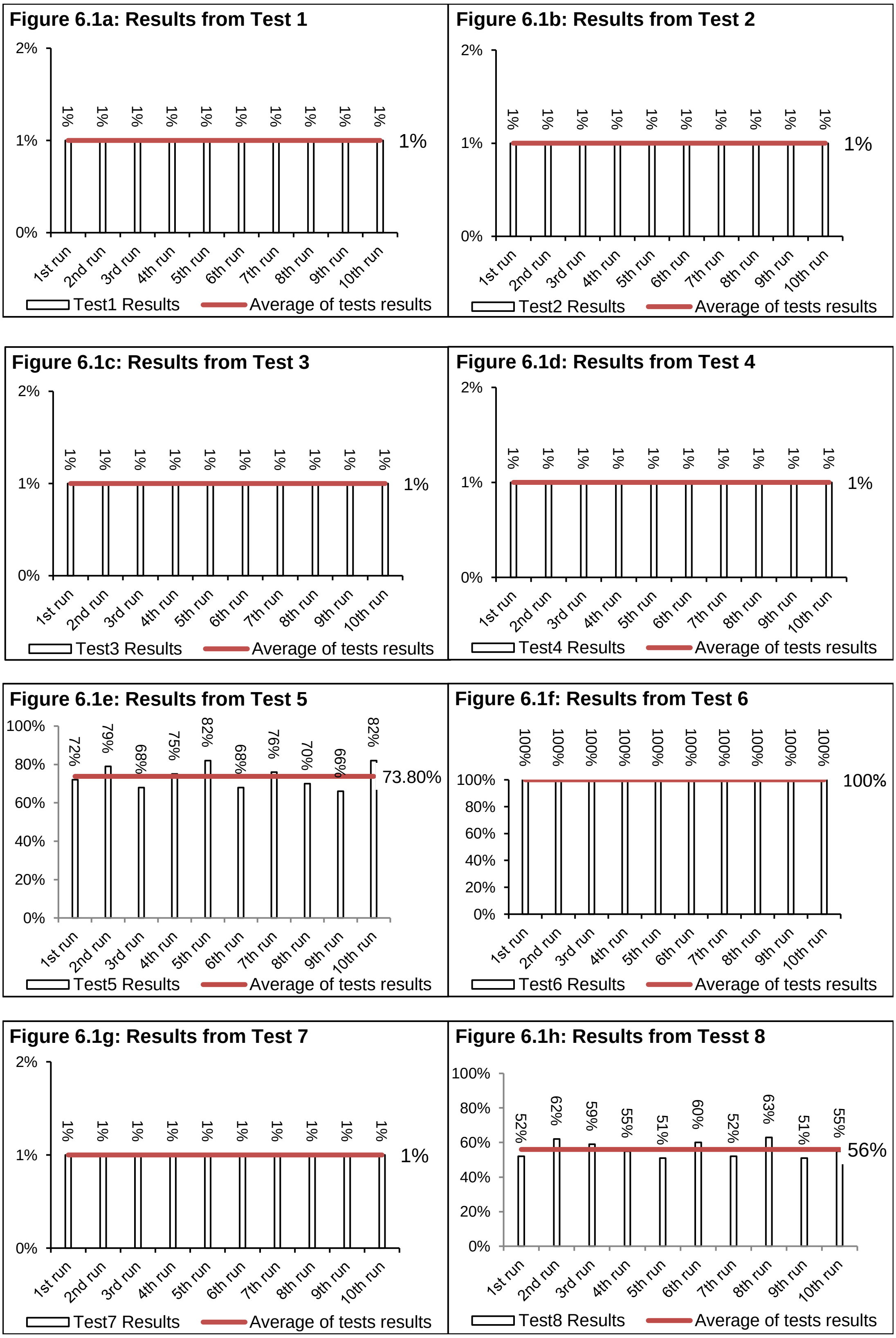


Figure 6.1: Penetration Tests Results for Tests 1-8 Performed on Axis1-4 WS (for information about each test and WS see Table 6.1 and Section 6.1.1, respectively)

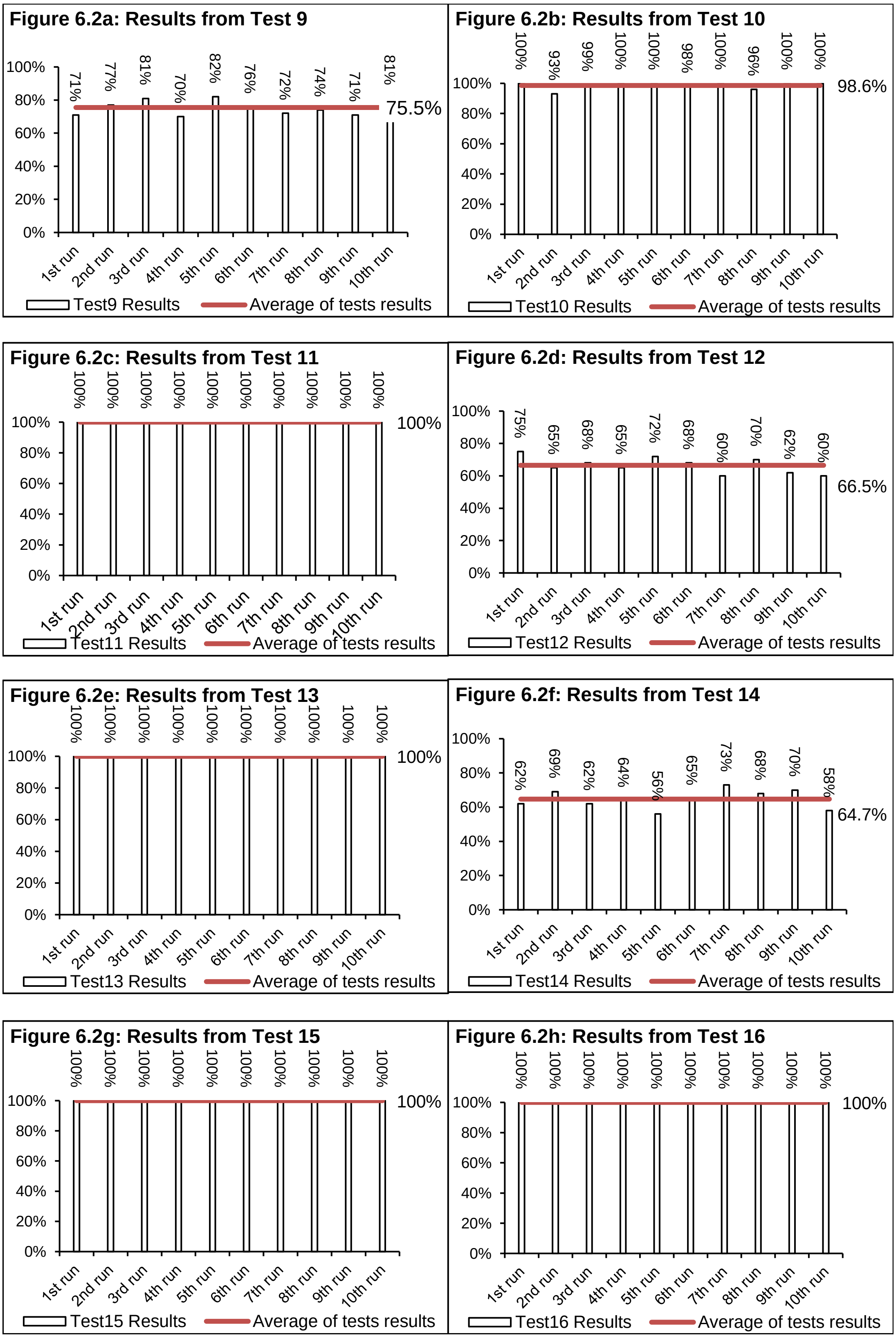


Figure 6.2: Penetration Tests Results for Tests 9-16 Performed on Axis1-4 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

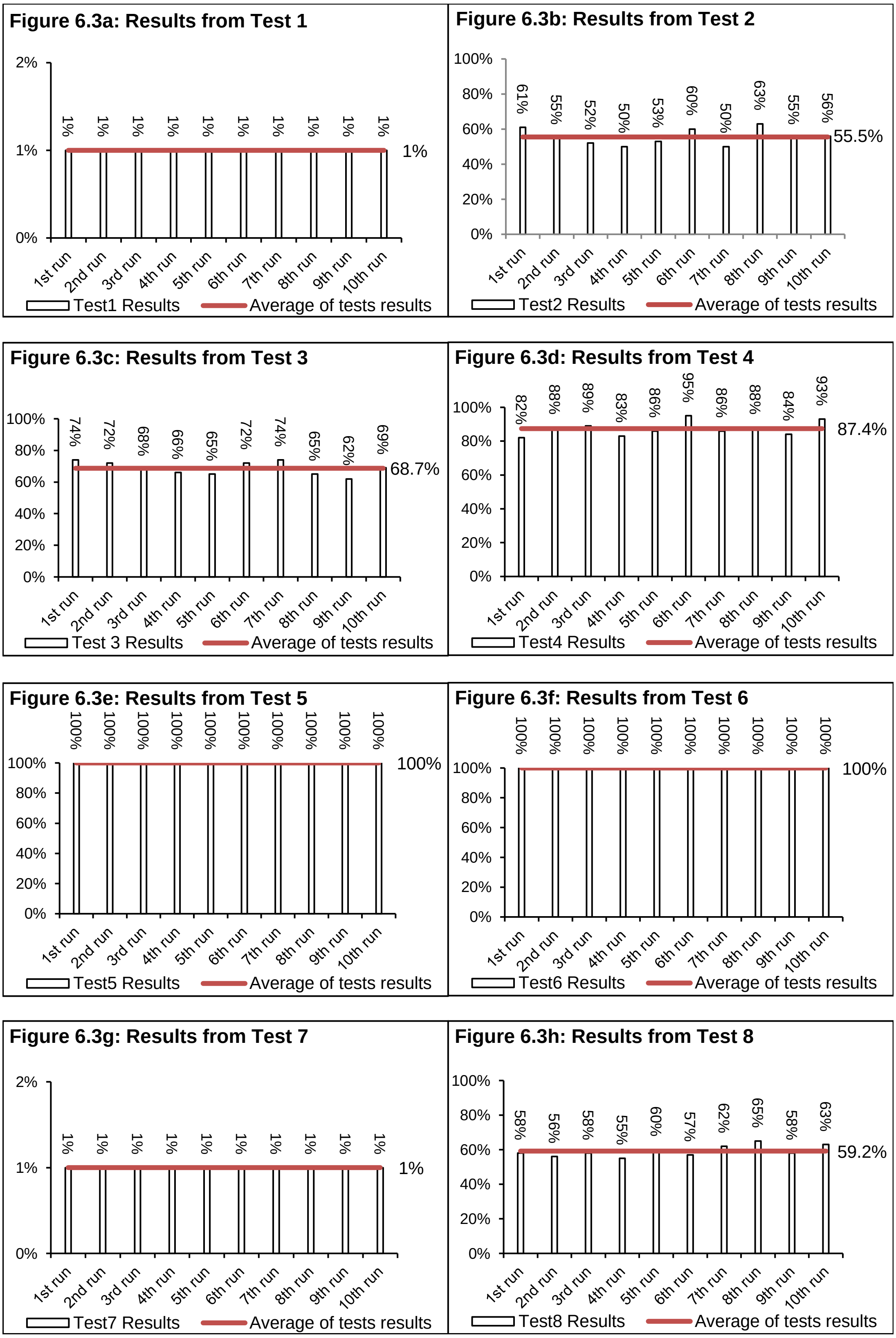


Figure 6.3: Penetration Tests Results for Tests 1-8 Performed on Axis2-1.5.1 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

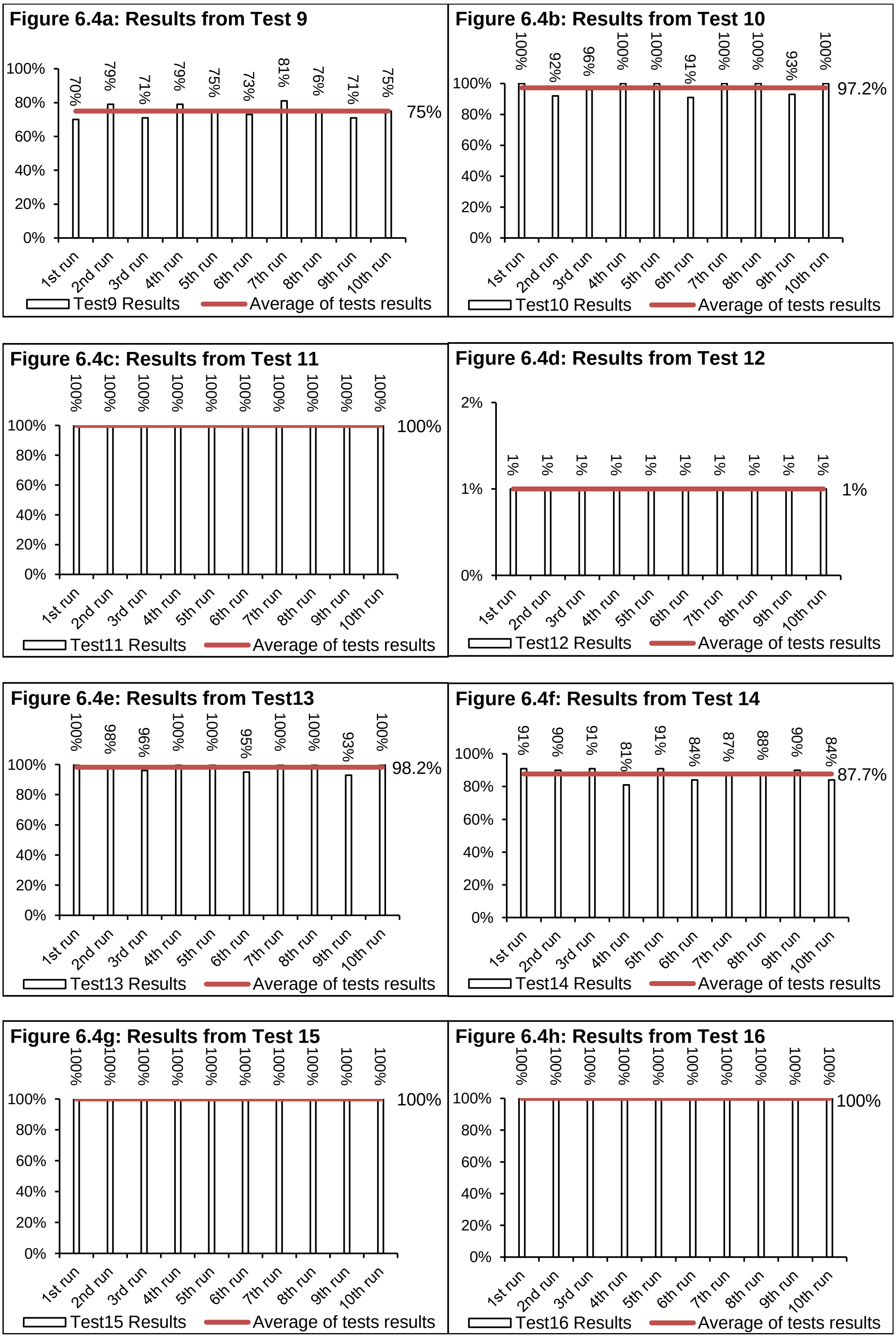


Figure 6.4: Penetration Tests Results for Tests 9-16 Performed on Axis2-1.5.1 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

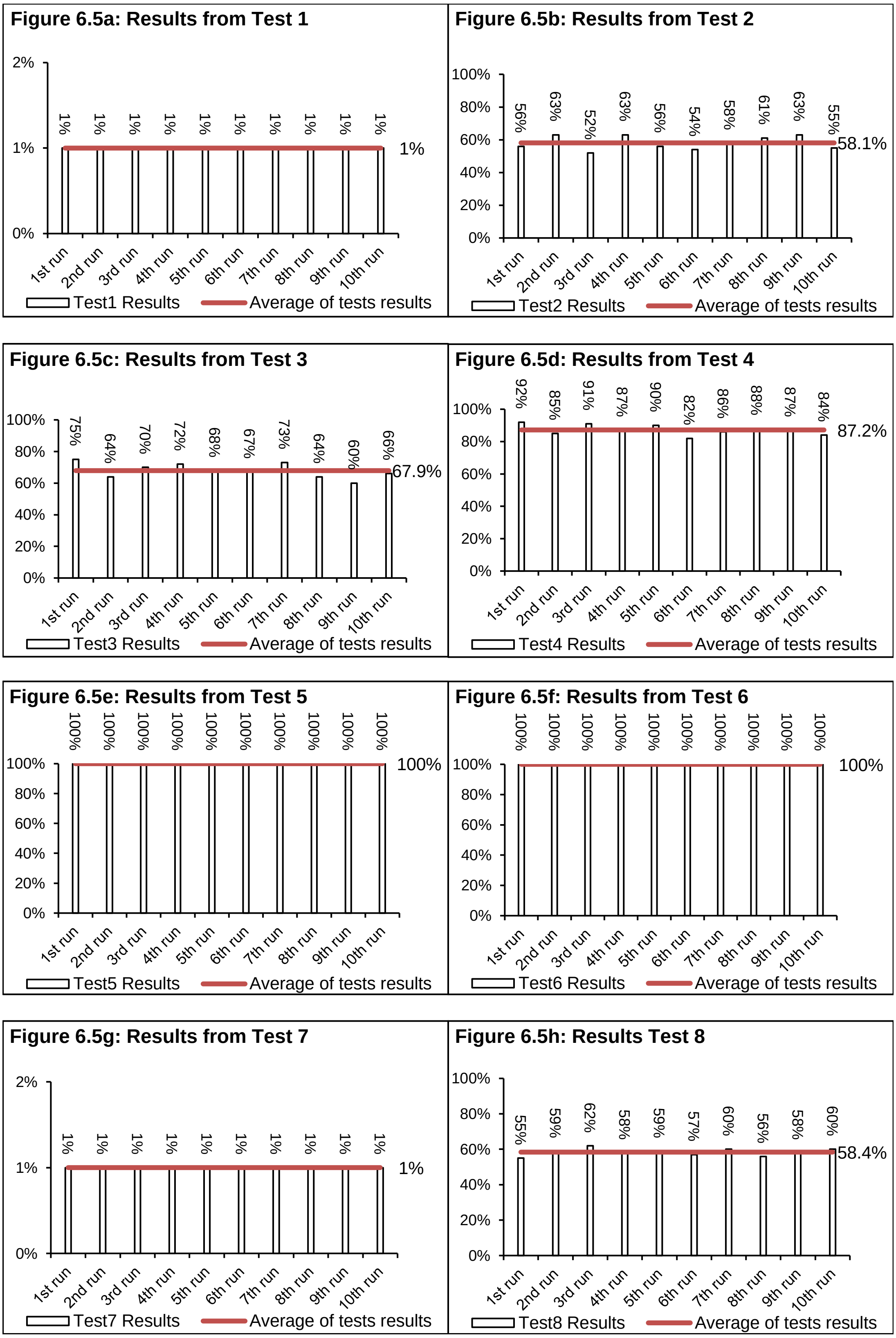


Figure 6.5: Penetration Tests Results for Tests 1-8 Performed on Axis2-1.6.1 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

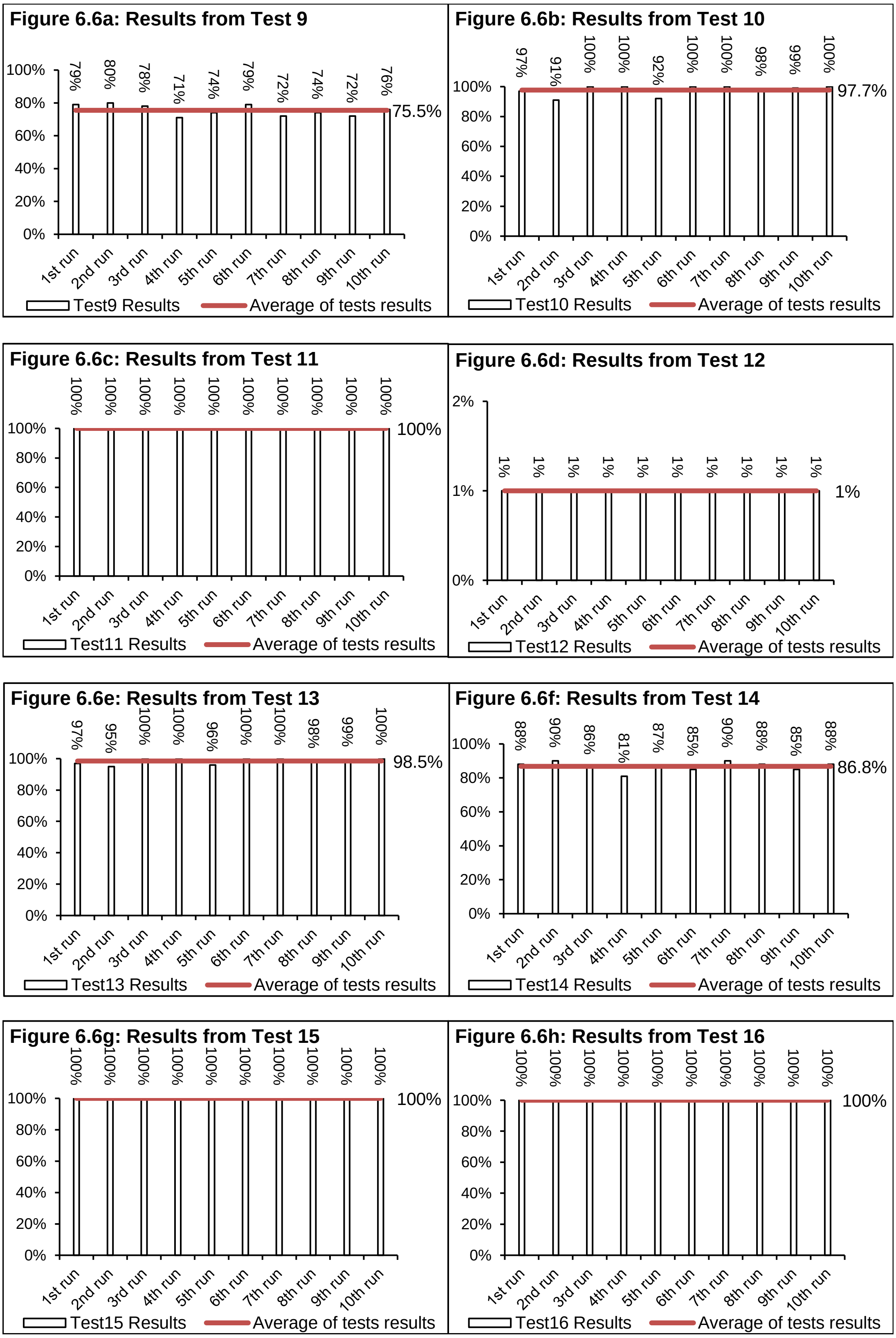


Figure 6.6: Penetration Tests Results for Tests 9-16 Performed on Axis2-1.6.1 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

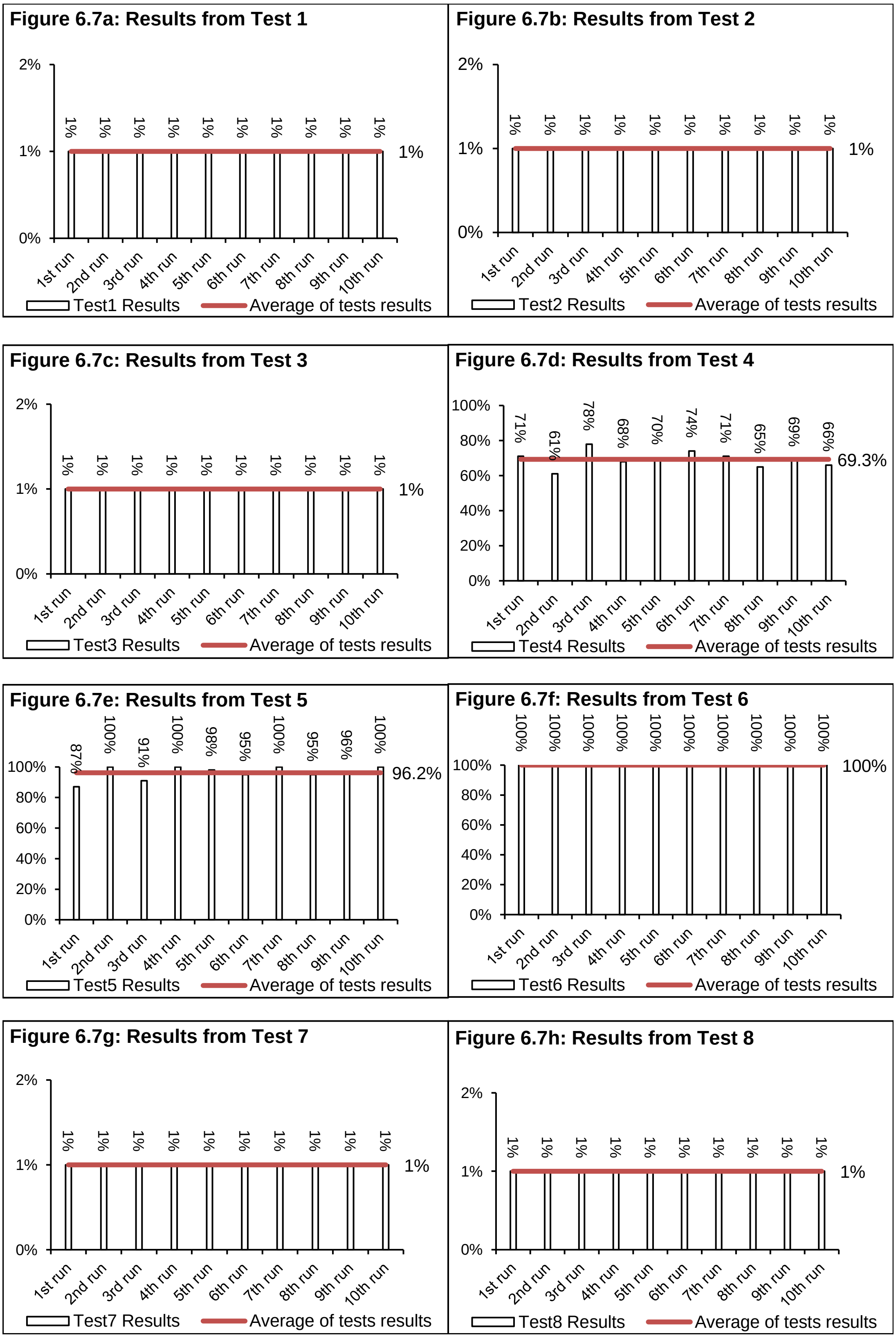


Figure 6.7: Penetration Tests Results for Tests 1-8 Performed on CXF-2.3.10 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

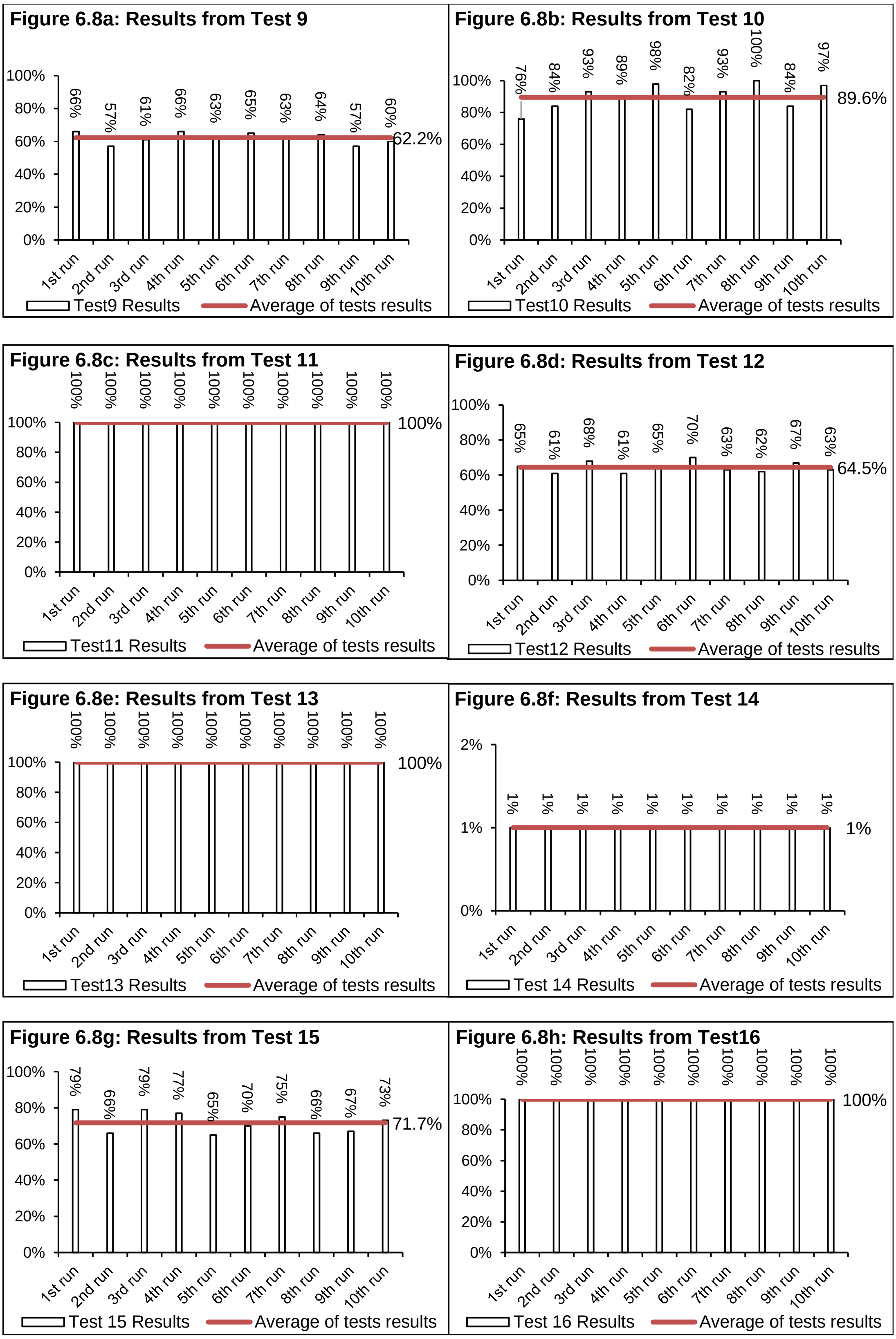


Figure 6.8: Penetration Tests Results for Tests 9-16 Performed on CXF-2.3.10 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

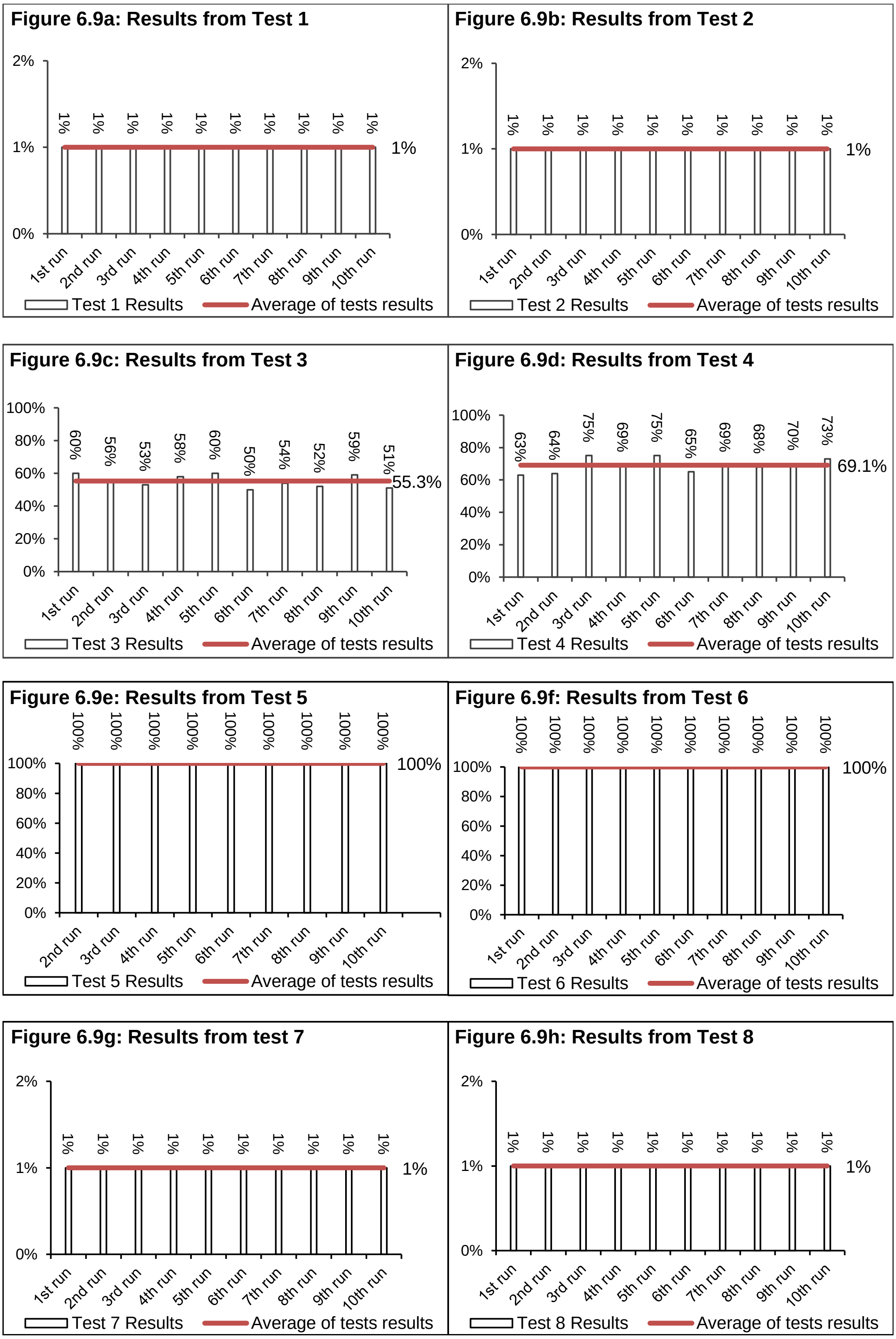


Figure 6.9: Penetration Tests Results for Tests 1-8 Performed on CXF-2.5.11 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

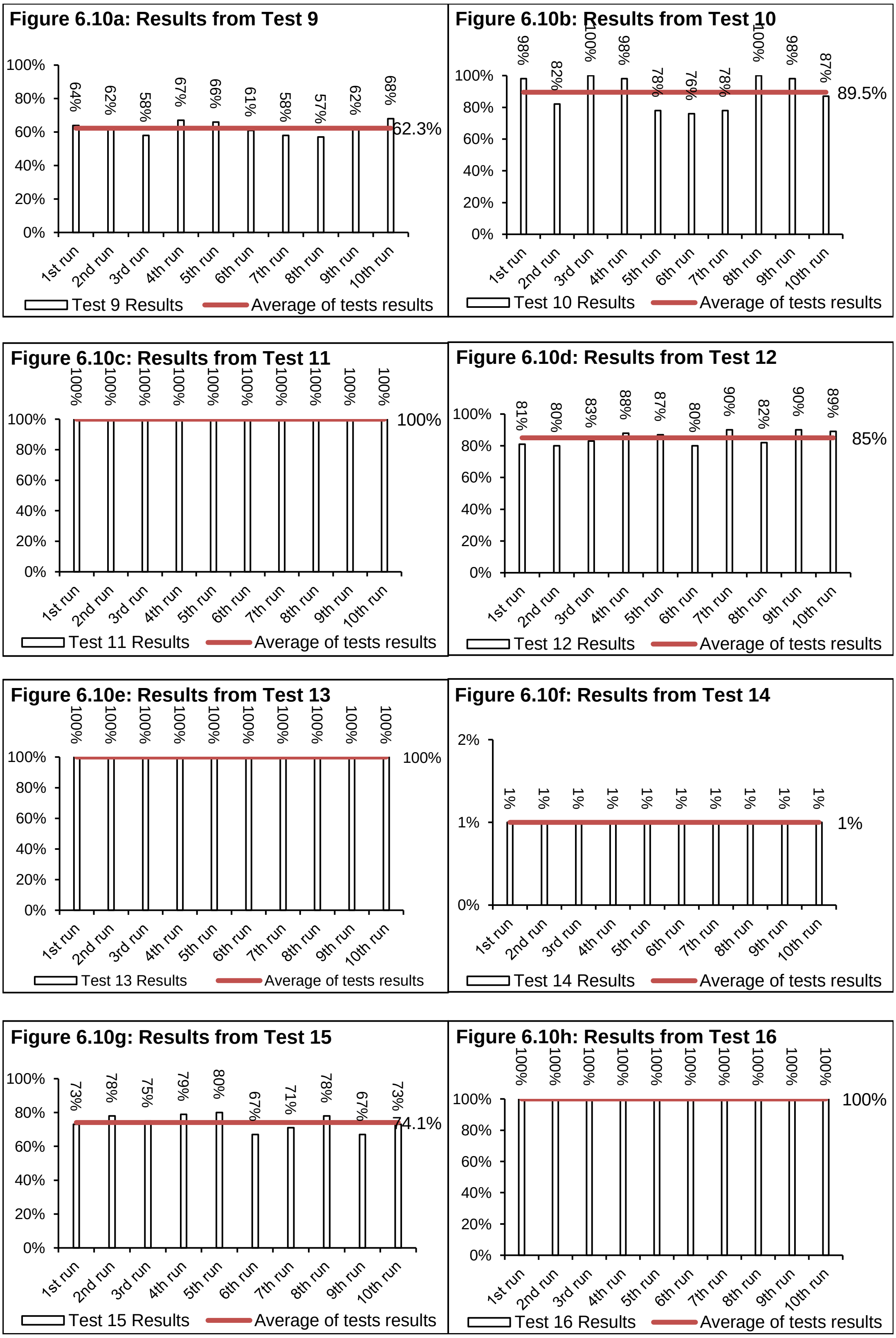


Figure 6.10: Penetration Tests Results for Tests 9-16 Performed on CXF-2.5.11 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

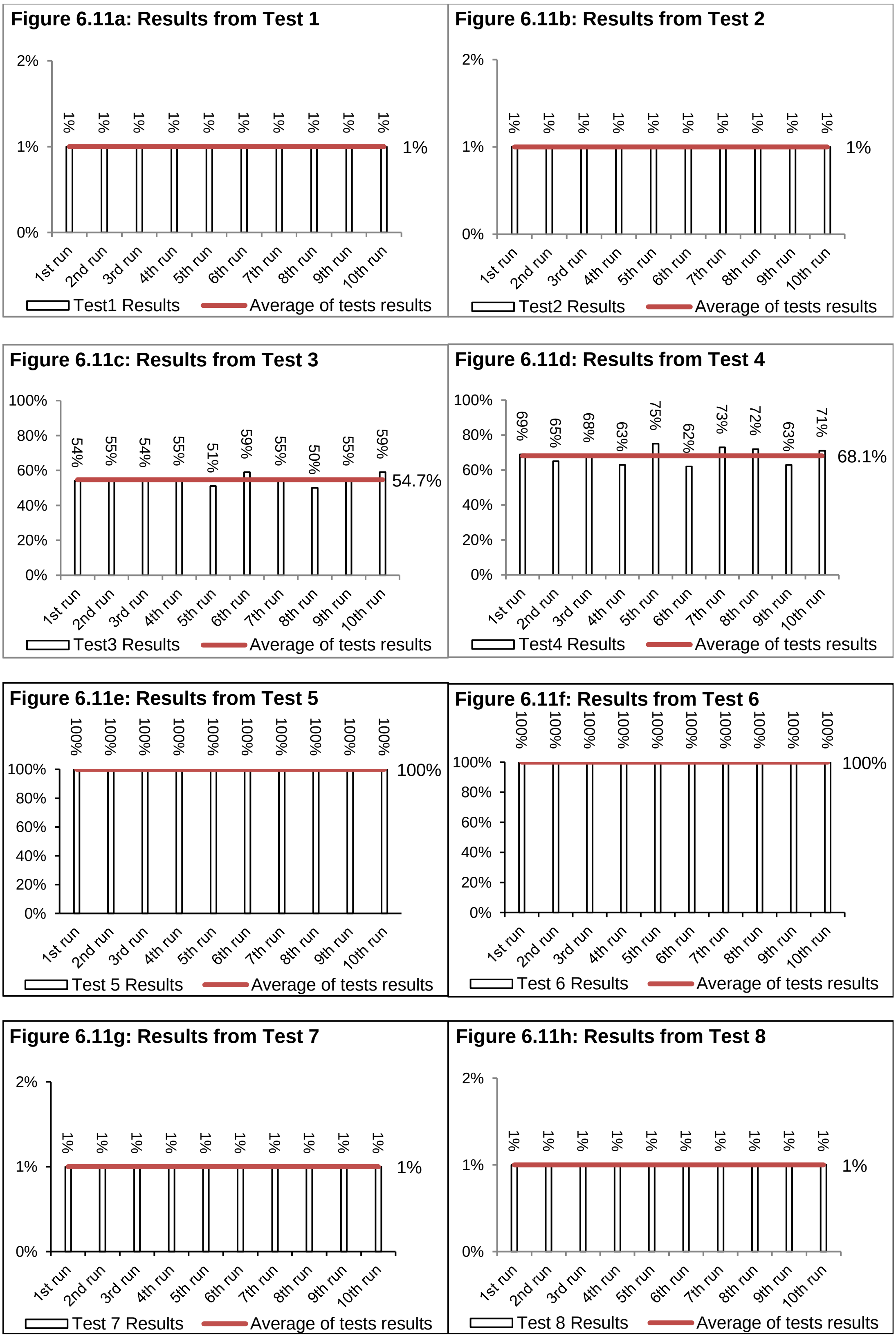


Figure 6.11: Penetration Tests Results for Tests 1-8 Performed on CXF-2.6.3 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

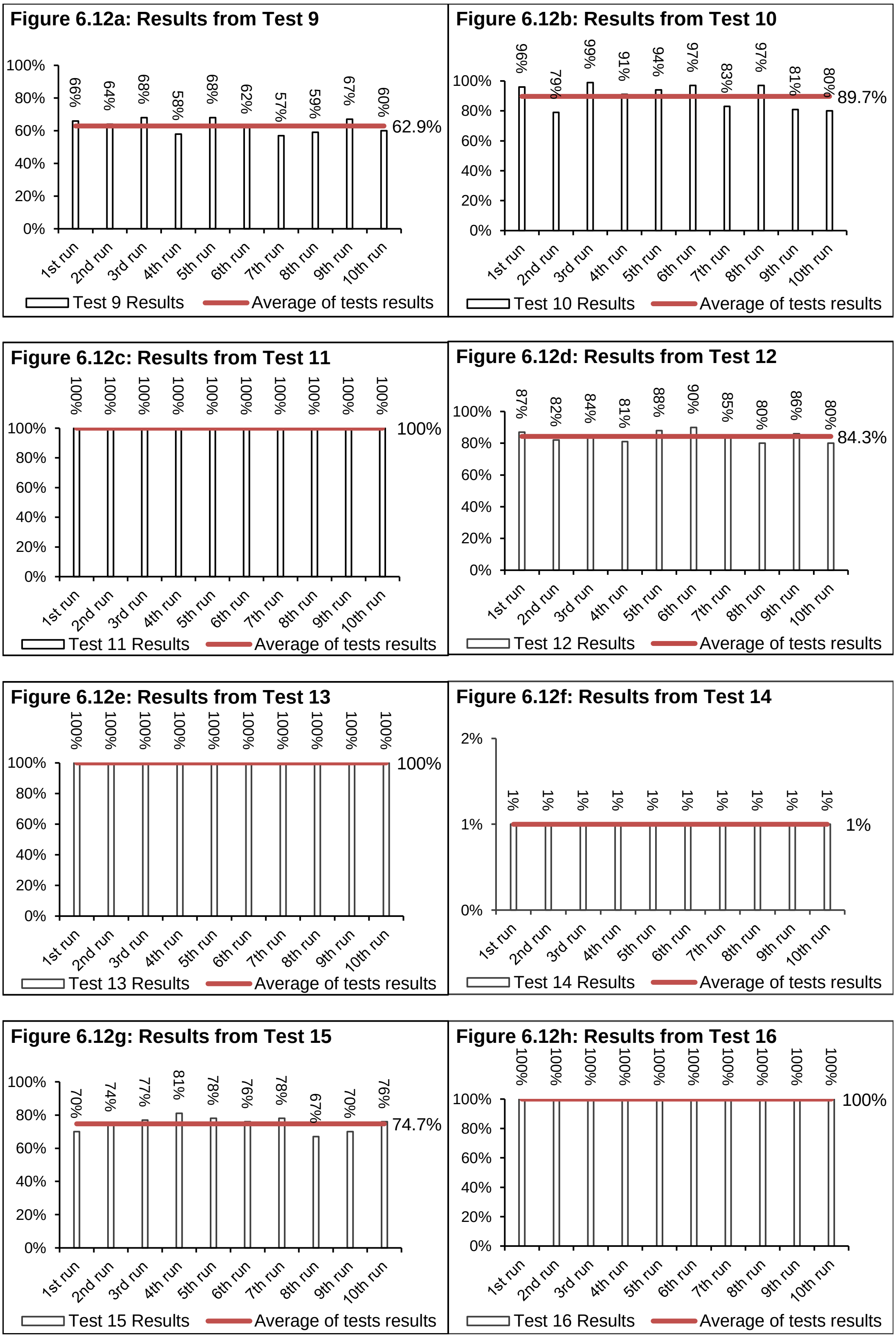


Figure 6.12: Penetration Tests Results for Tests 9-16 Performed on CXF-2.6.3 WS for information about each test and WS see Table 6.1 and Section 6.1.1, respectively

6.1.6 Principal Components Analysis of Candidate WS's Penetration Test Results

The objective of the service selection framework in this dissertation is to select group of *OTSWSs* with security vulnerabilities diversity (identified through penetration testing) for implementation of *ITWS*. To facilitate this service selection approach, *OTSWSs* should be divided into a number of groups according to their security vulnerabilities similarity, so that *ITWS* can be formed using services selected from these diverse groups.

Division of the *OTSWSs* can be achieved through *CA*. However, most *CA* algorithms cannot deal with data with high dimensionality (e.g., in the case of the proposed service selection framework, more than one *OTSWSs* each with various penetration test results) [86]. Hence, dimensionality reduction is important in *CA*, which reduces the computational costs and provides users with visual examination of the data. However, it causes loss of information. One practical approach for dimensionality reduction is to extract important components from the original data, which can contribute to forming the clusters [86].

PCA is one of the typical dimensionality reduction approaches, which is mainly used to reduce the dimensionality of the dataset while retaining the maximum information. Also, it is a common technique for finding patterns in data of high dimensions. Consequently, Principal Components (*PCs*) may be used as inputs for *CA*.

This section explains the steps for finding *PCs* of the *WSs'* penetration test results, obtained in Section 6.1.5. It also demonstrates the effectiveness of *PCA* in reducing the computational complexity of *CA* in the proposed service selection approach.

Step1: Collecting the Dataset

The first step in *PCA* is about collecting the dataset (e.g., observations in an experiment). In this work, the input to the *PCA* is the penetration test results of the *WSs* from Section 6.1.5, which has 16x6 dimensions (sixteen penetration test results for each of the six *WSs*). Table 6.2 and Figure 6.13 show the tabular and graphical representations of this data, respectively.

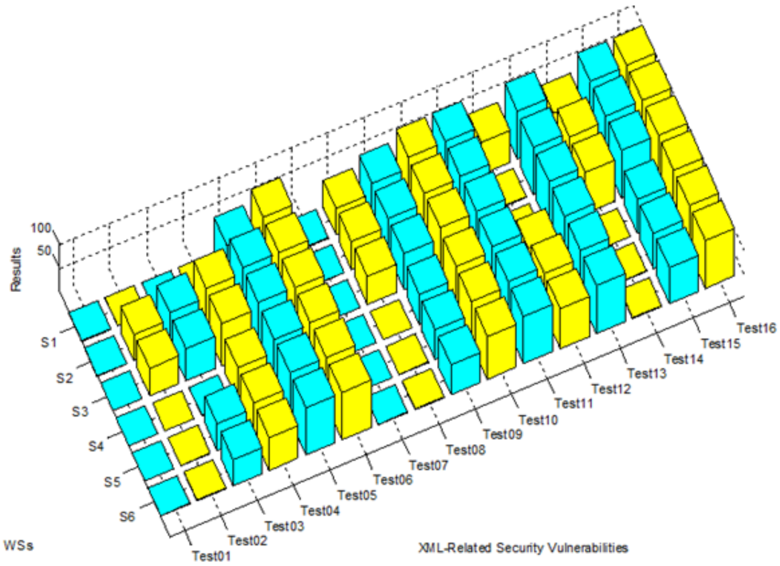


Figure 6.13: Plot of Candidate WSs' Penetration Tests Results, to be used as PCA inputs (for information about each test and WS see Table 6.1 and Section 6.1.1, respectively)

Step2: Subtracting the Mean

For *PCA* to work properly, the mean (the average across each data dimension) should be subtracted from each of the data dimensions to ensure that the first *PC* describes the direction of maximum variance, which eliminates misleading directions. The mean matrix (average of each test's results) and mean adjusted penetration test results are presented in Tables 6.3 and 6.4, respectively.

Step3: Calculating the Covariance Matrix

PCA uses correlation/covariance matrices of the original variables to find new directions. In literature, a number of authors prefer to use correlation matrix to find principal components [102]. However, the general rule of thumb is to use correlation matrix if the variables are of different units (scale) as it standardises the data (see [97] for further information and examples). Since in this case study the penetration test results are of the same unit, the covariance matrix (presented in Table 6.5) is used for *PCA* calculation, and it is worked out using mean adjusted penetration test results (from Table 6.4) and *MATLAB's cov()* command.

Table 6.2: WSs' Penetration Test Results to be used as PCA input (for information about each test and WS see Table 6.1 and Section 6.1.1, respectively)

	Test1	Test2	Test3	Test4	Test5	Test6	Test7	Test8	Test9	Test10	Test11	Test12	Test13	Test14	Test15	Test16
S1	1	1	1	1	73.8	100	1	56	75.5	98.6	100	66.5	100	64.7	100	100
S2	1	55.5	68.7	87.4	100	100	1	59.2	75	97.2	100	1	98.2	87.7	100	100
S3	1	58.1	67.9	87.2	100	100	1	58.4	75.5	97.7	100	1	98.5	86.8	100	100
S4	1	1	1	69.3	96.2	100	1	1	62.2	89.6	100	64.5	100	1	71.7	100
S5	1	1	55.3	69.1	100	100	1	1	62.3	89.5	100	85	100	1	74.1	100
S6	1	1	54.7	68.1	100	100	1	1	62.9	89.7	100	84.3	100	1	74.7	100

Table 6.3: Mean Matrix of the Penetration Test Results

Average of Test1 results	Average of Test2 results	Average of Test3 results	Average of Test4 results	Average of Test5 results	Average of Test6 results	Average of Test7 results	Average of Test8 results	Average of Test9 results	Average of Test10 results	Average Test11 results	Average Test12 results	Average Test13 results	Average Test14 results	Average Test15 results	Average Test16 results
1.0000	19.6000	41.4333	63.6833	95.0000	100.00	1.0000	29.4333	68.9000	93.7167	100.00	50.3833	99.4500	40.3667	86.7500	100.0000
1.0000	19.6000	41.4333	63.6833	95.0000	100.00	1.0000	29.4333	68.9000	93.7167	100.00	50.3833	99.4500	40.3667	86.7500	100.0000
1.0000	19.6000	41.4333	63.6833	95.0000	100.00	1.0000	29.4333	68.9000	93.7167	100.00	50.3833	99.4500	40.3667	86.7500	100.0000
1.0000	19.6000	41.4333	63.6833	95.0000	100.00	1.0000	29.4333	68.9000	93.7167	100.00	50.3833	99.4500	40.3667	86.7500	100.0000
1.0000	19.6000	41.4333	63.6833	95.0000	100.00	1.0000	29.4333	68.9000	93.7167	100.00	50.3833	99.4500	40.3667	86.7500	100.0000
1.0000	19.6000	41.4333	63.6833	95.0000	100.00	1.0000	29.4333	68.9000	93.7167	100.00	50.3833	99.4500	40.3667	86.7500	100.0000

Table 6.4: Mean Adjusted Penetration Test Results

Test1 - Average of Test1 results	Test2 - Average of Test2 results	Test3 - Average of Test3 results	Test4 - Average of Test4 results	Test5 - Average of Test5 results	Test6 - Average of Test6 results	Test7 - Average of Test7 results	Test8 - Average of Test8 results	Test9 - Average of Test9 results	Test10 - Average of Test10 results	Test11 - Average of Test11 results	Test12 - Average of Test12 results	Test13 - Average of Test13 results	Test14 - Average of Test14 results	Test15 - Average of Test15 results	Test16 - Average of Test16 results
0	-18.6	-40.4333	-62.6833	-21.2	0	0	26.5667	6.6	4.8833	0	16.1167	0.55	24.3333	13.25	0
0	35.9	27.2667	23.7167	5	0	0	29.7667	6.1	3.4833	0	-49.3833	-1.25	47.3333	13.25	0
0	38.5	26.4667	23.5167	5	0	0	28.9667	6.6	3.9833	0	-49.3833	-0.95	46.4333	13.25	0
0	-18.6	-40.4333	5.6167	1.2	0	0	-28.4333	-6.7	-4.1167	0	14.1167	0.55	-39.3667	-15.05	0
0	-18.6	13.8667	5.4167	5	0	0	-28.4333	-6.6	-4.2167	0	34.6167	0.55	-39.3667	-12.65	0
0	-18.6	13.2667	4.4167	5	0	0	-28.4333	-6	-4.0167	0	33.9167	0.55	-39.3667	-12.05	0

Table 6.5: Covariance Matrix of the Mean Adjusted Penetration Test Results

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.831	0.5995	0.5271	0.1116	0	0	0.6553	0.1419	0.0835	0	-1.1022	-0.0245	1.0462	0.2957	0
0	0.5995	1.0164	0.742	0.2426	0	0	0.1765	0.0348	0.0115	0	-0.5892	-0.0178	0.4119	0.0899	0
0	0.5271	0.742	1.025	0.3242	0	0	-0.1435	-0.0427	-0.0387	0	-0.5852	-0.0156	0.0162	-0.0822	0
0	0.1116	0.2426	0.3242	0.1102	0	0	-0.1176	-0.0295	-0.0225	0	-0.0952	-0.0033	-0.0976	-0.058	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0.6553	0.1765	-0.1435	-0.1176	0	0	0.9713	0.2194	0.14	0	-0.9645	-0.0194	1.3517	0.4521	0
0	0.1419	0.0348	-0.0427	-0.0295	0	0	0.2194	0.0498	0.0319	0	-0.2095	-0.0042	0.3031	0.1025	0
0	0.0835	0.0115	-0.0387	-0.0225	0	0	0.14	0.0319	0.0205	0	-0.1261	-0.0024	0.191	0.0655	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	-1.1022	-0.5892	-0.5852	-0.0952	0	0	-0.9645	-0.2095	-0.1261	0	1.537	0.0326	-1.4984	-0.4308	0
0	-0.0245	-0.0178	-0.0156	-0.0033	0	0	-0.0194	-0.0042	-0.0024	0	0.0326	0.0007	-0.031	-0.0087	0
0	1.0462	0.4119	0.0162	-0.0976	0	0	1.3517	0.3031	0.191	0	-1.4984	-0.031	1.9276	0.6259	0
0	0.2957	0.0899	-0.0822	-0.058	0	0	0.4521	0.1025	0.0655	0	-0.4308	-0.0087	0.6259	0.2117	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.6: Eigenvectors for the Covariance Matrix of the Mean Adjusted Penetration Test Results

0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0.0339	0.0174	-0.0362	0.1167	0	0	0	0	0.0006	-0.1694	-0.0402	-0.2966	-0.8257	-0.0988	-0.1697	0.3807
-0.1008	-0.0308	-0.1167	0.0391	0	0	0	0	0.0001	0.0452	-0.1483	0.1586	0.0608	0.7843	-0.5047	0.2256
0.2816	0.1795	0.0716	-0.1005	0	0	0	0	-0.0005	0.273	0.2111	-0.322	0.289	-0.33833	-0.6572	0.143
-0.1041	-0.1006	0.6527	-0.2149	0	0	0	0	-0.0003	-0.6069	0.1838	0.2198	0.0305	-0.04	-0.2315	0.0152
0	0	0	0	0.9855	0.1696	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0.1696	-0.9855	0	0	0	0	0	0	0	0	0	0
0.1848	0.4519	0.3634	-0.0884	0	0	0	0	-0.0003	-0.0378	-0.4979	-0.2606	0.2091	0.1362	0.3125	0.3803
-0.2299	0.5635	0.2689	0.1189	0	0	0	0	0.0007	0.4139	0.3973	0.3895	-0.2186	0.041	0.0762	0.0839
-0.085	-0.0802	-0.0784	-0.9334	0	0	0	0	-0.005	0.2485	-0.0401	0.0497	-0.1915	0.0249	0.056	0.0513
0	-0.0004	0.0011	0.0052	0	0	0	0	-1	0	0.0001	0	0	0	0	0
0.1904	0.1146	0.1894	-0.068	0	0	0	0	-0.0002	-0.005	0.3341	-0.5359	-0.1456	0.4571	0.0989	-0.5209
-0.0097	-0.5628	0.5519	0.1743	0	0	0	0	0.0017	0.5402	-0.2088	-0.0437	-0.1033	0.0028	0.005	-0.0113
-0.2173	-0.2832	-0.0499	0.009	0	0	0	0	0.0002	-0.0083	0.5401	-0.2829	0.2522	0.1238	0.3032	0.5722
0.849	-0.1346	-0.0192	-0.0155	0	0	0	0	0	-0.0025	0.2094	0.379	-0.0798	0.1176	0.1502	0.1742
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

Table 6.7: Ordered Eigenvalues

5302.7	2021.2	376.3	0.9	0.1	0	0	0	0	0	0	0	0	0	0	0

Table 6.8: Ordered Eigenvectors

0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0.3807	-0.1697	-0.0988	-0.8257	-0.2966	0.0339	-0.0402	0.0174	-0.1694	-0.0362	0.1167	0.0006	0	0	0	0
0.2256	-0.5047	0.7843	0.0608	0.1586	-0.1008	-0.1483	-0.0308	0.0452	-0.1167	0.0391	0.0001	0	0	0	0
0.1433	-0.6572	-0.3383	0.289	-0.322	0.2816	0.2111	0.1795	0.273	0.0716	-0.1005	-0.0005	0	0	0	0
0.0152	-0.2315	-0.04	0.0305	0.2198	-0.1041	0.1838	-0.1006	-0.6069	0.6527	-0.2149	-0.0003	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0.9855	0.1696	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0.1696	-0.9855	0	0
0.3803	0.3125	0.1362	0.2091	-0.2606	0.1848	-0.4979	0.4519	-0.0378	0.3634	-0.0884	-0.0003	0	0	0	0
0.0839	0.0762	0.041	-0.2186	0.3895	-0.2299	0.3973	0.5635	0.4139	0.2689	0.1189	0.0007	0	0	0	0
0.0513	0.056	0.0249	-0.1915	0.0497	-0.085	-0.0401	-0.0802	0.2485	-0.0784	-0.9334	-0.005	0	0	0	0
0	0	0	0	0	0	0.0001	-0.0004	0	0.0011	0.0052	-1	0	0	0	0
-0.5209	0.0989	0.4571	-0.1456	-0.5359	0.1904	0.3341	0.1146	-0.005	0.1894	-0.068	-0.0002	0	0	0	0
-0.0113	0.005	0.0028	-0.1033	-0.0437	-0.0097	-0.2088	-0.5628	0.5402	0.5519	0.1743	0.0017	0	0	0	0
0.5722	0.3032	0.1238	0.2522	-0.2829	-0.2173	0.5401	-0.2832	-0.0083	-0.0499	0.009	0.0002	0	0	0	0
0.1742	0.1502	0.1176	-0.0798	0.379	0.849	0.2094	-0.1346	-0.0025	-0.0192	-0.0155	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 6.9: Calculated Principal Components

PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15	PC16
-6.770	89.713	8.129	-0.009	-0.004	0	0	0	0	0	0	0	0	0	0	0
90.429	-15.185	-1.152	1.443	0.082	0	0	0	0	0	0	0	0	0	0	0
90.454	-15.547	-2.15	-1.439	-0.081	0	0	0	0	0	0	0	0	0	0	0
-59.471	-2.828	-36.263	0.029	-0.001	0	0	0	0	0	0	0	0	0	0	0
-57.446	-28.594	15.897	0.208	-0.533	0	0	0	0	0	0	0	0	0	0	0
-57.195	-27.556	15.545	-0.232	0.539	0	0	0	0	0	0	0	0	0	0	0

Step4: Calculating the Eigenvectors and Eigenvalues of the Covariance Matrix

Eigenvectors and eigenvalues are important, as they provide useful information (e.g., patterns in the data) about the dataset. In this case study, they are worked out using covariance matrix of the mean adjusted penetration test results (from Table 6.5) and following *MATLAB's* command:

```
[eigenvector,eigenvalue] = eig(covarience_matrix);
```

The calculated eigenvectors are presented in Table 6.6. In general, to order the *PCs* according to their significance, the eigenvalues should be sorted in descending order. The ordered eigenvalues should be used to sort the eigenvectors. The ordered eigenvalues and eigenvectors are presented in Tables 6.7 and 6.8, respectively and are calculated using following *MATLAB's* commands:

```
% sorting eigenvalues in descending order
[sorted_eigenvalue,index]=sort(-abs(diag(eigenvalue)));
% sorting eigenvectors using eigenvalues
sorted_eigenvector=eigenvector(:,index);
```

Step5: Calculating the PCs

PCs are the outputs of the *PCA* and are a set of linearly uncorrelated variables created from the original observation values. In this case study, they are calculated from the multiplication of the ordered eigenvectors (from Table 6.8) and mean adjusted penetration test results (from Table 6.4) and are presented in Table 6.9.

Step6: Choosing the PC's

This is the final step in *PCA* where the dimensionality reduction takes place. At this stage, the *PCs* with lesser significance can be ignored. There are some common rules of thumb to choose the number of *PCs* while retaining maximum information:

1. The first common rule is to choose the smallest number of *PCs* such that the desired percentage of explained variation is exceeded [102]. The total variance is the sum of variances of all *PCs* and the variance explained by a *PC* is the ratio between the cumulative variance of that *PC* and the total variance. For example, in this case study, the percentage of variance explained by *PC1* and *PC2* can be calculated as follows:

$$variance\ of\ PC1 = 5302.655$$
$$variance\ of\ PC2 = 2021.133$$
$$total\ variances\ of\ all\ PCs = 7701.035$$
$$percentage\ of\ variance\ explained\ by\ PC1 = \frac{5302.655}{7701.035} * 100 = 68.86\%$$
$$percentage\ of\ variance\ explained\ by\ PC2 = \frac{5302.655 + 2021.133}{7701.035} * 100 = 95.10\%$$

2. The second common approach is to use a *scree graph*, in which the eigenvalues are plotted against their respective component numbers. The number of *PCs* is then chosen so that the line in the *scree graph* is “steep” to its left but not to its right (*elbow* point) since the remaining eigenvalues (on the right-hand side of the *elbow* point) are relatively small and all about the same size [102].

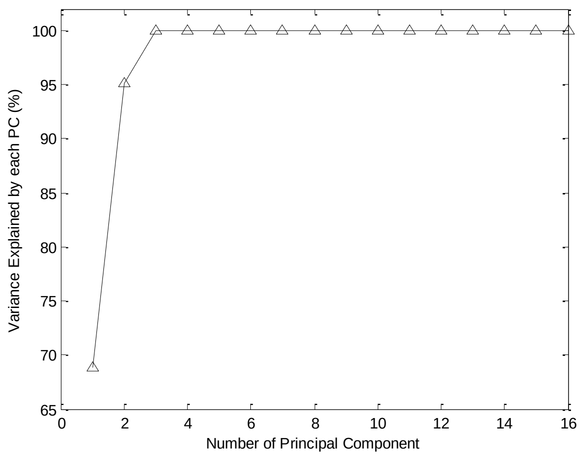


Figure 6.14: Variance Explained by each PC

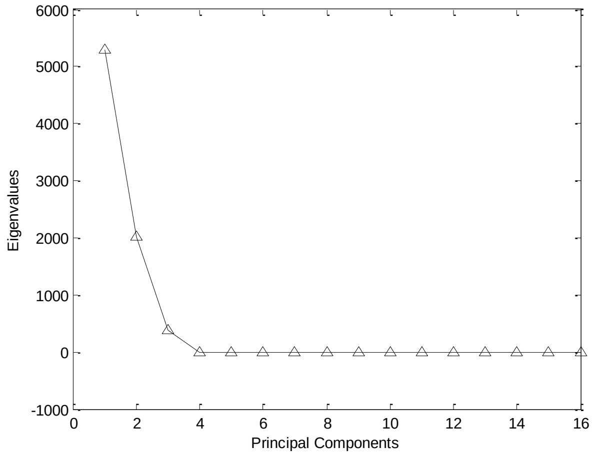


Figure 6.15: Scree Graph

Figures 6.14 and 6.15 illustrate the plots of the percentage of variance explained by each *PC* (from Table 6.9) and *scree graph* for this case study, respectively. As presented in Figure 6.14, the first three *PCs* have about 100% of the variations in the penetration test results. Hence, they are selected as inputs to *CA*.

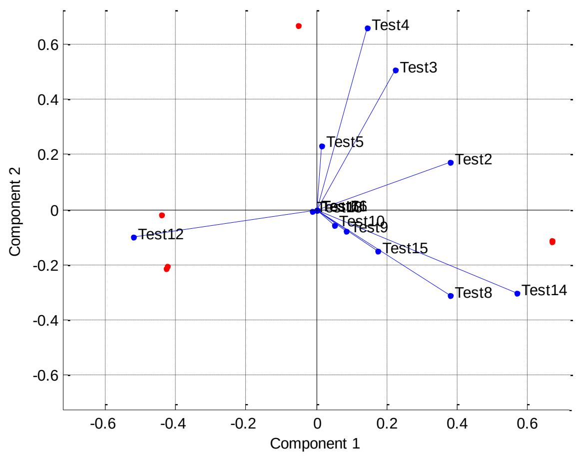


Figure 6.16: The WSs' Original Penetration Test Results against the First Two *PCs*

Recall from Section 2.5 that sometimes in literature *PCA* is employed to reduce the dimensions of the dataset before *CA*, hoping to reduce the running time for *CA's* computation using a fewer number of *PCs*. Figure 6.16 illustrates the plot of the original penetration test results of the *WSs,* in this case study, against the first two calculated *PCs* (from Table 6.9), which have about 95% of the variations in penetration test results (see Figure 6.14). The projections of the penetration test results on the first *PC* (the vertical axis) and the second *PC* (the horizontal axis) clearly highlight the separation between two clusters in the data, in each case (three clusters in total). It shows that *PCA* has successfully identified the patterns among this 16x6 dimension dataset. Hence, based on this information, the first three *PCs* (containing the majority of variations in penetration test results as explained previously) can be divided into three groups using *CA* (see next section).

6.1.7 Cluster Analysis based on Principal Component Analysis Results

As discussed previously, *CA* enables splitting up the data into a certain number of clusters, based on their similarities or dissimilarities [86]. Clustering approaches can be divided into two main groups of hierarchical and partitional [86]. The hierarchical approach groups data objects after a sequence of partitions, either from singleton clusters to a cluster containing all data objects or vice versa, while partitional clustering directly divides data objects into some pre-specified number of clusters without any hierarchical structure [86]. The hierarchical approaches are not suitable for large-scale datasets due to their quadratic computational complexities in both execution time and storage space [86]. However, *K*-means algorithm is linear in the number of data objects and for the same amount of data it will take much less amount of computational time [86]. Hence, in this framework, *K*-means is adopted as *CA* algorithm.

One of the issues in *CA* is to determine the number of clusters, which is called “the fundamental problem of cluster validity” by Dubes [126]. However, in this framework, the number of clusters are selected through *PCA* on the penetration test results of the *OTSWSs* (as presented in the previous section) and such that 2*f*+1 (2*f*+1 replicas can tolerate *f* simultaneous faults) *fault-tolerance* condition is satisfied (enabling majority voting).

In this case study, the selected *PCs* are split up into three clusters (see the previous section for further information) using following *MATLAB’s* commands:

```
first_three_pcs = [ -6.7709   89.7131    8.1297
                    90.4291  -15.1858   -1.1527
                    90.4547  -15.5472   -2.1560
                   -59.4717   -2.8288  -36.2632
                   -57.4461  -28.5946   15.8972
                   -57.1951  -27.5567   15.5451];
[idx,C,sumd,D] = kmeans(first_three_pcs,3);
```

In the above *MATLAB* command *idx* vector, *C* matrix, *sumd* vector and *D* matrix contain cluster indices for each *WS*, centroid location of each cluster, within-cluster sums of point-to-centroid distances and distances of each *WS* to every cluster's centroid, respectively.

The result of *WSs* clustering based on their security vulnerabilities diversity and the distances of each *WS* to the centre of each cluster are shown in Tables 6.10 and 6.11, respectively.

Table 6.10: Results of CA on selected PCs

WS	Cluster
S1	3
S2	1
S3	1
S4	2
S5	2
S6	2

Table 6.11: Distance between Each WS and the Cluster Centres (in 1.0e+04 scales)

WS	Cluster 1	Cluster 2	Cluster 3
S1	2.0588	1.4686	0.0000
S2	0.0000	2.2063	2.0538
S3	0.0000	2.2067	2.0638
S4	2.3829	0.1486	1.3312
S5	2.2354	0.0387	1.6625
S6	2.2241	0.0357	1.6350

Recall that the objective of the service selection framework in this dissertation is to select group of *OTSWSs* with security vulnerabilities diversity (identified through penetration testing) for implementation of *ITWS*. And to facilitate this service selection approach, *OTSWSs* should be clustered according to their security vulnerabilities similarity, so that groups of services with security vulnerabilities diversity can be formed based on services selected from these clusters (one service from each of the resultant clusters).

Hence, using the *CA* results presented in Table 6.10, the *WSs'* are grouped such that each group consists of one service from each of the clusters:

- **Group1:** S1, S2 and S4
- **Group2:** S1, S2 and S5
- **Group3:** S1, S2 and S6
- **Group4:** S1, S3 and S4
- **Group5:** S1, S3 and S5
- **Group6:** S1, S3 and S6

The next section explains the process of ordering these groups according to their overall security vulnerabilities.

6.1.8 WS-Groups Ordering using Penetration Testing

The final step in this service selection framework is about performing penetration testing on each group of services to identify their overall security vulnerabilities and using this information to order the groups so that the *ITWS* could be started with the most secure group and switch to the next group if the first group fails and so on.

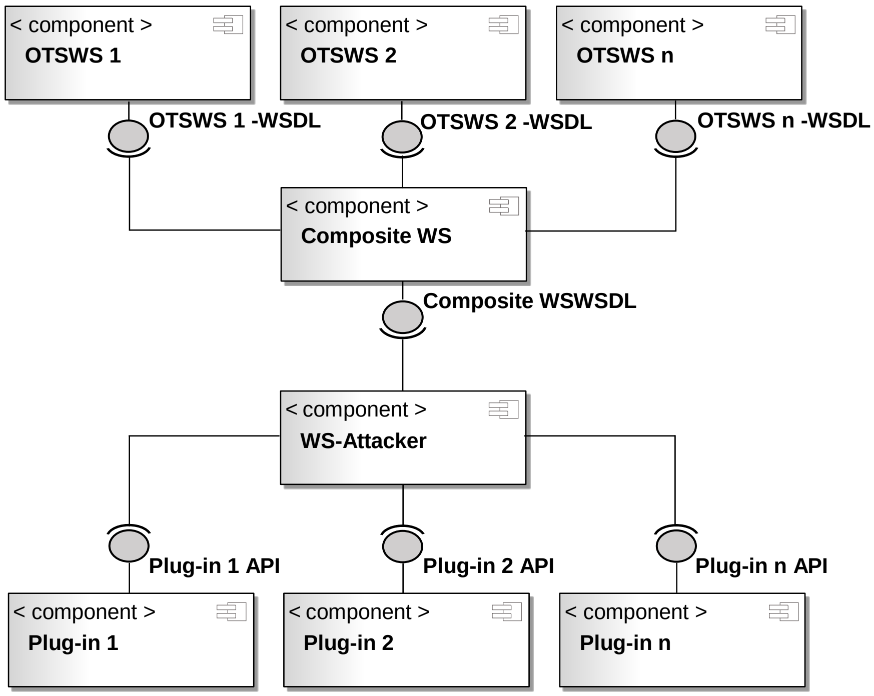


Figure 6.17: Component Diagram for Penetration Testing Each Group of WSs

Figure 6.17 shows the component diagram for this step indicating that the *ITWS* (called *CompositeWS* in this figure) and *WS-Attacker* consist of *OTSWSs* and attack plugins, respectively and that the *ITWS* can be tested through *WS-Attacker's* interface.

Each *WS*-group is developed through the composition of their associated *WSs,* using *BPEL* 2.0 plugin for *Eclipse Neon*.2 4.6.2. And is deployed on *Apache* 1.3.4 runtime (on top of *Tomcat* 5.5.26 server) running on the same machine that is hosting the *WSs* (*Intel*® *Core*™ i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System). The operation of these *WS*-groups was as follows:

1. Receives client's request.
2. Passes the client's request to each of the parallel invocation processes (each process invocates one of the three *WSs* associated with the group).
3. Each concurrent invocation process invokes its associated *WS*.
4. The business process replies to the client once a response is returned from each of the invoked *WSs*.

For ordering the *WS*-groups, *Coercive Parsing, DJBX31A Hash Collision, and XML Attribute Count* attacks are performed on each group. Table 6.12 presents the *WS-Attacker's* settings for each of these tests. In these tests, the attack element was either plotted in the header or the body of the test *SOAP* message as presented in Message 5.1 and Message 5.2, respectively.

Table 6.12: WS-Attacker's Settings

Test ID	Test Message Settings	***WS-Attacker's*** **other Settings**
Test 1	Coercive Parsing attack with 20,000 open tags plotted in the header of the SOAP message	2 parallel attack threads, 4 requests per thread, 9999 milliseconds between every testprobe request, 750 milliseconds between every attack request, 4 seconds server recovery time, 5 seconds stop after the last tampered request
Test 2	DJBX31A Hash Collision attack with 4,000 paired keys/values plotted in the body of the SOAP message	
Test 3	XML Attribute Count attacks with 60,000 paired keys/values plotted in the body of the SOAP message	

Figures 6.18-6.23 show the penetration test results for test attacks performed on these groups.

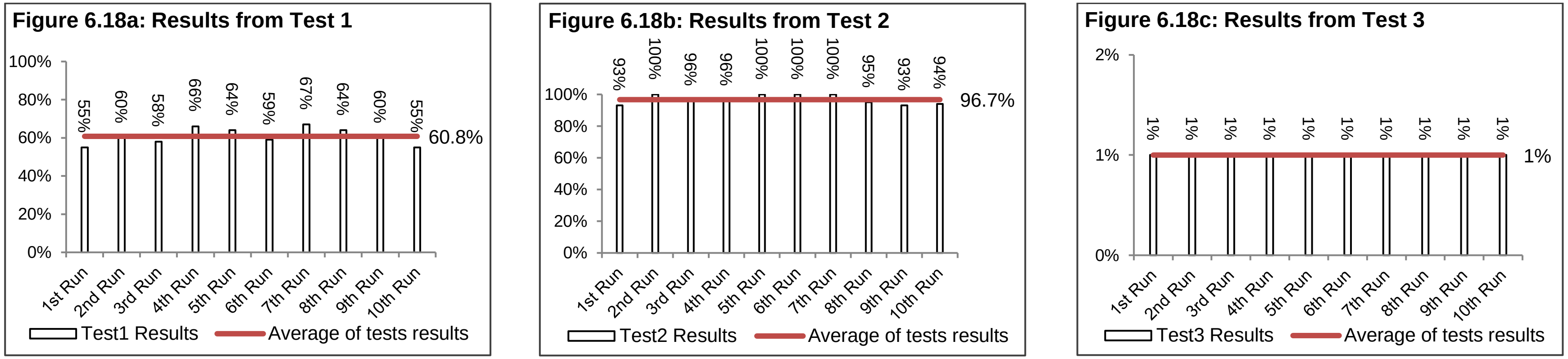


Figure 6.18: Penetration Test Results for WS-Group1 (for information about each test and WS-group see Table 6.12 and Section 6.1.7, respectively)

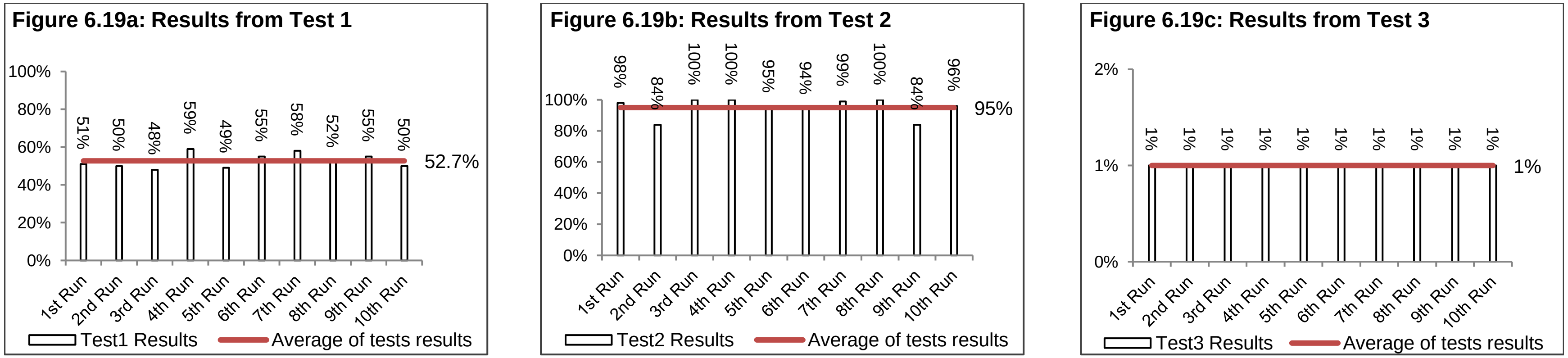


Figure 6.19: Penetration Test Results for WS-Group2 (for information about each test and WS-group see Table 6.12 and Section 6.1.7, respectively)

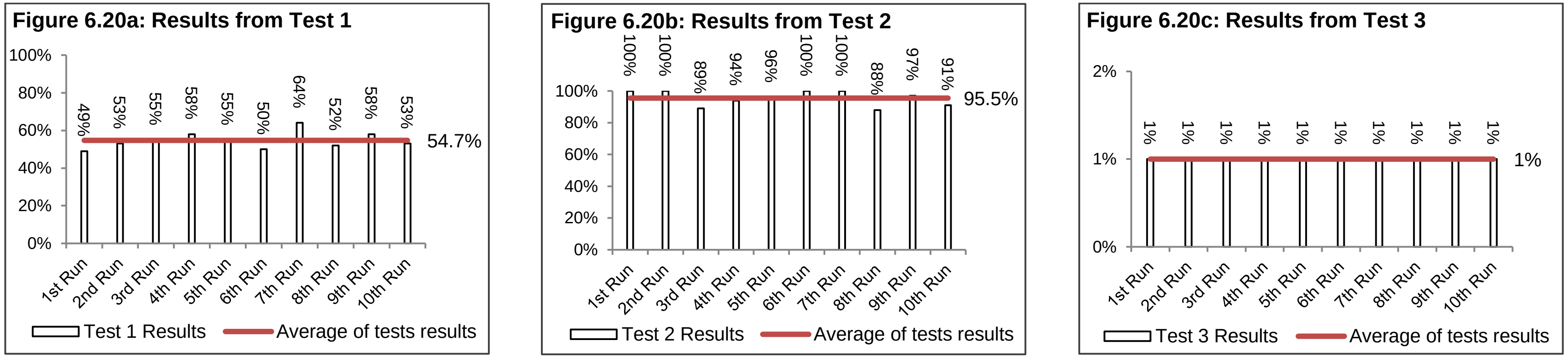


Figure 6.20: Penetration Test Results for WS-Group3 (for information about each test and WS-group see Table 6.12 and Section 6.1.7, respectively)

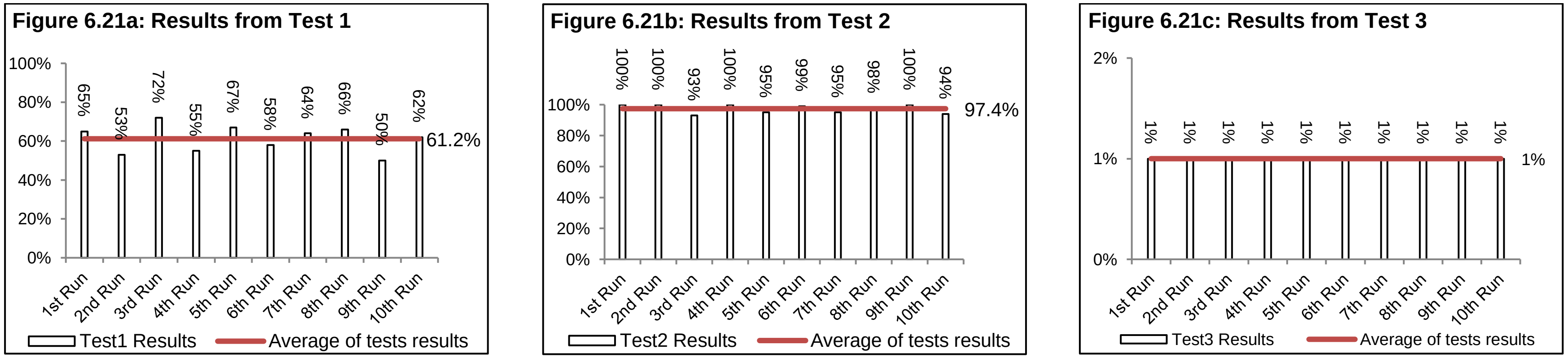


Figure 6.21: Penetration Test Results for WS-Group4 (for information about each test and WS-group see Table 6.12 and Section 6.1.7, respectively)

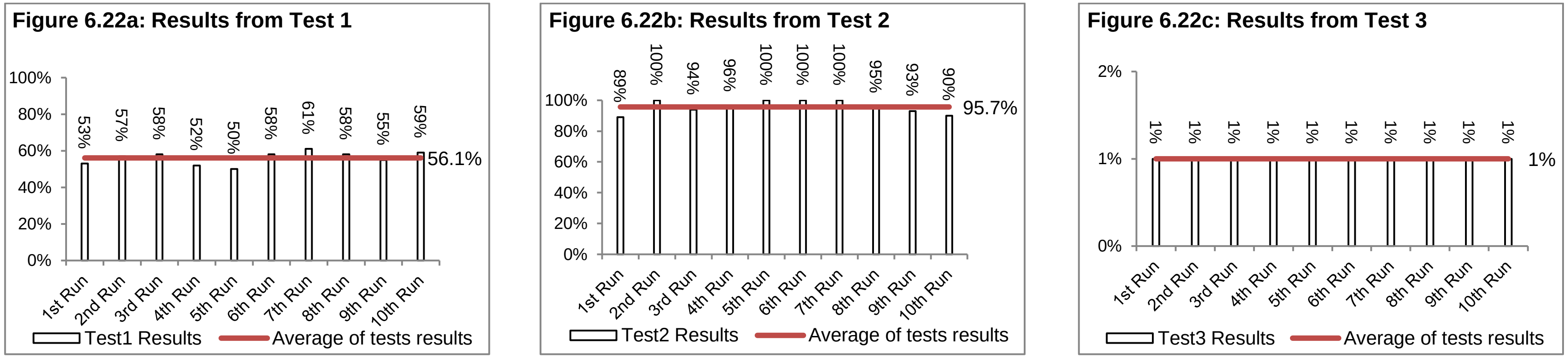


Figure 6.22: Penetration Test Results for WS-Group5 (for information about each test and WS-group see Table 6.12 and Section 6.1.7, respectively)

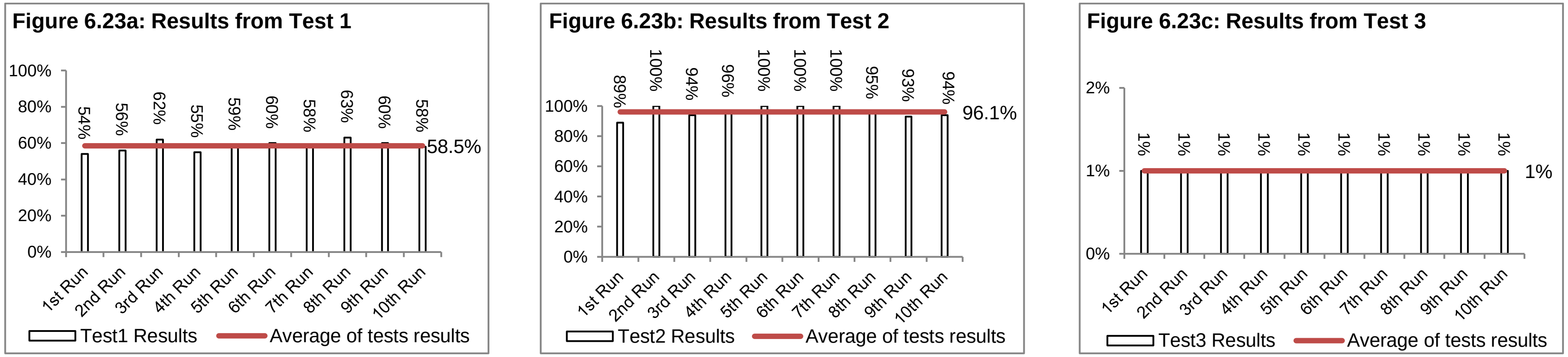


Figure 6.23: Penetration Test Results for WS-Group6 (for information about each test and WS-group see Table 6.12 and Section 6.1.7, respectively)

The penetration test results show the vulnerability of these *WS*-groups to the performed attacks in percentage so that 100% indicates that the group is very vulnerable to the attack and 1% shows that it does not have this security vulnerability.

Each test is repeated ten (to increase the confidence of the outcome of these tests) times and the average of the results is considered. Because, these test plugins decide on the security vulnerability of the *WSs* based on their response times that slightly differs every time the same test is performed. The vertical and horizontal lines in these graphs (Figures 6.18-6.23) show the result of the penetration test every time the same test is performed and the average of the penetration test results for each test, respectively.

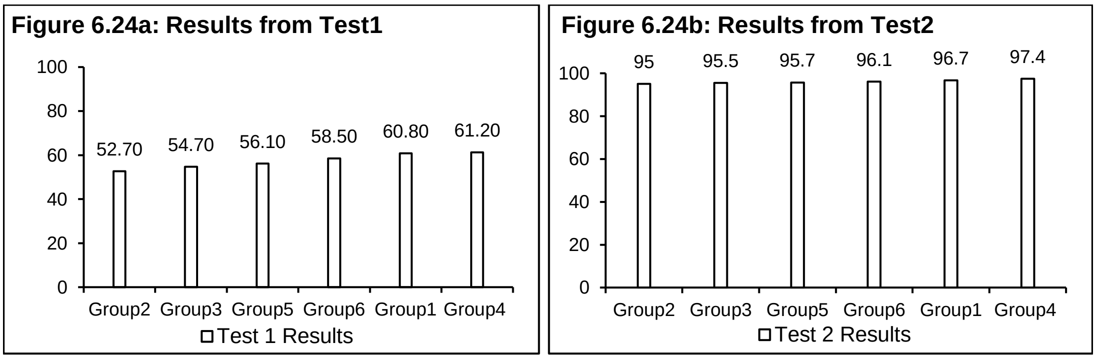


Figure 6.24: WS-Groups Sorted in Ascending Order According to their Penetration Test Results (for information about each test and WS-group see Table 6.12 and Section 6.1.7, respectively)

Finally, the *WS*-groups are ordered according to their penetration test result for each test (see Figure 6.24). For example, Group2 has the lowest penetration test result in each test, so it is the most secure group among others. The results for *XML Attribute Count* test are omitted in these comparisons as all these *WS*-groups have similar level of vulnerability to this attack (see Figures 6.18-6.23).

The penetration test results show the vulnerability of these *WS*-groups to the performed attacks in percentage so that 100% indicates that the group is very vulnerable to the attack and 1% shows that it does not have this security vulnerability.

Considering the results presented in Figures 6.24a and 6.24b the *WS*-groups can be classified according to their overall security vulnerabilities (in descending order) as follows:

- **Group2:** S1, S2 and S5
- **Group3:** S1, S2 and S6
- **Group5:** S1, S3 and S5
- **Group6:** S1, S3 and S6
- **Group1:** S1, S2 and S4
- **Group4:** S1, S3 and S4

6.2 Summary

This chapter illustrated the integration of the penetration test results of the *WSs*, *PCA,* and *CA* in the selection of security-aware *WSs* for implementation of *ITWSs* (the proposed service selection framework). It also explained why these approaches are adopted. The result of this case study is utilized in Chapter 8 to evaluate this framework.

CHAPTER

7

Dynamic Reconfiguration of ITWS Using BPEL and JAVA as BPEL Extension

Chapter 6 demonstrated the proposed service selection framework through a case study. This chapter uses different sets of case studies to illustrate the feasibility of implementing self-reconfigurable Intrusion-Tolerant Web Service (*ITWSs*) utilizing a combination of Business Process Engineering Language (*BPEL*) constructs and *Java* as *BPEL* extension, as well as using *Java* as *BPEL* extension only.

Section 7.1 presents the common setups for these case studies. Sections 7.2 and 7.3 demonstrate the implementation of self-reconfigurable *ITWSs* using a combination of *BPEL* constructs and *Java* as *BPEL* extension approach and utilizing only *Java* as *BPEL* extension approach, respectively. Finally, Section 7.4 summarizes the work presented in this chapter.

7.1 Setups for Case Studies

This section presents the common setups for the case studies demonstrated in this chapter.

7.1.1 WS Preparation

Recall that in service selection case study *OTSWSs* were not employed because we did not have permission to perform penetration tests on such services. However, the case studies presented in this chapter did not require to perform any penetration test on the involved *WSs,* and moreover, it was a good practice to adopt as many of *OTSWSs* as possible. For these case studies the following simple calculator Web Services (*WSs*) are developed using the source code presented in Code 5.1 (see Chapter 5):

- *WS* developed using *Apache Axis2* 1.5.1 framework and was deployed on *Apache Tomcat* 6.0.18 running on *Intel® Core™* i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System.
- *WS* developed using *Apache Axis2* 1.5.1 framework and was deployed on *Apache Tomcat* 6.0.18 running on *Intel® Xeon® CPU E3-1240 V2* @ 3.40GHz system with 16.0GB *RAM* and 64-bit Operating System.
- *WS* developed using .*NET* 4.0 framework and was deployed on *Intel® Core™* 2 *Duo CPU* P8400@ 2.26GHz system with 3.00GB *RAM* and 32-bit Operating System.

Also, two third-party *ASP.NET WSs* [127], [128], which provide similar calculator services, are employed.

7.1.2 DB Preparation

For these case studies, *Oracle Database* 12.1.0.1 is utilized and Table 7.1 is created to store the necessary information for invocation of the *ITWS's* constituent *WSs*. The *SERVICEGROUP* and *PRIORITY* are equivalent to *invocationId* and *orderNumber* properties in the proposed architecture (see Chapter 3 for further information), respectively.

Table 7.1: Service Table Storing Necessary Information for Invoking Candidate WSs

	COLUMN_NAME	DATA_TYPE	NULLABLE	DATA_DEFAULT	COLUMN_ID	COMMENTS
1	ID	VARCHAR2(5 BYTE)	No	(null)	1	(null)
2	NAME	VARCHAR2(30 BYTE)	Yes	(null)	2	(null)
3	ENDPOINT	VARCHAR2(200 BYTE)	Yes	(null)	3	(null)
4	TARGETNAMESPACE	VARCHAR2(200 BYTE)	Yes	(null)	4	(null)
5	SERVICEGROUP	VARCHAR2(30 BYTE)	Yes	(null)	5	(null)
6	PRIORITY	NUMBER(30,0)	Yes	(null)	6	(null)
7	OPERATION	VARCHAR2(30 BYTE)	Yes	(null)	7	(null)
8	INPUT	VARCHAR2(30 BYTE)	Yes	(null)	8	(null)
9	OUTPUT	VARCHAR2(50 BYTE)	Yes	(null)	9	(null)

7.1.3 Communication with DB

In these studies, the dynamic communication between the *BPEL* process and the Database (*DB*), for collection of the information required for invocation of the *WSs* associated with each group, is done through *Java* as *BPEL* extension and using *Java SQL* library (see Appendix G for complete *Java* class). The overview of this communication is as follows:

1. Receives from the *BPEL* process the information (*invocationId* and *orderNumber*) about the group of *WSs* that should be invoked.
2. Stablishes connection with the *DB*.
3. Runs:

("SELECT ENDPOINT, TARGETNAMESPACE, OPERATION, INPUT FROM HR.WEBSERVICES "+ "WHERE SERVICEGROUP =" + invocationId + "AND PRIORITY = " + orderNumber);

("SELECT PRIORITY FROM HR.WEBSERVICES");

4. From the results of the above queries, it prepares a string (the format that could be used by the business process) containing the information required for invoking the *WSs* associated with that group, the number of *WSs* within that group, and the maximum number of groups that are available to be used at that particular part of the business process. From the last information the business process would understand if there are any other groups available that could be used if the current group fails.
5. It returns the prepared information to the business process.

7.2: Case Study: Dynamic Reconfiguration Using a Combination of Java as BPEL Extension and BPEL Constructs

This section uses a case study to demonstrate the feasibility of implementing self-reconfigurable *ITWSs* utilizing a combination of *Java* as *BPEL* extension and *BPEL* constructs. For this study, a self-reconfigurable *ITWS* is developed using the *WSs* from the Section 7.1.1 and *BPEL* plugin for *Oracle SOA Suite* 12c running on *Intel*® *Core*™ i5-3320M *CPU* @

2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System. Figure 7.1 presents the *BPEL* diagram for this *ITWS*.

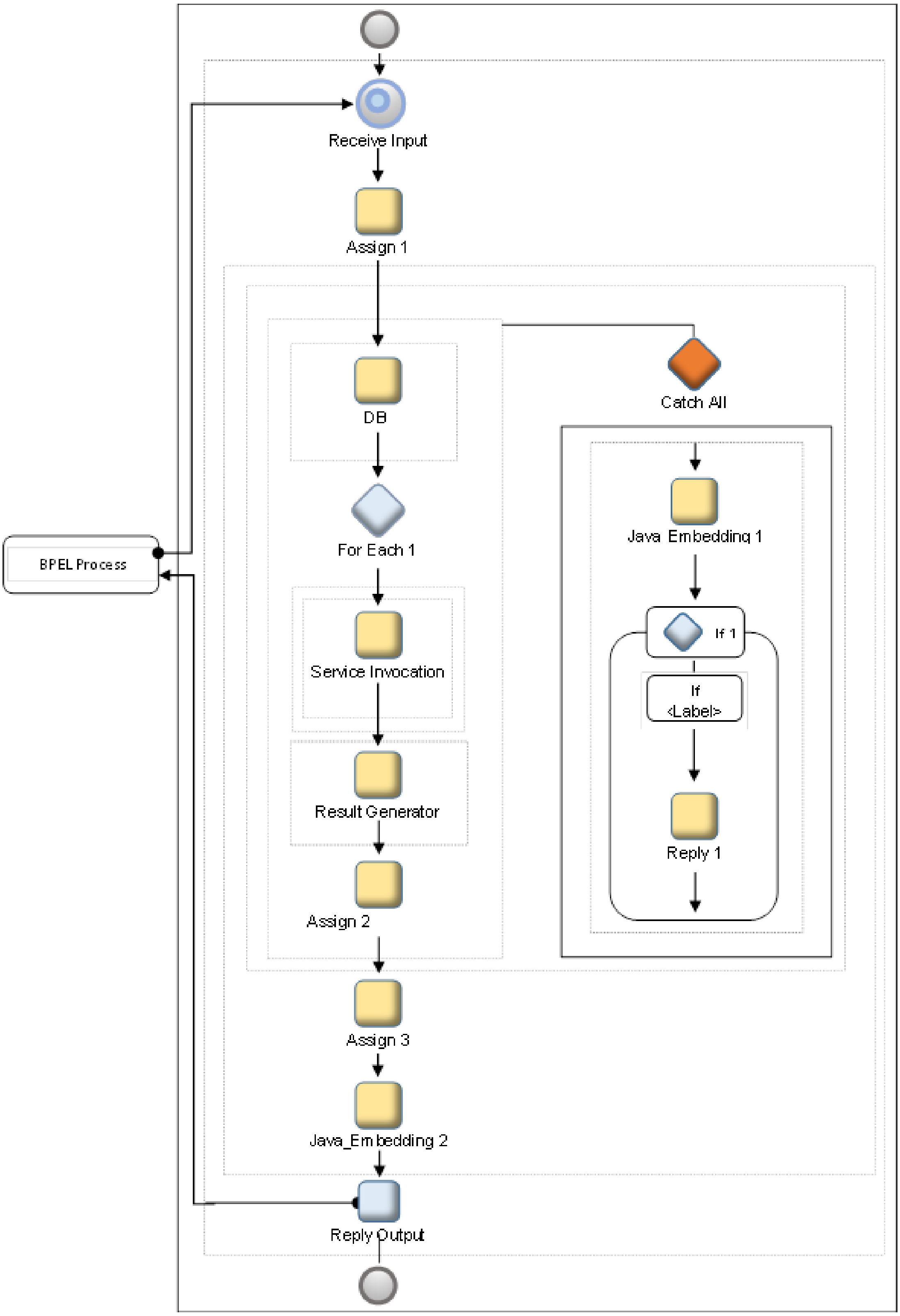


Figure 7.1: BPEL Diagram of Dynamically Reconfigurable ITWS, Implemented Using a Combination of Java as BPEL Extension and BPEL Constructs

The overview of the operation of the self-reconfigurable *ITWS* presented in Figure 7.1 is as follows:

1. Receives the client's request (start of the business process).
2. Stores the start time of the business process, which will be used to work out the response time of this self-reconfigurable *ITWS.*
3. Executes the *Java* class (from Section 7.1.3) responsible for retrieving, from *DB,* the information required for invoking the *WSs* associated with the *WS*-group that should be used (see Code J.1, in Appendix J).
4. Creates parallel process paths, using *ForEachN*[5] activity and the number of *WSs* associated with that group returned by the *DB* (see Section 7.1.3), for invoking the *WSs* from the previous step.
5. Each *WS* invocation path (created in the last step) uses the Code J.2 (see Appendix J) to execute the *Java* class (see Appendix H), which utilizes *Java's API* for *XML*-based *RPC* (*JAX-RPC*) [129] for dynamic invocation of its associated *WS*. The advantage of using a *Dynamic Invocation Interface* is that *WSs* can be invoked without the need for any pre-runtime information or any static operations (e.g., *WSDL* to *Java* mapping).
6. Checks whether sufficient (for performing majority voting) responses are returned by the *WSs.*
    - If adequate responses are returned, it performs majority voting on the *BPEL's* local variables that hold these responses, using the Code J.3 (see Appendix J) then executes step 7.
    - Else, it throws an exception
        - *BPEL's CatchAll* construct catches the thrown exception.
        - It uses Code J.4 (see Appendix J) to check whether an alternative group of services is available by comparing the *orderNumber* (see Chapter 3 for more information)

[5] *Oracle SOA Suite* 12c offers *ForEachN* activity, which creates parallel process paths at runtime [111]. This activity enables to dynamically implement *N-version programming* when the number of constituent *WSs* is only known at runtime.

for the current group and the maximum number of available groups provided by the *DB* (see Section 7.1.3).

- If an alternative group is available, it updates the *BPEL's* local variable storing the *orderNumber* for the group that should be used next and re-executes the *ITWS* from step 3
- Else, it throws an exception and terminates the *BPEL* process.

7. Assigns the result of successful execution of the *ITWS* to the output variable.
8. Uses Code J.6 (see Appendix J) to execute the *Java* class (Code J.5 in Appendix J) that writes the start and end times of the process into a file (to work out the response time of the process for evaluation purpose).
9. Returns the result of the execution of the *ITWS* to the client.

This *ITWS* is run once with three and once with five *WSs* and the response times of these executions are recorded (for evaluation purpose). These executions are repeated forty nine times (to increase the confidence on the evaluation results) and the average of the response times is considered as the response time of the process in each case. Because, the response time slightly varies every time the *ITWS* is executed.

Figures 7.2 and 7.3 present the response times for the execution of this *ITWS* running with three and five *WSs*, respectively. The vertical and horizontal lines in these graphs show the response time (ms) every time the *ITWS* is executed and the average of the response times (ms) respectively. These results will be used in Chapter 8 to evaluate the work presented in this dissertation.

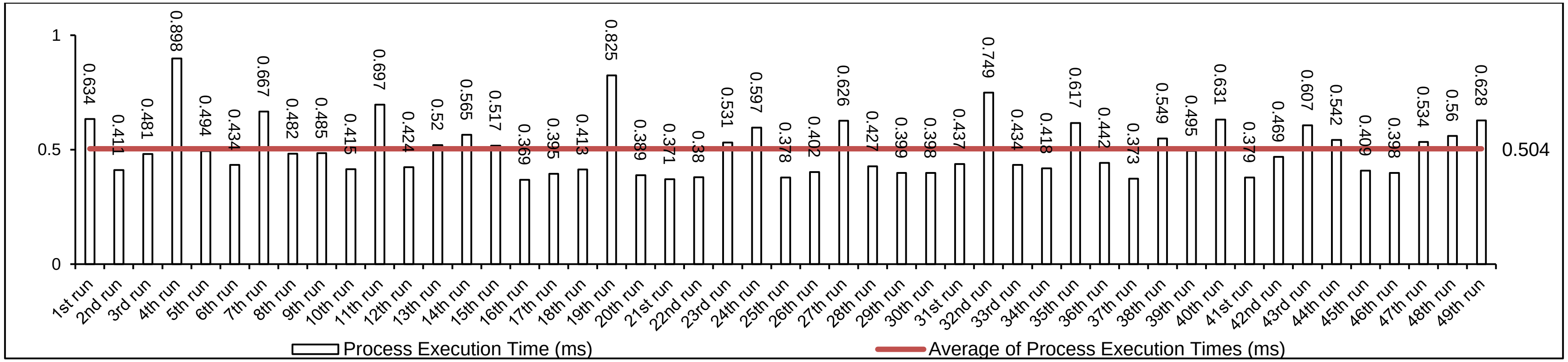


Figure 7.2: Process Execution Time (ms) for Dynamic ITWS Implemented using Combination of Java as BPEL Extension and BPEL constructs (ran with three diverse WSs)

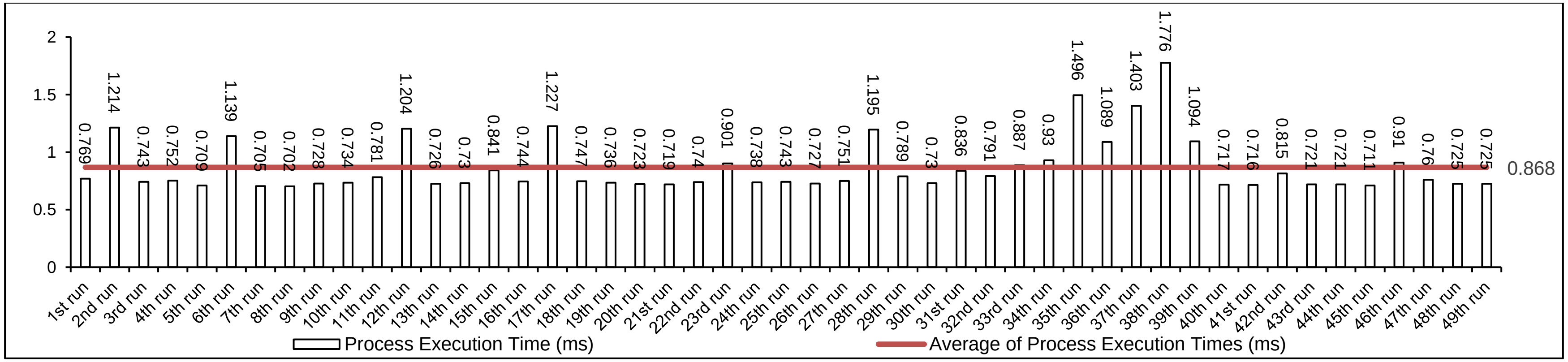


Figure 7.3: Process Execution Time (ms) for Dynamic ITWS Implemented using Combination of Java as BPEL Extension and BPEL constructs (ran with five diverse WSs)

7.3: Case Study: Dynamic Reconfiguration Using Only Java as BPEL Extension

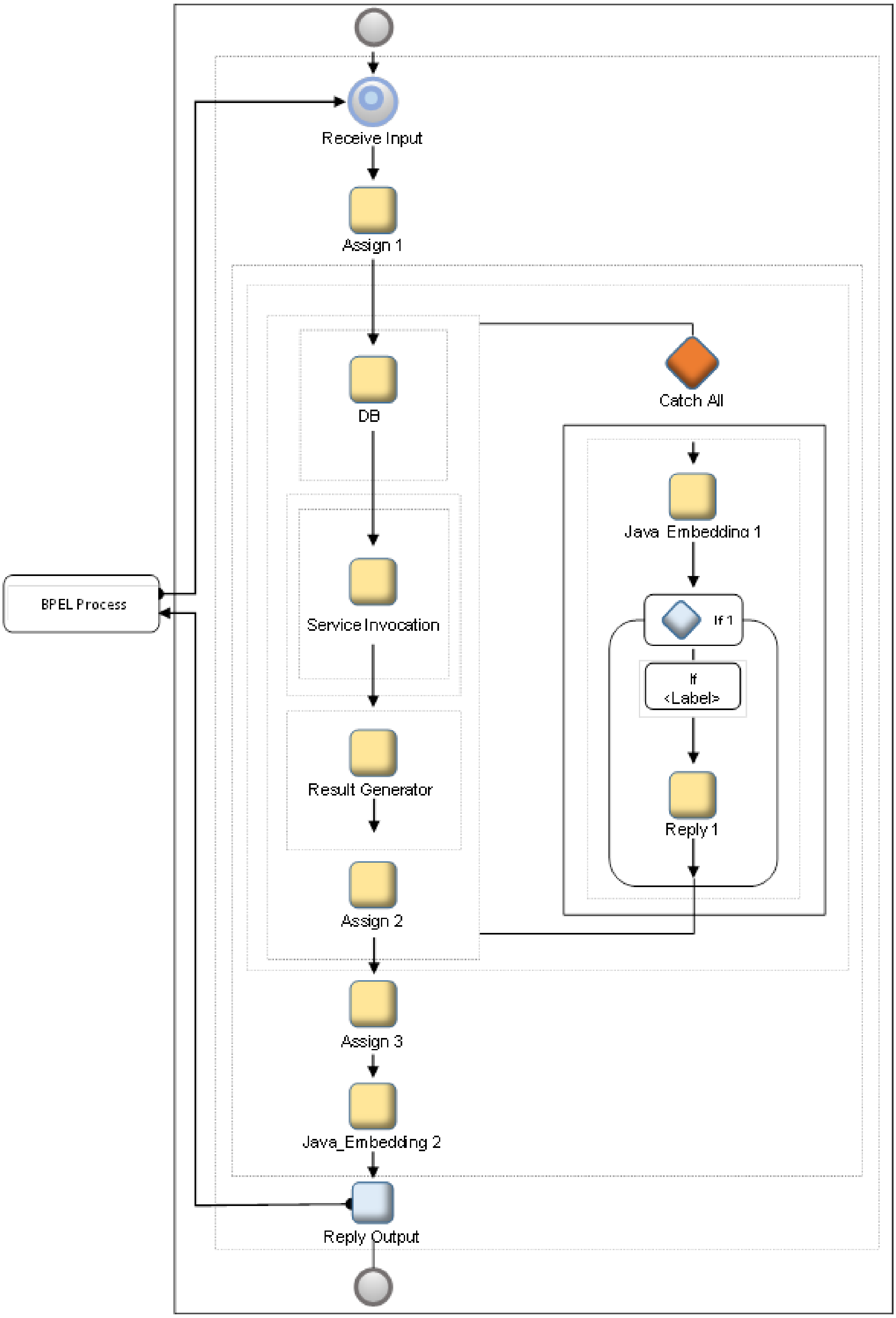


Figure 7.4: BPEL Diagram of Dynamic Reconfigurable ITWS, Implemented Using a Combination of Java as BPEL Extension and BPEL Constructs

This section uses a case study to demonstrate the feasibility of implementing self-reconfigurable *ITWSs* utilizing *Java* as *BPEL* extension only. For this study, a self-reconfigurable *ITWS* is developed using the *WSs* from the Section 7.1.1 and *BPEL* plugin for *Oracle SOA Suite* 12c running on *Intel*® *Core*™ i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System. Figure 7.4 presents the *BPEL* diagram for this *ITWS*.

The overview of the operation of the self-reconfigurable *ITWS* presented in Figure 7.4 is as follows:

1. Receives the client's request (start of the business process).
2. Stores the start time of the business process, which will be used to work out the response time of this self-reconfigurable *ITWS.*
3. Executes the *Java* class (from Section 7.1.3) responsible for retrieving, from *DB,* the information required for invoking the *WSs* associated with the *WS*-group that should be used (see Code J.7, in Appendix J).
4. Uses Code J.8 (see Appendix J) to execute the *Java* class (see Appendix I) responsible for dynamic parallel invocation of the *WSs* from last step. This dynamic invocation approach utilizes *Java* multi-threading library.
5. Checks whether sufficient (for performing majority voting) responses are returned by the *WSs.*
    - If adequate responses are returned, it performs majority voting on the *BPEL's* local variables that hold these responses, using the Code J.3 (see Appendix J) then executes step 6.
    - Else, it throws an exception
        - *BPEL's CatchAll* construct catches the thrown exception.
        - It uses Code J.4 (see Appendix J) to check whether an alternative group of services is available by comparing the *orderNumber* (see Chapter 3 for more information)

for the current group and the maximum number of available groups provided by the *DB* (see Section 7.1.3).

- If an alternative group is available, it updates the *BPEL's* local variable storing the *orderNumber* for the group that should be used next and re-executes the *ITWS* from step 3
- Else, it throws an exception and terminates the *BPEL* process.

6. Assigns the result of successful execution of the *ITWS* to the output variable.
7. Uses Code J.6 (see Appendix J) to execute the *Java* class (Code J.5 in Appendix J) that writes the start and end times of the process into a file (to work out the response time of the process for evaluation purpose).
8. Returns the result of the execution of the *ITWS* to the client.

This *ITWS* is run once with three and once with five *WSs* and the response times are recorded (for evaluation purpose). These executions are repeated forty nine times (to increase the confidence of the outcome of these tests) and the average of the response times is considered as the response time of the process in each case. Because, the response time slightly varies every time the *ITWS* is executed.

Figures 7.5 and 7.6 present the response times for the execution of this *ITWS* running with three and five *WSs*, respectively. The vertical and horizontal lines in these graphs show the response time (ms) every time the *ITWS* is executed and the average of the response times (ms) respectively. These results will be used in Chapter 8 to evaluate the work presented in this dissertation.

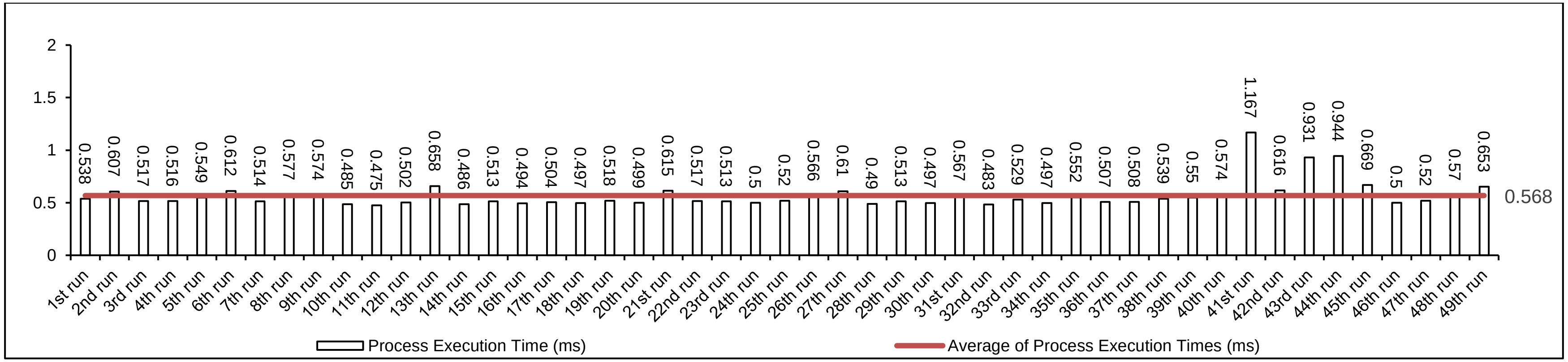


Figure 7.5: Process Execution Time (ms) for Dynamic ITWS Implemented using Java as BPEL Extension only (ran with three diverse WSs)

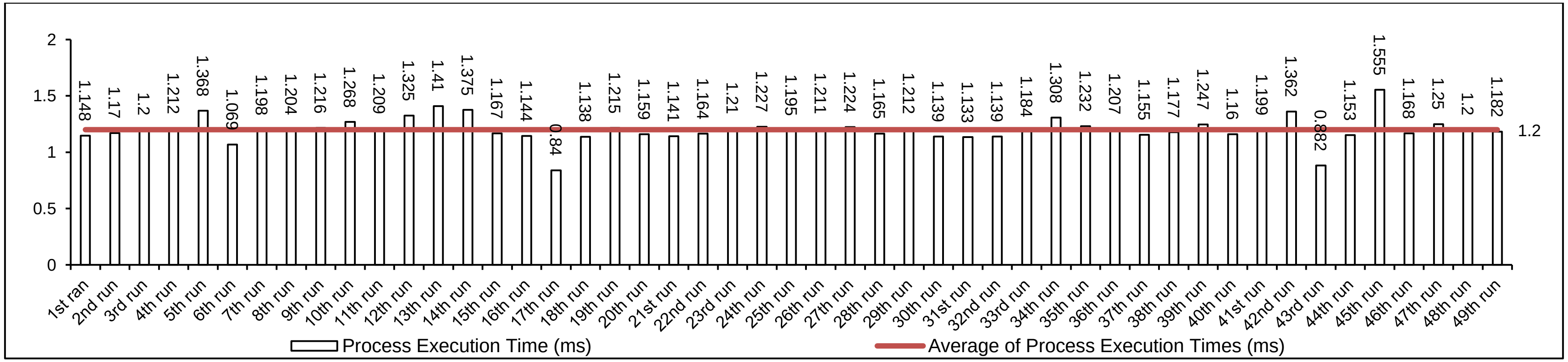


Figure 7.6: Process Execution Time (ms) for Dynamic ITWS Implemented using Java as BPEL Extension only (ran with five diverse WSs)

7.4: Summary

This chapter illustrated the feasibility of implementing self-reconfigurable *ITWSs* using a combination of *BPEL* constructs and *Java* as *BPEL* extension, as well as utilizing *Java* as *BPEL* extension only, through two case studies. The results of these case studies are utilized in Chapter 8 to evaluate this framework.

CHAPTER

8

Evaluation

Previous chapters have presented the background and motivations, the proposed framework architecture, the service selection framework and possible dynamic Business Process Engineering Language (*BPEL*) process reconfiguration for the work presented in this dissertation. This chapter uses the outcomes of the case studies presented in Chapters 4-7 to evaluate the proposed solutions in terms of the central question underlying this work:

Can a self-reconfigurable Intrusion-Tolerant Web Service (ITWS), implemented using N-version programming and diversity formed by composing Off-The-Shelf Web Services (OTSWSs) that are selected through penetration testing, Principal Component Analysis (PCA), and Cluster Analysis (CA) processes mitigate XML-related security vulnerabilities?

Section 8.1 evaluates the advantages, and disadvantages of the *ITWS* presented in this dissertation (as a countermeasure against *XML*-related cyber-attacks) over other existing countermeasure approaches. Section 8.2 evaluates the *ITWS*; formed based on penetration test results of candidate *OTSWSs*, in terms of mitigating the *XML*-related security vulnerabilities. Section 8.3 evaluates the effectiveness of *PCA* and *CA* utilization in security-aware service selection based on penetration tests results of the candidate *OTSWSs*. Section 8.4 evaluates the utilization of *Java* as *BPEL extension* in the implementation of self-reconfigurable *ITWS*.

8.1 Advantages and Limitations of the Presented ITWS

This section evaluates the *ITWS* framework presented in this dissertation in terms of its advantages, limitations, and extensibility as a countermeasure against *XML*-related cyber-attacks.

8.1.1 Advantages of the Presented ITWS

Compared to the disadvantages of existing countermeasures against *XML*-related cyber-attacks (presented in Chapter 2), this *ITWS* has the following advantages:

- It is independent of any *WS*-* security standard, hence:
    - It does not require any changes to the structure of the messages.
    - Revocation, limitations or improper utilization of such standards does not affect this framework.
- It does not require schema validation, hence:
    - It does not cause high *CPU* load and large memory consumption.
    - It does not require any arbitrary restriction on the number and length of the namespaces, which eliminates the unpredictable rejection of messages.
    - It does not require manual schema creation and/or update that may make Web Services (*WSs*) prone to cyber-attacks.
    - It does not introduce security vulnerabilities as a result of a loosely defined schema.
    - It is not prone to the cyber-attacks targeting a schema validator.

8.1.2 Extensibility of the Presented ITWS

The presented *ITWS* is extensible so that diversity can also be applied to penetration testing tools and tests. Furthermore, automation can be applied to its service discovery stage, which is currently the responsibility of the system's administrator.

8.1.3 Limitations of the Presented ITWS

However, this *ITWS* has the following limitations:

- There may not be enough number of *OTSWSs* to implement the *ITWS*.
- Penetration test results may differ if they were performed in the actual operational environment.
- The *ITWS* is wrapped in a *BPEL* process, which itself may be a single point of failure.
- Recall that *SM* tests all *OTSWSs* every *t+i* time unit (see Chapter 3), the security vulnerabilities of these services may change during these time units, which invalidates the existing service groups. However, this limitation is inevitable due to the dynamic nature of *WS's* operating environment. But this effect may be diminished by selecting *i* as smallest time unit that the *ITWS* system can support.

8.2 Feasibility of Implementing ITWS Based on Penetration Testing Results of Candidate WSs

- **Research Question One:** Does an *ITWS*, formed based on penetration test results of candidate *WSs*, mitigate *XML*-related security vulnerabilities?

Chapter 4 used a case study to demonstrate the feasibility of an *ITWS* implemented based on the penetration test results of its constituent *WSs*. In this case study, the *ITWS* was implemented using four *WSs* one of them having security vulnerability to *Coercive Parsing DoS* attack while other three *WSs* did not have this security vulnerability. The outcome of this study showed that the resultant *ITWS* also did not have this security vulnerability (see Chapter 4 for further details). Hence:

The answer to the research question one is yes, an ITWS, formed based on penetration testing results of candidate WSs, mitigates XML-related security vulnerabilities.

8.3 Feasibility of *PCA* and *CA* Utilization in Security-Aware Service Selection

- **Research Question Two:** Is *PCA* an effective pre-processing step to *CA* in this service selection framework?
- **Research Question Three:** Do *PCA* and *CA* improve the process of security-aware service selection based on penetration testing results of candidate *WSs*?
- **Research Question Four:** Does an *ITWS* in which *N-version programming* and *diversity* (formed by composing *OTSWSs* selected through *PCA* and *CA* analysis on their penetration testing results) are used, mitigate *XML*-related security vulnerabilities?

As demonstrated in Section 6.1.6 (Chapter 6), *PCA* has successfully reduced the dimensionality of the penetration test results of the *WSs* (from Section 6.1.2) and the computation complexity of *CA*. It also has identified the patterns among the penetration test results of these *WSs* and has enabled to determine the number of clusters, which is one of the issues with *CA*. Hence, it has proved to be a practical pre-*CA* approach in this service selection framework. Therefore,

The answer to the research question two is yes, PCA is an effective pre-processing step to CA in this service selection framework.

Recall that *CA* assigned S4, S5, and S6 to the same cluster (see Section 6.1.7), which means that these *WSs* have the minimum security vulnerabilities diversity among the services from Section 6.1.2. Hence, to evaluate this work in terms of research questions three and four (see above), the *WS*-groups formed in Section 6.1.7 are compared with a group containing S4, S5 and S6 (hereafter referred to as *WS*-group7).

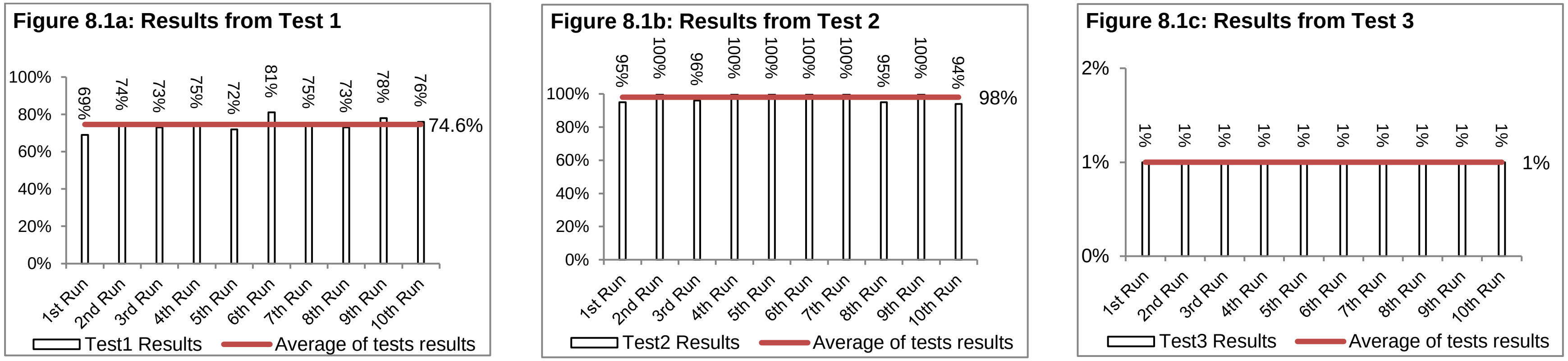


Figure 8.1: Penetration Test Results for WS-Group7 (for information about each test see Table 6.12)

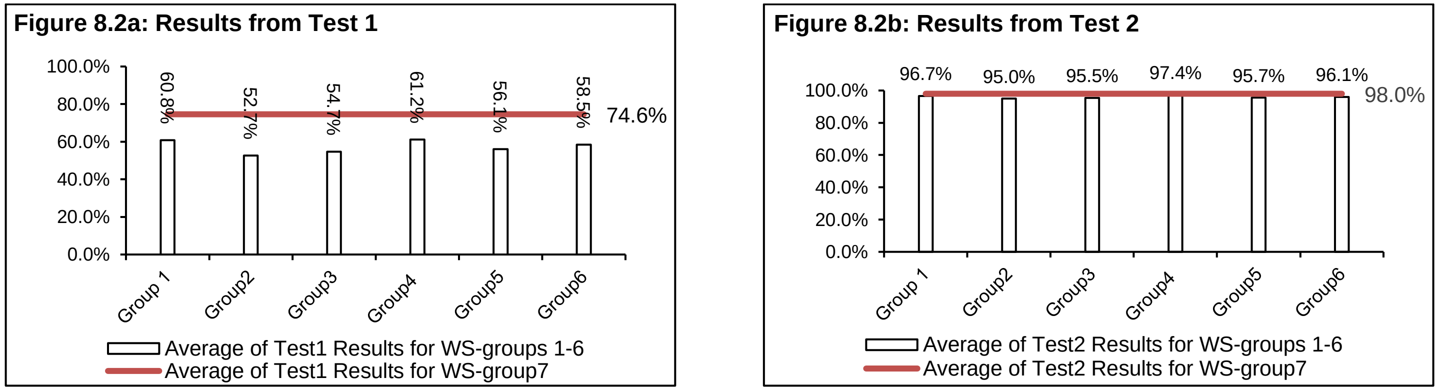


Figure 8.2: Average of Penetration Test Results for WS-Groups1-6 against Average of Penetration Test Results for WS-Group7 (for information about each test see Table 6.12)

WS-group7 is also developed as it is explained in Section 6.1.8 and is tested using *Coercive Parsing, DJBX31A Hash Collision, and XML Attribute Count* attacks with *WS-Attacker's* settings presented in Table 6.12. In these tests, the attack element was either plotted in the header or the body of the test *SOAP* message as presented in Message 5.1 and Message 5.2, respectively.

Figure 8.1 shows the results of the test attacks performed on *WS*-group7. These results show the vulnerability of this *WS*-group to the performed attacks in percentage so that 100% indicates that the group is very vulnerable to the attack and 1% shows that it does not have this security vulnerability.

Each test is repeated ten times (to increase the confidence of the outcome of these tests), and the average of the test results is considered as the final test result since these test plugins decide on the security vulnerability of the *WSs* based on their response times that slightly differs every time the same test is performed. The vertical and horizontal lines in these graphs (Figures 8.1a-8.1c) show the result of the penetration test every time the same test is performed and the average of the penetration test results for each test, respectively.

Figure 8.2 presents the average penetration test results of *WS*-groups1-6 against the average penetration test results of *WS*-group7 for *Coercive Parsing* and *Hash Collision* attacks. The results of *XML Attribute Count* attack test are excluded in this comparison as its result is similar for all these *WS*-groups. Comparing the penetration test results of *WS*-group7 (non-optimal group) with the optimal *WS*-groups (identified through *PCA* and *CA*) show 17.96%-29.36% and 0.61%-3.06% better overall security vulnerability to *Coercive Parsing* and *Hash Collision* attacks, respectively.

Table 8.1: 2-Samples Tests Results for Coercive Parsing Attack

Null hypothesis	Alternative hypothesis	Confidence interval	p-value	Null hypothesis rejected?
Group7 and Group1 are **equally vulnerable** to *Coercive Parsing* attack	Group7 is **more vulnerable** to *Coercive Parsing* attack than Group1	95%	0.000	Yes
Group7 and Group2 are **equally vulnerable** to *Coercive Parsing* attack	Group7 is **more vulnerable** to *Coercive Parsing* attack than Group2	95%	0.000	Yes
Group7 and Group3 are **equally vulnerable** to *Coercive Parsing* attack	Group7 is **more vulnerable** to *Coercive Parsing* attack than Group3	95%	0.000	Yes
Group7 and Group4 are **equally vulnerable** to *Coercive Parsing* attack	Group7 is **more vulnerable** to *Coercive Parsing* attack than Group4	95%	0.000	Yes
Group7 and Group5 are **equally vulnerable** to *Coercive Parsing* attack	Group7 is **more vulnerable** to *Coercive Parsing* attack than Group5	95%	0.000	Yes
Group7 and Group6 are **equally vulnerable** to *Coercive Parsing* attack	Group7 is **more vulnerable** to *Coercive Parsing* attack than Group6	95%	0.000	Yes

Table 8.2: 2-Samples Tests Results for Hash Collision Attack

Null hypothesis	Alternative hypothesis	Confidence interval	p-value	Null hypothesis rejected?
Group7 and Group1 are **equally vulnerable** to *Hash Collision* attack	Group7 is **more vulnerable** to *Hash Collision* attack than Group1	95%	0.159	No
Group7 and Group2 are **equally vulnerable** to *Hash Collision* attack	Group7 is **more vulnerable** to *Hash Collision* attack than Group2	95%	0.092	No
Group7 and Group3 are **equally vulnerable** to *Hash Collision* attack	Group7 is **more vulnerable** to *Hash Collision* attack than Group3	95%	0.085	No
Group7 and Group4 are **equally vulnerable** to *Hash Collision* attack	Group7 is **more vulnerable** to *Hash Collision* attack than Group4	95%	0.315	No
Group7 and Group5 are **equally vulnerable** to *Hash Collision* attack	Group7 is **more vulnerable** to *Hash Collision* attack than Group5	95%	0.083	No
Group7 and Group6 are **equally vulnerable** to *Hash Collision* attack	Group7 is **more vulnerable** to *Hash Collision* attack than Group6	95%	0.107	No

In Statistics, 2-samples t-test is a type of hypothesis test that allows comparing the means of two independent groups of observations. To further assess the proposed service selection framework; 2-samples t-tests are carried out on the penetration test results of *WS*-group7 and each of the other *WS*-groups (see Tables 8.1 and 8.2). These tables show the null and alternative hypothesis as well as the confidence level for these 2-samples tests. They also illustrate the p-values and indicate whether the null hypothesis is rejected (decided based on the p-value) in each case.

For 95% confidence level, the p-value should be 0.05 or less for null hypothesis to be accepted. Therefore, as shown in Tables 8.1 and 8.2, *WS*-group7 is more vulnerable to *Coercive Parsing* attack compared with *WS*-groups1-6. However, all these *WS*-groups are similarly vulnerable to *Hash Collision* attack. Hence,

<u>*The answer to the research question four is yes, an ITWS in which N-version programming and diversity (formed by composing OTSWSs selected through PCA and CA analysis on their penetration test results) are used, mitigates XML-related security vulnerabilities.*</u>

However, the above conclusion also requires comparison of the penetration test results of *WS*-groups1-6 with the *WS*-groups formed using remaining combinations of these *WSs* (identified by *PCA* and *CA* as non-optimal *WS*-groups according to their overall *XML*-related security vulnerabilities).

Finally, without utilization of *PCA* and *CA*, every combination of these *WSs* ($\frac{m!}{n!(m-n)!}$) had to be tested in order to select the most secure group. However, these approaches have reduced the number of required penetration tests significantly. For example, in this case study six *WSs* are available, and three should be selected so in the normal case, twenty different *WS*-groups had to be tested, whereas through utilization of *PCA* and *CA* this number is reduced to six *WS*-groups (70% less penetration testing). Therefore,

<u>The answer to the research question three is yes, PCA and CA improve the process of security-aware service selection based on penetration test results of candidate WSs.</u>

8.4 Feasibility of Implementing Self-Reconfigurable ITWS Using BPEL and JAVA as BPEL Extension

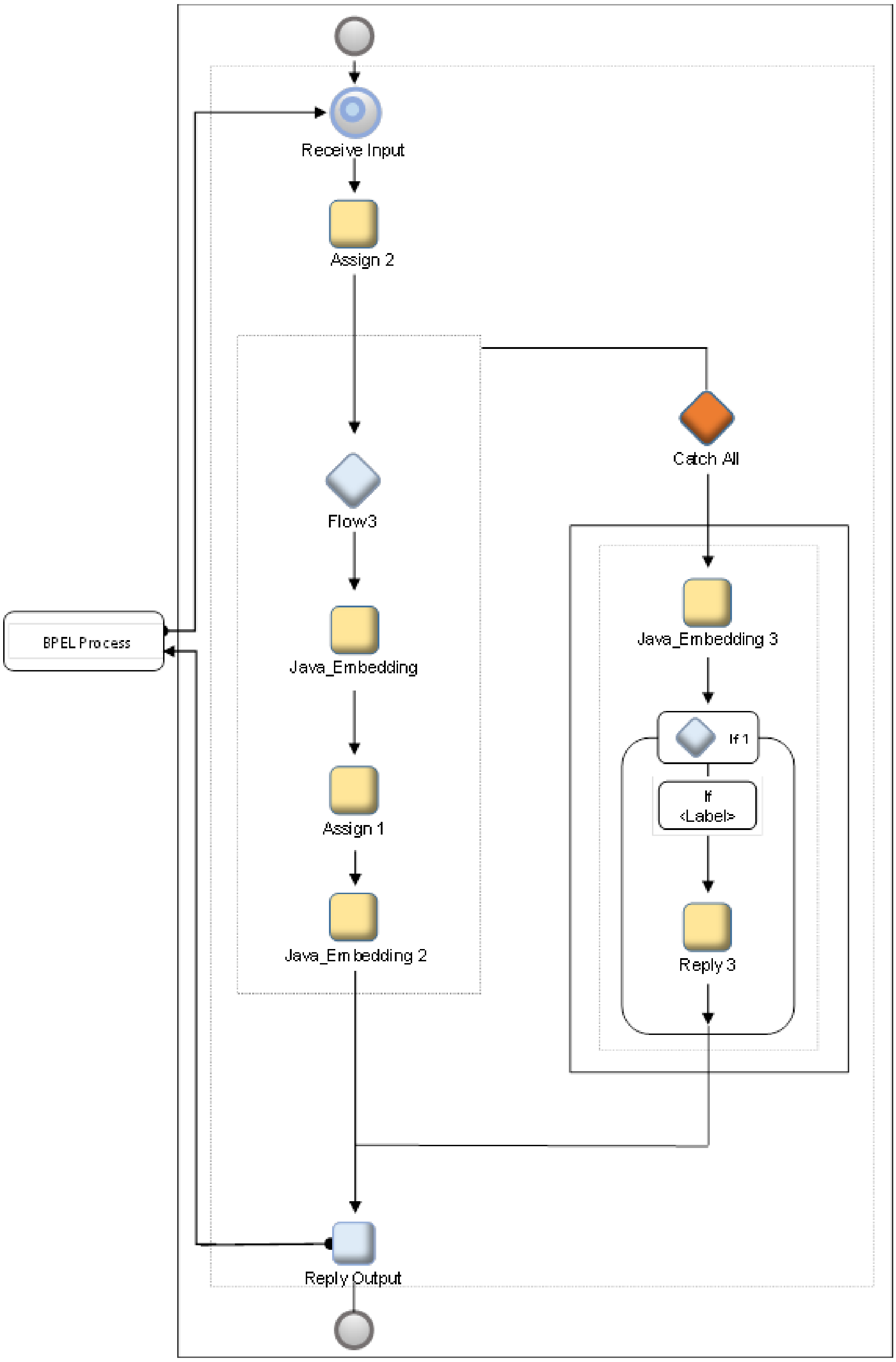


Figure 8.3: BPEL Diagram of Static ITWS Implemented for Evaluation Purpose

- **Research Question Five:** Does the use of *Java* as *BPEL* extension enables dynamic reconfiguration of *ITWS*?

Chapter 7 demonstrated the implementation of dynamically reconfigurable *ITWS* using a combination of *Java* as *BPEL* extension and *BPEL* constructs, as well as using only *Java* as *BPEL* extension. Hence, to evaluate this work in terms of research question five (see above), a static *ITWS* is implemented and is compared with the dynamic *ITWSs* from Section 7.

This static *ITWS* is developed using the *WSs* from the Section 7.1.1 and *BPEL* plugin for *Oracle SOA Suite* 12c running on *Intel® Core™* i5-3320M *CPU* @ 2.60GHz system with 7.88GB usable *RAM* and 64-bit Operating System. Figure 8.3 presents the *BPEL* diagram for this *ITWS*. The overview of the operation of this *ITWS* is as follows:

1. Receives the client's request (start of the business process).
2. Stores the start time of the business process, which will be used to work out the response time of this self-reconfigurable *ITWS.*
3. Invokes the *WSs* (from Section 7.1.1) concurrently. Each of the process paths of the *flow* activity invokes one of these *WSs* that is assigned to it at design time.
4. Checks whether sufficient (for performing majority voting) responses are returned by the *WSs.*
    - If adequate responses are returned, it performs majority voting on the *BPEL's* local variables that hold these responses, using the Code J.3 (see Appendix J) then executes step 5.
    - Else, it throws an exception
        - *BPEL's CatchAll* construct catches the thrown exception.
        - Checks if the pre-defined (by the developer of this *ITWS*) number of re-execution of the invocation process it met.
        - Re-executes the *ITWS* from step 3, if the pre-defined number of re-execution of the invocation process is not met.

- Else, it throws an exception and terminates the *BPEL* process.

5. Assigns the result of successful execution of the *ITWS* to the output variable.
6. Uses Code J.6 (see Appendix J) to execute the *Java* class (Code J.5 in Appendix J) that writes the start and end times of the process into a file (to work out the response time of the process for evaluation purpose).
7. Returns the result of the execution of the *ITWS* to the client.

This *ITWS* is executed once with three and once with five *WSs* and its response times are recorded. These executions are repeated forty nine times (to increase the confidence of the outcome of these tests) and the average of their response times is considered as the response time of the *ITWS* in each case. Because, the response time slightly varies every time the *ITWS* is executed.

Figures 8.4 and 8.5 present the response times for the executions of this *ITWS* running with three and five *WSs*, respectively. The vertical and horizontal lines in these graphs show the response time (ms) every time the *ITWS* is executed and the average of these executions' response times (ms), respectively.

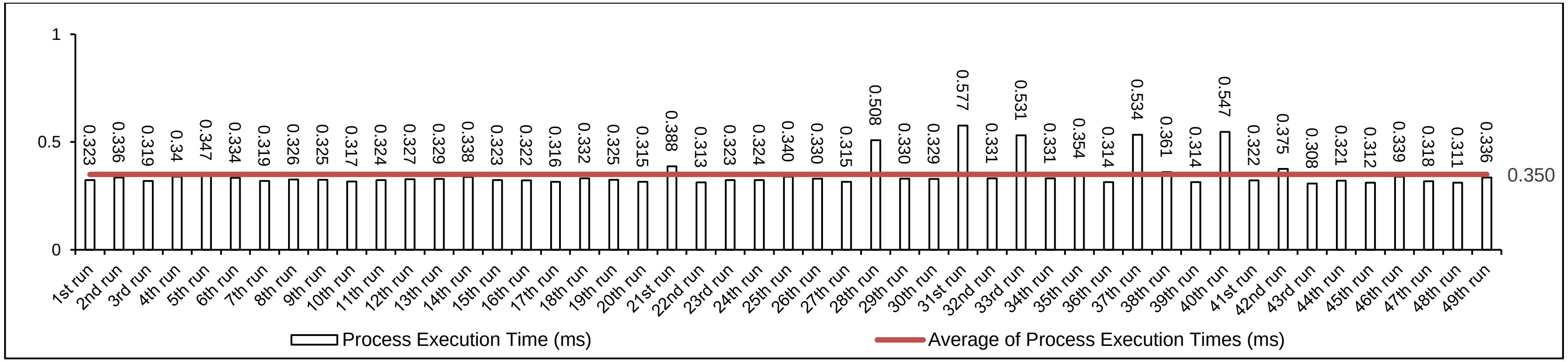


Figure 8.4: Process Execution Time (ms) for Static ITWS Implemented using BPEL Constructs only (ran with three diverse WSs from Section 7.1.1)

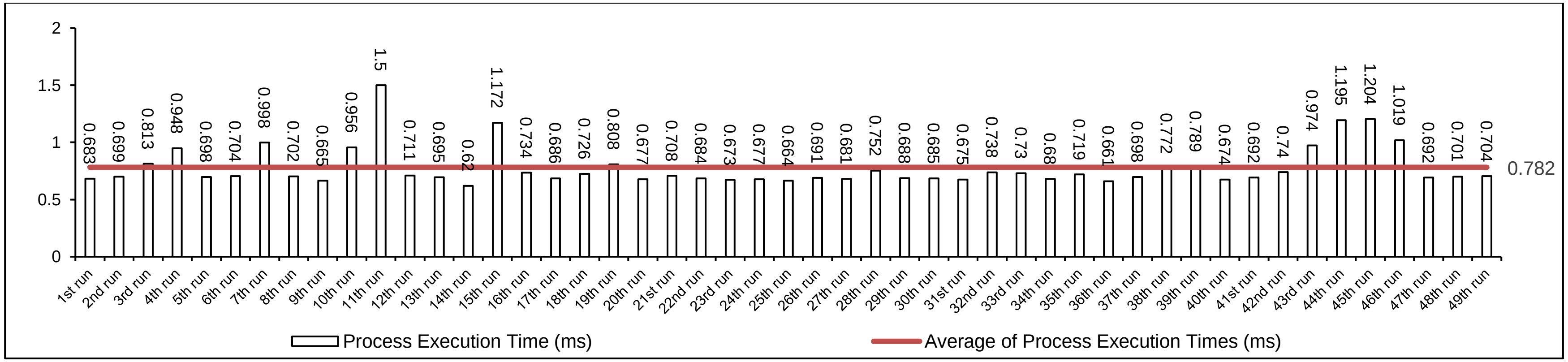
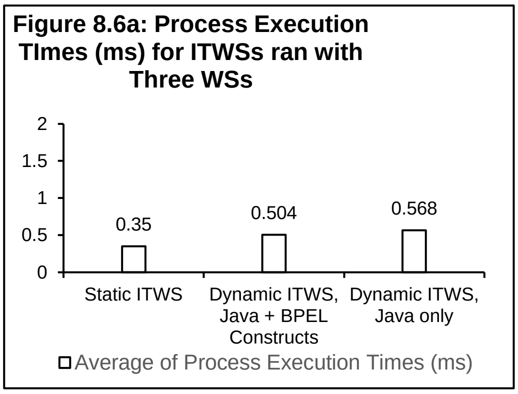


Figure 8.5: Process Execution Time (ms) for Static ITWS Implemented using BPEL Constructs only (ran with five diverse WSs from Section 7.1.1)



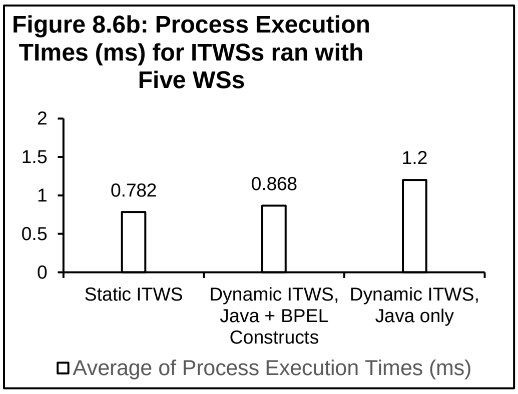


Figure 8.6: Average of Process Execution Times (ms) for Static ITWS against the Average of Process Execution Times (ms) for Dynamic ITWSs

Figures 8.6a and 8.6b illustrate the average response times for the executions of the static *ITWS* against the average response times for the executions of the dynamic *ITWSs* ran with three and five *WSs*. Comparing these results indicates that the introduction of dynamic reconfiguration has introduced execution time overheads (see Table 8.3).

Table 8.3: Execution Time Overheads

Business Processes	Execution time overhead for ITWS ran with three WSs	Execution time overhead for ITWS ran with five WSs
***BPEL + Java* vs *BPEL* constructs only**	44%	11%
***Java only* vs *BPEL* constructs only**	62.29%	53.45%
BPEL + Java vs Java only	12.70%	38.25%

To further examine these *ITWSs,* 2-samples t-tests are carried out on their process execution times (see Tables 8.3 and 8.4). These tables show the null and alternative hypothesis as well as the confidence level for these 2-samples tests. They also illustrate the p-values and indicate whether the null hypothesis is rejected (decided based on the p-value) in each case.

For 95% confidence level, the p-value should be 0.05 or less to accept the null hypothesis. Therefore, as shown in Tables 8.3 and 8.4, the utilization of *Java* as *BPEL* extension to implement self-reconfigurable *ITWS* introduces execution time overheads.

Table 8.4: 2-Sample Tests Results for ITWS ran with three WSs

Null hypothesis	Alternative hypothesis	Confidence interval	p-value	Null hypothesis rejected?
Execution of the *ITWS* implemented using a combination of *BPEL* constructs and *Java* as *BPEL* extension **takes the same time** as execution of the *ITWS* implemented using *BPEL* constructs only	Execution of the *ITWS* implemented using a combination of *BPEL* constructs and *Java* as *BPEL* extension **takes longer** than execution of the *ITWS* implemented using *BPEL* constructs only	95%	0.000	Yes
Execution of the *ITWS* implemented using *Java* as *BPEL* extension only **takes the same time** as execution of the *ITWS* implemented using *BPEL* constructs only	Execution of the *ITWS* implemented using *Java* as *BPEL* extension only **takes longer** than execution of the *ITWS* implemented using *BPEL* constructs only	95%	0.000	Yes
Execution of the *ITWS* implemented using *Java* as *BPEL* extension **only takes the same time** as execution of the *ITWS* implemented using a combination of *BPEL* constructs and *Java* as *BPEL* extension	Execution of the *ITWS* implemented using *Java* as *BPEL* extension only **takes longer** than execution of the *ITWS* implemented using a combination of *BPEL* constructs and *Java* as *BPEL* extension	95%	0.006	No

Table 8.5: 2-Sample Tests Results for ITWS ran with five WSs

Null hypothesis	Alternative hypothesis	Confidence interval	p-value	Null hypothesis rejected?
Execution of the *ITWS* implemented using a combination of *BPEL* constructs and *Java* as *BPEL* extension **takes the same time** as execution of the *ITWS* implemented using *BPEL* constructs only	Execution of the *ITWS* implemented using a combination of *BPEL* constructs and *Java* as *BPEL* extension **takes longer** than execution of the *ITWS* implemented using *BPEL* constructs only	95%	2.09	No
Execution of the *ITWS* implemented using *Java* as *BPEL* extension only **takes the same time** as execution of the *ITWS* implemented using *BPEL* constructs only	Execution of the *ITWS* implemented using *Java* as *BPEL* extension only **takes longer** than execution of the *ITWS* implemented using *BPEL* constructs only	95%	0.000	Yes
Execution of the *ITWS* implemented using *Java* as *BPEL* extension only **takes the same time** as execution of the *ITWS* implemented using a combination of BPEL constructs and *Java* as *BPEL* extension	Execution of the *ITWS* implemented using *Java* as *BPEL* extension only **takes longer** than execution of the *ITWS* implemented using a combination of BPEL constructs and *Java* as *BPEL* extension	95%	0.000	Yes

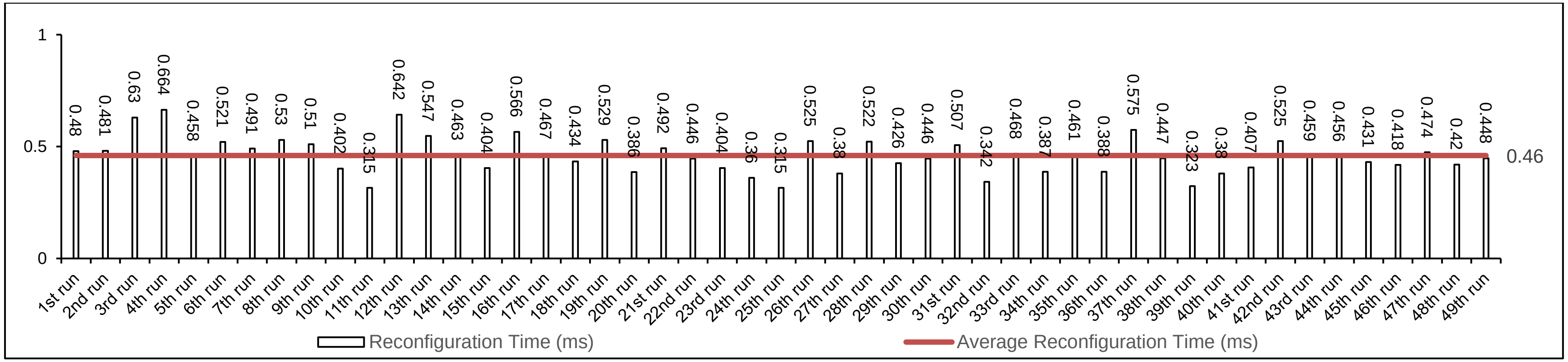


Figure 8.7: Dynamic Reconfiguration Time (ms) for ITWS Implemented using Combination of Java and BPEL Constructs

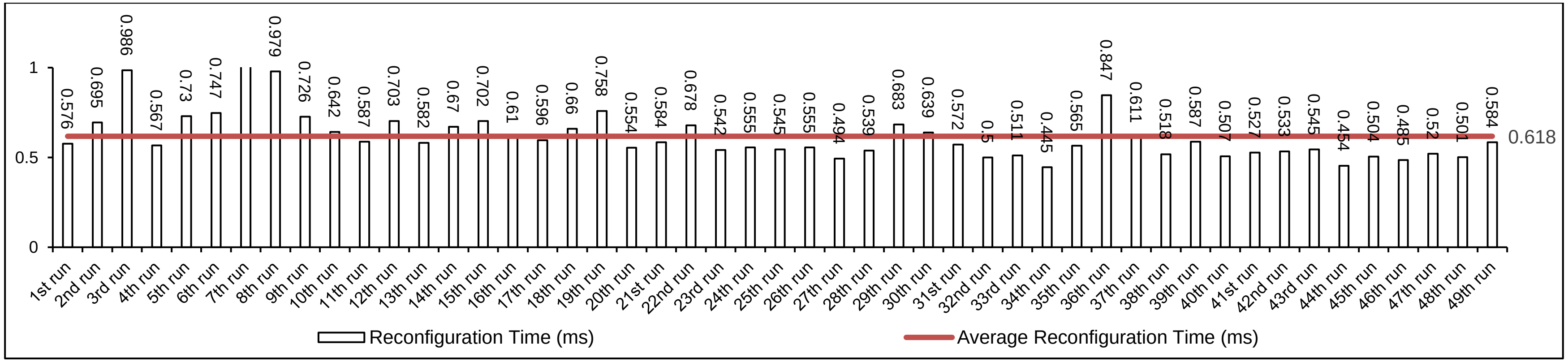


Figure 8.8: Dynamic Reconfiguration Time (ms) for ITWS Implemented using Java only

In addition to the previous evaluations, the reconfiguration times of *ITWS* implemented using *Java* as *BPEL* extension only and *ITWS* implemented using a combination of *BPEL* constructs and *Java* as *BPEL* extension are also compared (see Figures 8.7 and 8.8). For this examination, deliberate faults (two of the *WSs* developed in Section 7.1.1 are altered to return their response in unexpected format) are injected into these *ITWSs* forcing them to perform reconfiguration. The result shows 34.35% increase in the reconfiguration time in the case of *ITWS* implemented using only *Java* as *BPEL* extension approach.

As presented in this section, the answer to the research question five is yes, the use of Java as BPEL extension enables dynamic reconfiguration of ITWS.

And the answer to the central question underlying this work (*Can a self-reconfigurable ITWS, implemented using N-version programming and diversity formed by composing OTSWSs that are selected through penetration testing, PCA, and CA processes mitigate XML-related security vulnerabilities?*) is:

Yes, a composite WS implemented in BPEL can be converted to a self-reconfigurable ITWS using the proposed approaches, presented in this dissertation, to mitigate XML-related security vulnerabilities.

CHAPTER

9

Literature Review

This chapter presents work related to this dissertation. Section 9.1 discusses related security standards, Intrusion Detection (*ID*) and Intrusion Prevention (*IP*) approaches. It also reviews a number of other *Intrusion-Tolerant* systems solutions. Section 9.2 presents other service selection solutions, including those based on *PCA* and *CA* approaches and compares them to the service selection framework of this dissertation. Finally, Section 9.3 discusses other works related to the dynamic reconfiguration and adaptation of composite *WSs*.

9.1 Intrusion Detection, Prevention and Tolerant Systems

This section reviews related security standards and a number of related *ID*/*IP* approaches specific to *WSs* as well as a number of related *IT-WSs*.

9.1.1 Related Security Standards

Various standards (including *WS-Security*, *WS-Policy*, *WS-Trust*, *WS-Privacy*, *WS-Federation*, *WS-SecureConversation*, *WS-Authorization* and etc.) have been created to be used as building blocks of the *WSs* to protect them against *XML*-related cyber-attacks [130]. However, they have limitations; such as their implementation might introduce some complexity and that they may cause security vulnerabilities if not implemented properly (see Chapter 2 for more details).

9.1.2 Related ID/IP Approaches

Lindstrom [51] proposed to first validate *XML* documents, using format and syntax inspection and validation approaches, to conform to the *XML* and *SOAP* specifications then perform a deeper inspection of the content, looking for any policy violations (e.g., oversized documents). Loh *et al*. [131] proposed an *ID*/*IP* framework for *WSs*, which is a combination of syntax parsing on *SOAP* messages (to check the structure of *XML* for syntax errors), filtering policy to check and restrict the size of the *SOAP* message (to prevent *Oversized Payload* attacks) and *XML* schema validation (to counter *SOAP* flooding attacks). Similarly, Yee *et al*. [132] proposed an adaptive *ID*/*IP* framework for *WSs*, which consists of agents that act as sensors, data mining techniques such as clustering, association and sequential rule coupled with *fuzzy* logic to detect violations to the normal profile. The anomalies are then further analysed using *fuzzy* logic to determine genuine attacks to reduce false alarms. In the event of an attack, the action provider either blocks, rejects or terminates the activity. In [133] an *ID* framework is proposed that detects cyber-attacks on *WSs* using *XML* similarity classifiers. This framework consists of: (1) monitoring every request/response for identification of any special characters that may cause *SQL*/*XML Injection* attacks; (2) a validation scheme using *WSDL* definition of the WS with the aim of preventing *XML* DoS attacks; and (3) a normal dataset of requests (based on the normal behaviours of the previous traces) as a reference for comparing both the structure and the semantics of every input request. Gorbenko *et al*. [134] proposed a diversity-aware *IP* framework based on multi-level software diversity and dynamic software reconfiguration for deploying *WSs* in a cloud. In this framework, the vulnerability information from sources such as *NVD* and *CVE* are utilized at real-time to compute the vulnerability scores for the available diverse software infrastructures. The infrastructure with the less vulnerability score is then chosen and redeployed if a different infrastructure is currently deployed. They do not consider replicated systems but choose the best single configuration from a pool of diverse options.

Generally, the ID/IP systems may effectively detect pre-defined attacks but have limitations in responding to continuously created novel attacks.

9.1.3 Related Intrusion-Tolerant Systems

A considerable volume of work in this area has focused on implementing *Intrusion-Tolerant* systems based on diverse redundant components [135]–[138]. The basic intuition is that design diversity reduces the possibility of common security vulnerabilities that are exploited by an attack. These systems are based on active replication techniques. There are proxy servers which interface with the external world mediating access to the actual servers. The inputs to the servers and the responses from the servers are passed through validity checks. Voting is performed on the responses from the servers and any disagreement acts as a trigger for the reconfiguration (e.g., bringing in a different server).

Kalkhoran *et al*. [139] proposed an *ITWS* that uses simple primary and backup scheme (both services have the same implementation, hence, the same security vulnerabilities). In this framework, the available operations are extracted from the *WSDL* of the *WS,* and then an *XML* schema is generated and hardened and used to validate the incoming messages. The objective of this *ITWS* is to prevent previously detected attacks from occurring continually on the system. For this purpose, the system's activity patterns are utilized to detect misuses or abnormal behaviours. Following detection of the malicious requests, the containment module tries to extend these requests to attack patterns and add them to the attack patterns database. In the event of a successful intrusion, the compromised services are disabled and the reconfiguration manager checks whether the service level is satisfactory. Otherwise, the online server is restored to a clean state and the hot standby copy is promoted to the online server.

9.2 Service Selection

Existing approaches to service discovery and selection are mainly based on non-functional properties such as *QoS*, policies, trust, and reputation from client perspective [140].In these approaches, the security property is defined as a set of high-level *QoS* attributes (e.g., confidentiality and integrity) usually claimed by the service providers with no supporting evidence. The service selection approach presented in [141] is based on both functional and non-functional requirements and contains a *QoS* certifier that checks the *QoS* claims made by the service providers. Maximilien and Singh [142] proposed a runtime service selection framework that utilizes agents (acting as proxies between the clients and the services) discovering services based on semantics and *QoS* policies. Quing *et al*. [140] present a survey of service selection approaches based on non-functional requirements. Yau and Yin [143] proposed a service selection framework based on *QoS* metrics integrated into a single satisfaction score. The service selection solutions presented in [144] is based on the client's preferences and WS's properties. It combines logic-based and optimization methods. Chaari *et al*. [145] proposed a service selection approach based on ontology reasoning and an extension to WS-Policy. The service selection framework presented in [146] is based on the trust and the reputation of the *WSs*. This approach evaluates the trustworthiness of the providers based on their reputation then provides a reputation-based service discovery methodology driven by clients' *QoS* preferences. Anisetti *et al*. [147] proposed a service selection framework that selects the *WSs* based on their security certificates that best satisfy the client's preference. Finally, Qi *et al*. [148] proposed service selection method based on weighted *PCA*. They have argued that the weighted *PCA* may reduce the number of *QoS* criteria simplifying the service selection process and eliminate the correlations between different *QoS* criteria increasing service selection accuracy.

The service selection framework presented in this dissertation differs from the above solutions as it is based on tested security vulnerabilities of the *WSs* (not just the service provider's claim)

9.3 Reconfiguration/Adaptation

In standard *BPEL* processes, the interactions with other *WSs* are enabled through *PortTypes*, which are defined statically during the implementation of the business process**.** A much more controllable and hence flexible approach is to enable dynamic runtime lookup, selection, and binding to such business processes.

Ezenwoye *et al*. [149] presented *RobustBPEL* framework, which can generate an adaptable version of an existing *BPEL* process. The *BP* generated through this framework monitors the invocation of partner *WSs* and invokes a static proxy service in the event of a failure. This proxy looks for an equivalent service to replace the failed one. In this approach, the information about the equivalent services is hardcoded at proxy generation time. Later they proposed *RobustBPEL2* [150], which is uses *dynamic proxies* that enables the runtime discovery of equivalent services. Furthermore, *RobustBPEL2* adds self-optimizing capabilities to existing *BPEL* processes. While their work is similar to the reconfiguration approaches presented in this dissertation in respect to their aim to improve reliability in the context of *BPEL* and *WSs*, they are using a proxy based approach, which requires the interface of the equivalent services to match the proxy service, to monitor process execution and improve process performance, whereas the approaches presented in this dissertation leverages *Java* as *BPEL* extension, which enables invocation of any equivalent service, to improve dependability of the *BP*. Hence, the approaches presented in this dissertation enable better self-reconfiguration. *RobustBPEL2* uses *UDDI* to discover alternative services in the event of a failure. However, it does not incorporate selection criteria when multiple services are found, while this work chooses the most secure available group of *WSs* from the database.

In [151], Baresi *et al*. proposed a framework enabling self-healing capabilities for *BPEL* processes. Their framework is based on implementation of the *Dynamo* [152] framework (a supervision framework), which consists of *an AOP-extended* version of the *ActiveBPEL* and is built using the *JBoss Rule Engine*. Similarly, they employ *BPEL* extensions however, of *AOP* type not *Java*. Their solution does not explicitly address the problem of selecting alternative services whereas; the solution presented in this work provides a viable way to select alternative services.

AO4BPEL [153] is an extension to *BPEL4WS*. It is an aspect-oriented approach to *WSs* composition, which provides aspect-oriented modularity mechanism. Aspects are defined in *XML* documents and in the case of *AO4BPEL* they are *BPEL* activities that implement cross-cutting concerns (e.g., security) or workflow changes. To employ the aspect, it must be registered with the BPEL's execution engine. This registration can be done during the runtime of the *BP*. However, it requires information such as the *WSDL* and port address of the service, as well as the *partnerLinkTypes* (necessary information for establishing communication with the external *WSs*) that are to be used by the aspect. Then, *AO4BPEL* can supports dynamically changing the deployed process through activating/deactivating aspects. Whereas, one of the advantages of the self-reconfiguration approaches demonstrated in this work is that the *BP* collects the necessary information for establishing communication with the external *WSs* during its execution time. This feature gives the backend of the *BP* the freedom of updating the services' records in the *DB* (including adding and deleting services), which enables the *ITWS* to stay up to date.

In [154], Kongdenfha *et al*. proposed an aspect-oriented framework enabling service adaptation. Their approach uses aspect-based templates to automate the task of handling interface mismatches (including *protocol* mismatches). Whereas, the approaches presented in this work utilize self-reconfiguration to support *Intrusion-Tolerance*.

CHAPTER

10

Conclusions and Future Work

This dissertation is concerned with improving the dependability of Web Services (*WSs*) especially when Off-The-Shelf Web Services (*OTSWSs)* are employed. It introduced a novel framework to increase dependability by constructing Intrusion-Tolerant Web Services (*ITWSs*) in which *N-version programming* and *diversity*, formed by composing *OTSWSs*, are used. It also demonstrated implementation of self-reconfiguration *ITWS* using a combination of Business Process Engineering Language (*BPEL*) constructs and *Java* as *BPEL* extension approach and using only *Java* as *BPEL* extension approach.

10.1 Summary

Chapter 1 introduced this work and its context (using an exemplary *WS*). It also briefly discussed the motivation for this work and presented the central research question it was going to answer as well as its contributions and distinctions. Finally, it briefly outlined the other chapters.

Chapter 2 presented the overview of *WSs'* architecture and introduced its main technologies (*SOAP*, *WSDL,* and *UDDI*). It then explained that *WSs* are at risk of security vulnerabilities related to their specific implementation technologies (e.g., *XML*) as well as those, of their underlying platforms (e.g., operating systems) and web Applications (e.g., vulnerability to *SQL Injection* attacks). Afterward, it introduced a number of existing countermeasures against attacks targeting *WSs' XML*-related vulnerabilities followed by a list of their limitations and argued that the issue gets more challenging when *OTSWSs* are employed as they are ready-made black boxes of unknown quality and their security is out of the control of their client thus, tolerating their security vulnerabilities through a reconfigurable *ITWS* is a more appropriate approach. It then briefly introduced dependability approaches and explained that *ITWS* could be achieved using dependability techniques which, is the approach adopted in this work and is achieved through the integration of *WSs'* composability, Principal Component Analysis (*PCA*), Cluster Analysis (*CA*) and penetration testing. After that, it briefly introduced each of these concepts and explained the motivation for their adoption in this work.

Chapter 3 presented the architecture for this framework along with its objectives and the assumptions made. It then explained the role of each of its components and the interactions among them.

Chapter 4 introduced the penetration testing tool, utilized in the case studies presenting the proposed service selection framework. It then demonstrated the feasibility of *ITWS* implementation based on penetration test results of the candidate *WSs*.

Chapter 5 showed that *BPEL* could affect the *XML*-related security vulnerabilities of the candidate (for *ITWS* implementation) *WSs* and argued that these effects should be considered in service selection process.

Chapter 6 demonstrated, how penetration test results of the candidate *WSs, PCA,* and *CA* could be used to group *WSs* based on their *XML*-related security vulnerabilities and how these groups could be sorted using further penetration testing.

Chapter 7 demonstrated the implementation of self-reconfigurable *WS* using a combination of *BPEL* constructs and *Java* as *BPEL* 2.0 extension approach and utilizing only *Java* as *BPEL* extension approach through two case studies.

Chapter 8 evaluated this work using the experimental results collected from the case studies that demonstrated different dimensions of the work presented in this dissertation. It discussed the advantages, extensibility, and limitations of the proposed framework. Finally, it answered the underlying central research question.

Chapter 9 discussed other related approaches.

10.2 Future Work

During this work, the author identified extensions of the current dissertation and future directions of this research as outlined below.

- Diversity could also be applied to penetration testing tools and tests.
- *XML* hardening could be applied to some of the utilized *WSs* to make them more secure aiming to increase diversity among the *WSs*.
- Diversity could also be applied at the composition level since the *BPEL* itself could be a single point of failure.
- Automation could be applied to service discovery stage, which is currently the responsibility of the system's administrator.
- Recall that *WS-Attacker's* plugins also simulate concurrent legitimate users. These experiments could be repeated while this feature is completely switched off (to diminish the fluctuations in the penetration testing results).
- The proposed service selection framework could be further evaluated using *WS*-groups formed based on remaining combinations of the *WSs* (identified by *PCA* and *CA* as non-optimal *WS*-groups according to their overall *XML*-related security vulnerabilities).

10.3 Conclusions

This dissertation makes the following main conclusions:

An *ITWS* formed based on penetration test results of candidate *WSs*, is a feasible approach to mitigate *XML*-related security vulnerabilities.

PCA and *CA* improve the process of security-aware service selection based on penetration testing results of candidate *WSs*.

PCA is an effective pre-processing step to *CA* in the proposed service selection framework.

An *ITWS* in which *N-version programming* and *diversity*, formed by composing *SOAP-OTSWSs* (elected through *PCA* and *CA* analysis on their penetration testing results) is used, is a feasible approach to mitigate *XML*-related security vulnerabilities.

Java as *BPEL* extension enables to implement self-reconfigurable *ITWS* in return for the cost of longer execution time.

And the answer to the central question underlying this work (*Can a self-reconfigurable ITWS, implemented using N-version programming and diversity formed by composing OTSWSs that are selected through penetration testing, PCA, and CA processes mitigate XML-related security vulnerabilities?*) is:

Yes, a composite WS implemented in BPEL can be converted to a self-reconfigurable ITWS using the proposed approaches, presented in this dissertation, to mitigate XML-related security vulnerabilities.

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Appendix A: WSDL of Axis1-4 WS running on apache-tomcat-6.0.18 server


```
<?xml version="1.0" encoding="UTF-8"?>
   <wsdl:definitions targetNamespace="http://Axis_Tom_6"
   xmlns:apachesoap="http://xml.apache.org/xml-soap" xmlns:impl="http://Axis_Tom_6"
   xmlns:intf="http://Axis_Tom_6" xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/"
   xmlns:wsdlsoap="http://schemas.xmlsoap.org/wsdl/soap/"
   xmlns:xsd="http://www.w3.org/2001/XMLSchema">
   <!--WSDL created by Apache Axis version: 1.4
   Built on Apr 22, 2006 (06:55:48 PDT)-->
   <wsdl:types>
      <schema elementFormDefault="qualified"  targeNamespace=http://Axis_Tom_6
       xmlns="http://www.w3.org/2001/XMLSchema">
      <element name="factorial">
         <complexType>
            <sequence>
               <element name="n" type="xsd:int"/>
            </sequence>
         </complexType>
      </element>
      <element name="factorialResponse">
         <complexType>
            <sequence>
               <element name="factorialReturn" type="xsd:int"/>
            </sequence>
          </complexType>
      </element>
      <element name="addIntegers">
         <complexType>
            <sequence>
               <element name="firstNum" type="xsd:int"/>
               <element name="secondNum" type="xsd:int"/>
           </sequence>
       </complexType>
    </element>
    <element name="addIntegersResponse">
      <complexType>
                                             <sequence>
                                                    <element name=
```

```
                                                    "addIntegersReturn" type="xsd:int"/>
                                        </sequence>
                                  </complexType>
            </element>
            </schema>
 </wsdl:types>
<wsdl:message name="factorialResponse">
   <wsdl:part element="impl:factorialResponse" name="parameters">
            </wsdl:part>
  </wsdl:message>
  <wsdl:message name="factorialRequest">
  <wsdl:part element="impl:factorial" name="parameters">
      </wsdl:part>
   </wsdl:message>
   <wsdl:message name="addIntegersRequest">
      <wsdl:part element="impl:addIntegers" name="parameters">
      </wsdl:part>
   </wsdl:message>
   <wsdl:message name="addIntegersResponse">
      <wsdl:part element="impl:addIntegersResponse" name="parameters">
      </wsdl:part>
   </wsdl:message>
   <wsdl:portType name="Axis_Tom_6_sum">
      <wsdl:operation name="factorial">
         <wsdl:input message="impl:factorialRequest" name="factorialRequest">
       </wsdl:input>
         <wsdl:output message="impl:factorialResponse" name="factorialResponse">
       </wsdl:output>
      </wsdl:operation>
      <wsdl:operation name="addIntegers">
         <wsdl:input message="impl:addIntegersRequest" name="addIntegersRequest">
       </wsdl:input>
         <wsdl:output message="impl:addIntegersResponse" name="addIntegersResponse">
       </wsdl:output>
      </wsdl:operation>
   </wsdl:portType>
   <wsdl:binding name="Axis_Tom_6_sumSoapBinding" type="impl:Axis_Tom_6_sum">
      <wsdlsoap:binding style="document"
transport="http://schemas.xmlsoap.org/soap/http"/>
      <wsdl:operation name="factorial">
```

```
      <wsdlsoap:operation soapAction=""/>
      <wsdl:input name="factorialRequest">
        <wsdlsoap:body use="literal"/>
      </wsdl:input>
      <wsdl:output name="factorialResponse">
        <wsdlsoap:body use="literal"/>
      </wsdl:output>
    </wsdl:operation>
    <wsdl:operation name="addIntegers">
      <wsdlsoap:operation soapAction=""/>
      <wsdl:input name="addIntegersRequest">
        <wsdlsoap:body use="literal"/>
      </wsdl:input>
      <wsdl:output name="addIntegersResponse">
        <wsdlsoap:body use="literal"/>
      </wsdl:output>
    </wsdl:operation>
  </wsdl:binding>
  <wsdl:service name="Axis_Tom_6_sumService">
    <wsdl:port binding="impl:Axis_Tom_6_sumSoapBinding" name="Axis_Tom_6_sum">
      <wsdlsoap:address loca-
tion="http://localhost:8888/Axis_Tom_6/services/Axis_Tom_6_sum"/>
    </wsdl:port>
  </wsdl:service>
</wsdl:definitions>
```

Appendix B: WSDL of Axis2-1.5.1 WS running on apache-tomcat-6.0.18 server


```
<?xml version="1.0" encoding="UTF-8"?><wsdl:definitions
xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/" xmlns:ns="http://Axis2_1_5_1_Tom_6"
xmlns:wsaw="http://www.w3.org/2006/05/addressing/wsdl"
xmlns:mime="http://schemas.xmlsoap.org/wsdl/mime/"
xmlns:http="http://schemas.xmlsoap.org/wsdl/http/"
xmlns:xs="http://www.w3.org/2001/XMLSchema"
xmlns:soap12="http://schemas.xmlsoap.org/wsdl/soap12/"
xmlns:ns1="http://org.apache.axis2/xsd"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/" target-
Namespace="http://Axis2_1_5_1_Tom_6">
  <wsdl:documentation>
                    Please Type your service description here
        </wsdl:documentation>
  <wsdl:types>
    <xs:schema attributeFormDefault="qualified" elementFormDefault="qualified" target-
Namespace="http://Axis2_1_5_1_Tom_6">
      <xs:element name="addIntegers">
        <xs:complexType>
          <xs:sequence>
            <xs:element minOccurs="0" name="firstNum" type="xs:int"/>
            <xs:element minOccurs="0" name="secondNum" type="xs:int"/>
          </xs:sequence>
        </xs:complexType>
      </xs:element>
      <xs:element name="addIntegersResponse">
        <xs:complexType>
          <xs:sequence>
            <xs:element minOccurs="0" name="return" type="xs:int"/>
          </xs:sequence>
        </xs:complexType>
      </xs:element>
      <xs:element name="factorial">
        <xs:complexType>
          <xs:sequence>
            <xs:element minOccurs="0" name="n" type="xs:int"/>
          </xs:sequence>
        </xs:complexType>
```

```
            </xs:element>
            <xs:element name="factorialResponse">
                <xs:complexType>
                    <xs:sequence>
                        <xs:element minOccurs="0" name="return" type="xs:int"/>
                    </xs:sequence>
                </xs:complexType>
            </xs:element>
        </xs:schema>
    </wsdl:types>
    <wsdl:message name="factorialRequest">
        <wsdl:part name="parameters" element="ns:factorial"/>
    </wsdl:message>
    <wsdl:message name="factorialResponse">
        <wsdl:part name="parameters" element="ns:factorialResponse"/>
    </wsdl:message>
    <wsdl:message name="addIntegersRequest">
        <wsdl:part name="parameters" element="ns:addIntegers"/>
    </wsdl:message>
    <wsdl:message name="addIntegersResponse">
        <wsdl:part name="parameters" element="ns:addIntegersResponse"/>
    </wsdl:message>
    <wsdl:portType name="Axis2_1_5_1_Tom_6_sumPortType">
        <wsdl:operation name="factorial">
            <wsdl:input message="ns:factorialRequest" wsaw:Action="urn:factorial"/>
            <wsdl:output message="ns:factorialResponse"
wsaw:Action="urn:factorialResponse"/>
        </wsdl:operation>
        <wsdl:operation name="addIntegers">
            <wsdl:input message="ns:addIntegersRequest" wsaw:Action="urn:addIntegers"/>
            <wsdl:output message="ns:addIntegersResponse"
wsaw:Action="urn:addIntegersResponse"/>
        </wsdl:operation>
    </wsdl:portType>
    <wsdl:binding name="Axis2_1_5_1_Tom_6_sumSoap11Binding"
type="ns:Axis2_1_5_1_Tom_6_sumPortType">
        <soap:binding transport="http://schemas.xmlsoap.org/soap/http" style="document"/>
        <wsdl:operation name="factorial">
            <soap:operation soapAction="urn:factorial" style="document"/>
            <wsdl:input>
```

```
                <soap:body use="literal"/>
            </wsdl:input>
            <wsdl:output>
                <soap:body use="literal"/>
            </wsdl:output>
        </wsdl:operation>
        <wsdl:operation name="addIntegers">
            <soap:operation soapAction="urn:addIntegers" style="document"/>
            <wsdl:input>
                <soap:body use="literal"/>
            </wsdl:input>
            <wsdl:output>
                <soap:body use="literal"/>
            </wsdl:output>
        </wsdl:operation>
    </wsdl:binding>
    <wsdl:binding name="Axis2_1_5_1_Tom_6_sumSoap12Binding"
type="ns:Axis2_1_5_1_Tom_6_sumPortType">
        <soap12:binding transport="http://schemas.xmlsoap.org/soap/http" style="document"/>
        <wsdl:operation name="factorial">
            <soap12:operation soapAction="urn:factorial" style="document"/>
            <wsdl:input>
                <soap12:body use="literal"/>
            </wsdl:input>
            <wsdl:output>
                <soap12:body use="literal"/>
            </wsdl:output>
        </wsdl:operation>
        <wsdl:operation name="addIntegers">
            <soap12:operation soapAction="urn:addIntegers" style="document"/>
            <wsdl:input>
                <soap12:body use="literal"/>
            </wsdl:input>
            <wsdl:output>
                <soap12:body use="literal"/>
            </wsdl:output>
        </wsdl:operation>
    </wsdl:binding>
    <wsdl:binding name="Axis2_1_5_1_Tom_6_sumHttpBinding"
type="ns:Axis2_1_5_1_Tom_6_sumPortType">
```

```
        <http:binding verb="POST"/>
        <wsdl:operation name="factorial">
            <http:operation location="Axis2_1_5_1_Tom_6_sum/factorial"/>
            <wsdl:input>
                <mime:content type="text/xml" part="factorial"/>
            </wsdl:input>
            <wsdl:output>
                <mime:content type="text/xml" part="factorial"/>
            </wsdl:output>
        </wsdl:operation>
        <wsdl:operation name="addIntegers">
            <http:operation location="Axis2_1_5_1_Tom_6_sum/addIntegers"/>
            <wsdl:input>
                <mime:content type="text/xml" part="addIntegers"/>
            </wsdl:input>
            <wsdl:output>
                <mime:content type="text/xml" part="addIntegers"/>
            </wsdl:output>
        </wsdl:operation>
    </wsdl:binding>
    <wsdl:service name="Axis2_1_5_1_Tom_6_sum">
        <wsdl:port name="Axis2_1_5_1_Tom_6_sumHttpSoap11Endpoint" bind-
ing="ns:Axis2_1_5_1_Tom_6_sumSoap11Binding">
            <soap:address loca-
tion="http://localhost:8888/Axis2_1_5_1_Tom_6/services/Axis2_1_5_1_Tom_6_sum.Axis2_
1_5_1_Tom_6_sumHttpSoap11Endpoint/"/>
        </wsdl:port>
        <wsdl:port name="Axis2_1_5_1_Tom_6_sumHttpSoap12Endpoint" bind-
ing="ns:Axis2_1_5_1_Tom_6_sumSoap12Binding">
            <soap12:address loca-
tion="http://localhost:8888/Axis2_1_5_1_Tom_6/services/Axis2_1_5_1_Tom_6_sum.Axis2_
1_5_1_Tom_6_sumHttpSoap12Endpoint/"/>
        </wsdl:port>
        <wsdl:port name="Axis2_1_5_1_Tom_6_sumHttpEndpoint" bind-
ing="ns:Axis2_1_5_1_Tom_6_sumHttpBinding">
            <http:address loca-
tion="http://localhost:8888/Axis2_1_5_1_Tom_6/services/Axis2_1_5_1_Tom_6_sum.Axis2_
1_5_1_Tom_6_sumHttpEndpoint/"/>
        </wsdl:port>
    </wsdl:service>
</wsdl:definitions>
```

Appendix C: WSDL of Axis2-1.6.1 WS running on apache-tomcat-6.0.18 server


```xml
<?xml version="1.0" encoding="UTF-8"?><wsdl:definitions
xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/" xmlns:ns="http://Axis2_1_6_1_Tom_6"
xmlns:wsaw="http://www.w3.org/2006/05/addressing/wsdl"
xmlns:mime="http://schemas.xmlsoap.org/wsdl/mime/"
xmlns:http="http://schemas.xmlsoap.org/wsdl/http/"
xmlns:xs="http://www.w3.org/2001/XMLSchema"
xmlns:soap12="http://schemas.xmlsoap.org/wsdl/soap12/"
xmlns:ns1="http://org.apache.axis2/xsd"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/" target-
Namespace="http://Axis2_1_6_1_Tom_6">
  <wsdl:documentation>
              Please Type your service description here
        </wsdl:documentation>
  <wsdl:types>
    <xs:schema attributeFormDefault="qualified" elementFormDefault="qualified" target-
Namespace="http://Axis2_1_6_1_Tom_6">
      <xs:element name="addIntegers">
        <xs:complexType>
          <xs:sequence>
            <xs:element minOccurs="0" name="firstNum" type="xs:int"/>
            <xs:element minOccurs="0" name="secondNum" type="xs:int"/>
          </xs:sequence>
        </xs:complexType>
      </xs:element>
      <xs:element name="addIntegersResponse">
        <xs:complexType>
          <xs:sequence>
            <xs:element minOccurs="0" name="return" type="xs:int"/>
          </xs:sequence>
        </xs:complexType>
      </xs:element>
      <xs:element name="factorial">
        <xs:complexType>
          <xs:sequence>
            <xs:element minOccurs="0" name="n" type="xs:int"/>
          </xs:sequence>
        </xs:complexType>
```

```
         </xs:element>
         <xs:element name="factorialResponse">
            <xs:complexType>
               <xs:sequence>
                  <xs:element minOccurs="0" name="return" type="xs:int"/>
               </xs:sequence>
            </xs:complexType>
         </xs:element>
      </xs:schema>
   </wsdl:types>
   <wsdl:message name="factorialRequest">
      <wsdl:part name="parameters" element="ns:factorial"/>
   </wsdl:message>
   <wsdl:message name="factorialResponse">
      <wsdl:part name="parameters" element="ns:factorialResponse"/>
   </wsdl:message>
   <wsdl:message name="addIntegersRequest">
      <wsdl:part name="parameters" element="ns:addIntegers"/>
   </wsdl:message>
   <wsdl:message name="addIntegersResponse">
      <wsdl:part name="parameters" element="ns:addIntegersResponse"/>
   </wsdl:message>
   <wsdl:portType name="Axis2_1_6_1_Tom_6_sumPortType">
      <wsdl:operation name="factorial">
         <wsdl:input message="ns:factorialRequest" wsaw:Action="urn:factorial"/>
         <wsdl:output message="ns:factorialResponse"
wsaw:Action="urn:factorialResponse"/>
      </wsdl:operation>
      <wsdl:operation name="addIntegers">
         <wsdl:input message="ns:addIntegersRequest" wsaw:Action="urn:addIntegers"/>
         <wsdl:output message="ns:addIntegersResponse"
wsaw:Action="urn:addIntegersResponse"/>
      </wsdl:operation>
   </wsdl:portType>
   <wsdl:binding name="Axis2_1_6_1_Tom_6_sumSoap11Binding"
type="ns:Axis2_1_6_1_Tom_6_sumPortType">
      <soap:binding transport="http://schemas.xmlsoap.org/soap/http" style="document"/>
      <wsdl:operation name="factorial">
         <soap:operation soapAction="urn:factorial" style="document"/>
         <wsdl:input>
```

```
            <soap:body use="literal"/>
        </wsdl:input>
        <wsdl:output>
            <soap:body use="literal"/>
        </wsdl:output>
    </wsdl:operation>
    <wsdl:operation name="addIntegers">
        <soap:operation soapAction="urn:addIntegers" style="document"/>
        <wsdl:input>
            <soap:body use="literal"/>
        </wsdl:input>
        <wsdl:output>
            <soap:body use="literal"/>
        </wsdl:output>
    </wsdl:operation>
</wsdl:binding>
<wsdl:binding name="Axis2_1_6_1_Tom_6_sumSoap12Binding"
type="ns:Axis2_1_6_1_Tom_6_sumPortType">
    <soap12:binding transport="http://schemas.xmlsoap.org/soap/http" style="document"/>
    <wsdl:operation name="factorial">
        <soap12:operation soapAction="urn:factorial" style="document"/>
        <wsdl:input>
            <soap12:body use="literal"/>
        </wsdl:input>
        <wsdl:output>
            <soap12:body use="literal"/>
        </wsdl:output>
    </wsdl:operation>
    <wsdl:operation name="addIntegers">
        <soap12:operation soapAction="urn:addIntegers" style="document"/>
        <wsdl:input>
            <soap12:body use="literal"/>
        </wsdl:input>
        <wsdl:output>
            <soap12:body use="literal"/>
        </wsdl:output>
    </wsdl:operation>
</wsdl:binding>
<wsdl:binding name="Axis2_1_6_1_Tom_6_sumHttpBinding"
type="ns:Axis2_1_6_1_Tom_6_sumPortType">
```

```
        <http:binding verb="POST"/>
        <wsdl:operation name="factorial">
            <http:operation location="factorial"/>
            <wsdl:input>
                <mime:content type="text/xml" part="parameters"/>
            </wsdl:input>
            <wsdl:output>
                <mime:content type="text/xml" part="parameters"/>
            </wsdl:output>
        </wsdl:operation>
        <wsdl:operation name="addIntegers">
            <http:operation location="addIntegers"/>
            <wsdl:input>
                <mime:content type="text/xml" part="parameters"/>
            </wsdl:input>
            <wsdl:output>
                <mime:content type="text/xml" part="parameters"/>
            </wsdl:output>
        </wsdl:operation>
    </wsdl:binding>
    <wsdl:service name="Axis2_1_6_1_Tom_6_sum">
        <wsdl:port name="Axis2_1_6_1_Tom_6_sumHttpSoap11Endpoint" bind-
ing="ns:Axis2_1_6_1_Tom_6_sumSoap11Binding">
            <soap:address loca-
tion="http://localhost:8888/Axis2_1_6_1_Tom_6/services/Axis2_1_6_1_Tom_6_sum.Axis2_
1_6_1_Tom_6_sumHttpSoap11Endpoint/"/>
        </wsdl:port>
        <wsdl:port name="Axis2_1_6_1_Tom_6_sumHttpSoap12Endpoint" bind-
ing="ns:Axis2_1_6_1_Tom_6_sumSoap12Binding">
            <soap12:address loca-
tion="http://localhost:8888/Axis2_1_6_1_Tom_6/services/Axis2_1_6_1_Tom_6_sum.Axis2_
1_6_1_Tom_6_sumHttpSoap12Endpoint/"/>
        </wsdl:port>
        <wsdl:port name="Axis2_1_6_1_Tom_6_sumHttpEndpoint" bind-
ing="ns:Axis2_1_6_1_Tom_6_sumHttpBinding">
            <http:address loca-
tion="http://localhost:8888/Axis2_1_6_1_Tom_6/services/Axis2_1_6_1_Tom_6_sum.Axis2_
1_6_1_Tom_6_sumHttpEndpoint/"/>
        </wsdl:port>
    </wsdl:service>
</wsdl:definitions>
```

Appendix D: WSDL of CXF-2.5.11 WS running on apache-tomcat-7.0.72 server


```xml
<?xml version='1.0' encoding='UTF-8'?><wsdl:definitions
xmlns:xsd="http://www.w3.org/2001/XMLSchema"
xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/" xmlns:tns="http://CXF_2__5_11_Tom_7/"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
name="CXF_2__5_11_Tom_7_sumService" target-
Namespace="http://CXF_2__5_11_Tom_7/">
 <wsdl:types>
<schema xmlns:xsd="http://www.w3.org/2001/XMLSchema"
xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/" xmlns:tns="http://CXF_2__5_11_Tom_7/"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
xmlns="http://www.w3.org/2001/XMLSchema">
<import namespace="http://CXF_2__5_11_Tom_7/" schemaLoca-
tion="cxf_2__5_11_tom_7_sum_schema1.xsd"/>
</schema>
 </wsdl:types>
 <wsdl:message name="addIntegers">
  <wsdl:part element="tns:addIntegers" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="factorialResponse">
  <wsdl:part element="tns:factorialResponse" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="addIntegersResponse">
  <wsdl:part element="tns:addIntegersResponse" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="factorial">
  <wsdl:part element="tns:factorial" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:portType name="CXF_2__5_11_Tom_7_sum">
  <wsdl:operation name="addIntegers">
   <wsdl:input message="tns:addIntegers" name="addIntegers">
  </wsdl:input>
   <wsdl:output message="tns:addIntegersResponse" name="addIntegersResponse">
  </wsdl:output>
```

```
    </wsdl:operation>
    <wsdl:operation name="factorial">
      <wsdl:input message="tns:factorial" name="factorial">
    </wsdl:input>
      <wsdl:output message="tns:factorialResponse" name="factorialResponse">
    </wsdl:output>
    </wsdl:operation>
  </wsdl:portType>
  <wsdl:binding name="CXF_2__5_11_Tom_7_sumServiceSoapBinding"
type="tns:CXF_2__5_11_Tom_7_sum">
    <soap:binding style="document" transport="http://schemas.xmlsoap.org/soap/http"/>
    <wsdl:operation name="addIntegers">
      <soap:operation soapAction="" style="document"/>
      <wsdl:input name="addIntegers">
        <soap:body use="literal"/>
      </wsdl:input>
      <wsdl:output name="addIntegersResponse">
        <soap:body use="literal"/>
      </wsdl:output>
    </wsdl:operation>
    <wsdl:operation name="factorial">
      <soap:operation soapAction="" style="document"/>
      <wsdl:input name="factorial">
        <soap:body use="literal"/>
      </wsdl:input>
      <wsdl:output name="factorialResponse">
        <soap:body use="literal"/>
      </wsdl:output>
    </wsdl:operation>
  </wsdl:binding>
  <wsdl:service name="CXF_2__5_11_Tom_7_sumService">
    <wsdl:port binding="tns:CXF_2__5_11_Tom_7_sumServiceSoapBinding"
name="CXF_2__5_11_Tom_7_sumPort">
      <soap:address loca-
tion="http://localhost:8889/CXF_2__5_11_Tom_7/services/CXF_2__5_11_Tom_7_sumPort
"/>
    </wsdl:port>
  </wsdl:service>
</wsdl:definitions>
```

Appendix E: WSDL of CXF-2.3.10 WS running on apache-tomcat-6.0.18 server


```
<?xml version='1.0' encoding='UTF-8'?><wsdl:definitions
name="CXF_2_3_10_Tom_6_sumService" target-
Namespace="http://CXF_2_3_10_Tom_6/"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
xmlns:tns="http://CXF_2_3_10_Tom_6/" xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/"
xmlns:xsd="http://www.w3.org/2001/XMLSchema">
 <wsdl:types>
<schema xmlns="http://www.w3.org/2001/XMLSchema"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
xmlns:tns="http://CXF_2_3_10_Tom_6/" xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/"
xmlns:xsd="http://www.w3.org/2001/XMLSchema">
<import namespace="http://CXF_2_3_10_Tom_6/" schemaLoca-
tion="cxf_2_3_10_tom_6_sum_schema1.xsd"/>
</schema>
 </wsdl:types>
 <wsdl:message name="factorial">
  <wsdl:part element="tns:factorial" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="addIntegersResponse">
  <wsdl:part element="tns:addIntegersResponse" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="factorialResponse">
  <wsdl:part element="tns:factorialResponse" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="addIntegers">
  <wsdl:part element="tns:addIntegers" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:portType name="CXF_2_3_10_Tom_6_sum">
  <wsdl:operation name="factorial">
   <wsdl:input message="tns:factorial" name="factorial">
  </wsdl:input>
   <wsdl:output message="tns:factorialResponse" name="factorialResponse">
  </wsdl:output>
```

```
    </wsdl:operation>
    <wsdl:operation name="addIntegers">
      <wsdl:input message="tns:addIntegers" name="addIntegers">
    </wsdl:input>
      <wsdl:output message="tns:addIntegersResponse" name="addIntegersResponse">
    </wsdl:output>
    </wsdl:operation>
  </wsdl:portType>
  <wsdl:binding name="CXF_2_3_10_Tom_6_sumServiceSoapBinding"
type="tns:CXF_2_3_10_Tom_6_sum">
    <soap:binding style="document" transport="http://schemas.xmlsoap.org/soap/http"/>
    <wsdl:operation name="factorial">
      <soap:operation soapAction="" style="document"/>
      <wsdl:input name="factorial">
        <soap:body use="literal"/>
      </wsdl:input>
      <wsdl:output name="factorialResponse">
        <soap:body use="literal"/>
      </wsdl:output>
    </wsdl:operation>
    <wsdl:operation name="addIntegers">
      <soap:operation soapAction="" style="document"/>
      <wsdl:input name="addIntegers">
        <soap:body use="literal"/>
      </wsdl:input>
      <wsdl:output name="addIntegersResponse">
        <soap:body use="literal"/>
      </wsdl:output>
    </wsdl:operation>
  </wsdl:binding>
  <wsdl:service name="CXF_2_3_10_Tom_6_sumService">
    <wsdl:port binding="tns:CXF_2_3_10_Tom_6_sumServiceSoapBinding"
name="CXF_2_3_10_Tom_6_sumPort">
      <soap:address loca-
tion="http://localhost:8888/CXF_2_3_10_Tom_6/services/CXF_2_3_10_Tom_6_sumPort"/>
    </wsdl:port>
  </wsdl:service>
</wsdl:definitions>
```

Appendix F: WSDL of CXF-2.6.3 WS running on apache-tomcat-7.0.72 server

```
<?xml version='1.0' encoding='UTF-8'?><wsdl:definitions
xmlns:xsd="http://www.w3.org/2001/XMLSchema"
xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/" xmlns:tns="http://CXF_2_6_3_Tom_7/"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
name="CXF_2_6_3_Tom_7_sumService" targetNamespace="http://CXF_2_6_3_Tom_7/">
 <wsdl:types>
<schema xmlns:xsd="http://www.w3.org/2001/XMLSchema"
xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/" xmlns:tns="http://CXF_2_6_3_Tom_7/"
xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
xmlns="http://www.w3.org/2001/XMLSchema">
<import namespace="http://CXF_2_6_3_Tom_7/" schemaLoca-
tion="cxf_2_6_3_tom_7_sum_schema1.xsd"/>
</schema>
 </wsdl:types>
 <wsdl:message name="factorial">
  <wsdl:part element="tns:factorial" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="factorialResponse">
  <wsdl:part element="tns:factorialResponse" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="addIntegers">
  <wsdl:part element="tns:addIntegers" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:message name="addIntegersResponse">
  <wsdl:part element="tns:addIntegersResponse" name="parameters">
  </wsdl:part>
 </wsdl:message>
 <wsdl:portType name="CXF_2_6_3_Tom_7_sum">
  <wsdl:operation name="factorial">
   <wsdl:input message="tns:factorial" name="factorial">
  </wsdl:input>
   <wsdl:output message="tns:factorialResponse" name="factorialResponse">
  </wsdl:output>
  </wsdl:operation>
```

```
    <wsdl:operation name="addIntegers">
      <wsdl:input message="tns:addIntegers" name="addIntegers">
    </wsdl:input>
      <wsdl:output message="tns:addIntegersResponse" name="addIntegersResponse">
    </wsdl:output>
    </wsdl:operation>
  </wsdl:portType>
  <wsdl:binding name="CXF_2_6_3_Tom_7_sumServiceSoapBinding"
type="tns:CXF_2_6_3_Tom_7_sum">
    <soap:binding style="document" transport="http://schemas.xmlsoap.org/soap/http"/>
    <wsdl:operation name="factorial">
      <soap:operation soapAction="" style="document"/>
      <wsdl:input name="factorial">
        <soap:body use="literal"/>
      </wsdl:input>
      <wsdl:output name="factorialResponse">
        <soap:body use="literal"/>
      </wsdl:output>
    </wsdl:operation>
    <wsdl:operation name="addIntegers">
      <soap:operation soapAction="" style="document"/>
      <wsdl:input name="addIntegers">
        <soap:body use="literal"/>
      </wsdl:input>
      <wsdl:output name="addIntegersResponse">
        <soap:body use="literal"/>
      </wsdl:output>
    </wsdl:operation>
  </wsdl:binding>
  <wsdl:service name="CXF_2_6_3_Tom_7_sumService">
    <wsdl:port binding="tns:CXF_2_6_3_Tom_7_sumServiceSoapBinding"
name="CXF_2_6_3_Tom_7_sumPort">
      <soap:address loca-
tion="http://localhost:8889/CXF_2_6_3_Tom_7/services/CXF_2_6_3_Tom_7_sumPort"/>
    </wsdl:port>
  </wsdl:service>
</wsdl:definitions>
```

Appendix G: Java Class for Communication between ITWS and Database

```
import java.sql.Connection;
import java.sql.DriverManager;
import java.sql.ResultSet;
import java.sql.Statement;
import java.util.ArrayList;
import java.util.Collections;

public class DBClass {
   public static String create(int group, int priority){
      String result = "";
      try{
         Connection conn = DriverManager.getConnection
            ("jdbc:oracle:thin:@//localhost:1521/xe", "sys as sysdba", "Passwor123");
         Statement stmt =
conn.createStatement(ResultSet.TYPE_SCROLL_SENSITIVE,ResultSet.CONCUR_READ
_ONLY);
         Statement stmt2 =
conn.createStatement(ResultSet.TYPE_SCROLL_SENSITIVE,ResultSet.CONCUR_READ
_ONLY);
         ResultSet rset = stmt.executeQuery("SELECT
ENDPOINT,TARGETNAMESPACE,OPERATION,INPUT FROM HR.WEBSERVICES " +
            "WHERE SERVICEGROUP =" + group + "AND PRIORITY = " + priority);
         int i = 0;
         ArrayList<String> ENDPOINTS = new ArrayList<String>();
         ArrayList<String> TARGETNAMESPACES = new ArrayList<String>();
         ArrayList<String> OPERATIONS = new ArrayList<String>();
         ArrayList<String> INPUTS = new ArrayList<String>();
         while (rset.next()) {
            ENDPOINTS.add(i, rset.getString("ENDPOINT"));
            TARGETNAMESPACES.add(i, rset.getString("TARGETNAMESPACE"));
            OPERATIONS.add(i, rset.getString("OPERATION"));
            INPUTS.add(i, rset.getString("INPUT"));
            i++;
            }
         for (int j = 0; j < ENDPOINTS.size(); j++) {
            result += ENDPOINTS.get(j) + "," + TARGETNAMESPACES.get(j) + "," +
OPERATIONS.get(j)
```

```
                + "," + INPUTS.get(j) + "]";
            }
        ResultSet rset2 = stmt2.executeQuery("SELECT PRIORITY FROM
HR.WEBSERVICES");
        int x = 0;
        ArrayList<Integer> PRIORITY = new ArrayList<Integer>();

        while (rset2.next()) {
            PRIORITY.add(x, Integer.parseInt(rset2.getString("PRIORITY")));
            i++;
            }
        result += String.valueOf(Collections.max(PRIORITY));
        conn.close();
    } catch (Exception ex) {
        ex.printStackTrace();
        }
    return result;
    }
}
```

Appendix H: Java Class for Dynamic WS Invocation Using RPC Library

```
import java.util.Iterator;
import javax.xml.soap.MessageFactory;
import javax.xml.soap.MimeHeaders;
import javax.xml.soap.SOAPBody;
import javax.xml.soap.SOAPBodyElement;
import javax.xml.soap.SOAPConnection;
import javax.xml.soap.SOAPConnectionFactory;
import javax.xml.soap.SOAPElement;
import javax.xml.soap.SOAPEnvelope;
import javax.xml.soap.SOAPMessage;
import javax.xml.soap.SOAPPart;

public class Client {

    //Starting point for the SAAJ - SOAP Client Testing
    public static String create(String serviceInfo) {
        String result = "";
        String[] serviceInformation = serviceInfo.split("\\,");
        try {
            // Create SOAP Connection
            SOAPConnectionFactory soapConnectionFactory = SOAPConnectionFacto-
ry.newInstance();
            SOAPConnection soapConnection = soapConnectionFactory.createConnection();

            // Send SOAP Message to SOAP Server
            String url = serviceInformation[0];
            SOAPMessage soapResponse = soapConnec-
tion.call(createSOAPRequest(serviceInformation[1], serviceInformation[2],
                                                    serviceInformation[3], serviceInfor-
mation[4]), url);

            // Process the SOAP Response
            result = printSOAPResponse(soapResponse);
            soapConnection.close();

        } catch (Exception e) {
            System.err.println("Error occurred while sending SOAP Request to Server");
```

```
        e.printStackTrace();
      }
      return result;
    }
    /**
     * Method used to print the SOAP Response
     */
    private static String printSOAPResponse(SOAPMessage soapResponse) throws Excep-
tion {
      String result = "";
      SOAPBody responseBody = soapResponse.getSOAPBody();
      Iterator it1 = responseBody.getChildElements();
       while (it1.hasNext()) {
          SOAPBodyElement bodyEl = (SOAPBodyElement)it1.next();
          Iterator it2 = bodyEl.getChildElements();
          while (it2.hasNext()) {
             SOAPElement child2 = (SOAPElement)it2.next();
             result = child2.getValue();
             }
          }
       return result;
    }
private static SOAPMessage createSOAPRequest(String namespace, String operation,
String input1, String input2) throws Exception {
      MessageFactory messageFactory = MessageFactory.newInstance();
      SOAPMessage soapMessage = messageFactory.createMessage();
      SOAPPart soapPart = soapMessage.getSOAPPart();
      String serverURI = namespace;
      // SOAP Envelope
      SOAPEnvelope envelope = soapPart.getEnvelope();
      envelope.addNamespaceDeclaration("example", serverURI);
      // SOAP Body
      SOAPBody soapBody = envelope.getBody();
      SOAPElement soapBodyElem = soapBody.addChildElement(operation, "example");
      SOAPElement soapBodyElem1 = soapBodyElem.addChildElement(input1, "example");
      soapBodyElem1.addTextNode("10");
      SOAPElement soapBodyElem2 = soapBodyElem.addChildElement(input2, "example");
      soapBodyElem2.addTextNode("12");
      MimeHeaders headers = soapMessage.getMimeHeaders();
      headers.addHeader("SOAPAction", serverURI  + operation);
```

```
        soapMessage.saveChanges();
        /* Print the request message */
        System.out.print("Request SOAP Message = ");
        soapMessage.writeTo(System.out);
        System.out.println();
        return soapMessage;
    }
}
```

Appendix I: Java Class for Dynamic WS Invocation through RPC and Java Multi-Threading Libraries

```
import java.util.HashSet;
import java.util.Iterator;
import java.util.List;
import java.util.Set;
import java.util.concurrent.Callable;
import java.util.concurrent.ExecutorService;
import java.util.concurrent.Executors;
import java.util.concurrent.Future;

import javax.xml.soap.MessageFactory;
import javax.xml.soap.MimeHeaders;
import javax.xml.soap.SOAPBody;
import javax.xml.soap.SOAPBodyElement;
import javax.xml.soap.SOAPConnection;
import javax.xml.soap.SOAPConnectionFactory;
import javax.xml.soap.SOAPElement;
import javax.xml.soap.SOAPEnvelope;
import javax.xml.soap.SOAPMessage;
import javax.xml.soap.SOAPPart;


public class Client2 {

    public static String create(String input) {
        String result = "";
        ExecutorService executorService = Executors.newSingleThreadExecutor();
        Set<Callable<String>> callables = new HashSet<Callable<String>>();
        String[] serviceInfo = input.split("\\]");

        for (int i = 0; i < (serviceInfo.length)-1; i++) {
            final int counter = i;
            callables.add(new Callable<String>() {
                public String call() throws Exception {
                    return serviceClient(serviceInfo[counter]);
                }
            });
```

```
        }
        try {
            List<Future<String>> futures = executorService.invokeAll(callables);
            for(Future<String> future : futures){
                System.out.println("future.get = " + future.get());
                result += future.get() + ",";
                }
            executorService.shutdown();
        } catch (Exception e) {
            e.printStackTrace();
        }

        return result;
        }

public static String serviceClient(String input) {
        String result = "";
        String[] serviceInfo = input.split("\\,");
        try {
            // Create SOAP Connection
            SOAPConnectionFactory soapConnectionFactory = SOAPConnectionFacto-
ry.newInstance();
            SOAPConnection soapConnection = soapConnectionFactory.createConnection();
            // Send SOAP Message to SOAP Server
            String url = serviceInfo[0];
            SOAPMessage soapResponse = soapConnec-
tion.call(createSOAPRequest(serviceInfo[1], serviceInfo[2],
                                                        serviceInfo[3], serviceInfo[4]), url);
            result = printSOAPResponse(soapResponse);
            soapConnection.close();
        } catch (Exception e) {
            System.err.println("Error occurred while sending SOAP Request to Server");
            e.printStackTrace();
        }
        return result;
        }
    private static SOAPMessage createSOAPRequest(String namespace, String operation,
String input1, String input2) throws Exception {
        MessageFactory messageFactory = MessageFactory.newInstance();
        SOAPMessage soapMessage = messageFactory.createMessage();
```

```
        SOAPPart soapPart = soapMessage.getSOAPPart();
        String serverURI = namespace;
        SOAPEnvelope envelope = soapPart.getEnvelope();
        envelope.addNamespaceDeclaration("example", serverURI);
        SOAPBody soapBody = envelope.getBody();
        SOAPElement soapBodyElem = soapBody.addChildElement(operation, "example");
        SOAPElement soapBodyElem1 = soapBodyElem.addChildElement(input1, "example");
        soapBodyElem1.addTextNode("10");
        SOAPElement soapBodyElem2 = soapBodyElem.addChildElement(input2, "example");
        soapBodyElem2.addTextNode("12");
        MimeHeaders headers = soapMessage.getMimeHeaders();
        headers.addHeader("SOAPAction", serverURI  + operation);
        soapMessage.saveChanges();
        System.out.print("Request SOAP Message = ");
        soapMessage.writeTo(System.out);
        System.out.println();
        return soapMessage;
        }
// Method used to print the SOAP Response
    private static String printSOAPResponse(SOAPMessage soapResponse) throws Excep-
tion {
        String result = "";
        SOAPBody responseBody = soapResponse.getSOAPBody();
        Iterator it1 = responseBody.getChildElements();
         while (it1.hasNext()) {
             SOAPBodyElement bodyEl = (SOAPBodyElement)it1.next();
             Iterator it2 = bodyEl.getChildElements();
             while (it2.hasNext()) {
                 SOAPElement child2 = (SOAPElement)it2.next();
                 result = child2.getValue();
                 }
             }
         return result;
        }
        }
```

Appendix J: Remaining Java Codes for Chapter 7

Code J.1 Java as BPEL Extension for Executing Database Query Class

```
String priority1 = (String) getVariableData("Priority");
String group1 = (String) getVariableData("Service-Group");
int priority = Integer.parseInt(priority1);
int group = Integer.parseInt(group1);

String result = DBClass.create(group, priority);
setVariableData("DB-Result", result);

 String[] counter = result.split("\\[");
setVariableData("Loop-Cycles", Integer.parseInt(counter[1]));
String[] result2 = counter[0].split("\\]");
setVariableData("Max-Priority-From-DB",result2[(result2.length)-1]);
```

Code J.2 Java as BPEL Extension for Executing Dynamic Service Invocation Class

```
String input = (String) getVariableData("DB-Result");
int counter = (int) getVariableData("ForEach1Counter");
String[] result = input.split("\\]");
setVariableData("Invocation-Result",getVariableData("Invocation-Result") + Cli-
ent.create(result[counter-1]) +",");
```

Code J.3 Java Code for Performing Majority Voting

```
String value = (String) getVariableData("Invocation-Result");
String[] values = value.split(",");
int maxValue = 0, maxCount = 0;
for (int i = 0; i < values.length; i++) {
    int count = 0;
    for (int j = 0; j < values.length; ++j) {
        if (values [j] == values [i]) {
            ++count;
        }
        if (count > maxCount) {
            maxCount = count;
            maxValue = values[i];
        }
}
setVariableData("output", maxValue);
```

Code J.4 Java Code for Performing Fault-Tolerance

```
 String priority1 = (String) getVariableData("Priority");
int priority = Integer.parseInt(priority1);

String maximum1 = (String) getVariableData("Max-Priority-From-DB");
int maximum = Integer.parseInt(maximum1);

if(priority <= maximum) {
  setVariableData("Priority", String.valueOf(priority+1));
} else {
  setVariableData("Flag", String.valueOf(0));
}
```

Code J.5 Java code for Writing BP's Start and End Times into a File

```
import java.io.BufferedWriter;
import java.io.FileWriter;
public class StringTampering {
    public static void test(String start, String end) {
        try {
            FileWriter fstream = new FileWriter("C:\\Users\\...", true);
            BufferedWriter out = new BufferedWriter(fstream);
            String start1 = start.replace(":", ".");
            String end1 = end.replace(":", ".");
            Float result = Float.valueOf(end1)-Float.valueOf(start1);
            out.write(String.format("%.3f", result));
            out.newLine();
            //close buffer writer
            out.close();
        } catch (Exception e) {
            System.out.println(e);
        }
    }
}
```

Code J.6 Java Code for Writing the BP's Start and End Times into a File

```
StringTampering.test((String)getVariableData("Start"),(String)getVariableData("End"));
```

Code J.7 Java Code for Executing Database Query Class

```
String priority1 = (String) getVariableData("Priority");
String group1 = (String) getVariableData("Service-Group");
int priority = Integer.parseInt(priority1);
int group = Integer.parseInt(group1);

String result = DBClass.create(group, priority);
setVariableData("DB-Result", result);

String[] result2 = result.split("\\]");
setVariableData("Max-Priority-From-DB",result2[result2.length-1]);
```

Code J.8 Java Code for Executing Dynamic Service Invocation Class

```
String input = (String) getVariableData("DB-Result");
setVariableData("Invocation-Result",Client2.create(input));
```