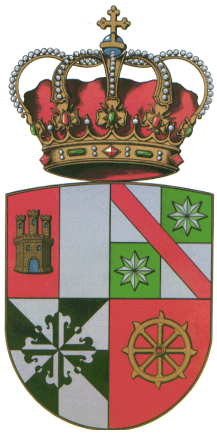
Verification and Validation of Web Service Compositions using Formal Methods



Dissertation for the degree of Doctor of Computer Science to be presented with due permission of the Department of Computer Science, for public examination and debate

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Author: *José Antonio Mateo Cortés*

Supervisors: *Dr. Valentín Valero Ruiz*

Dr. Jiří Srba

Acknowledgements

Abstract

Nowadays, most of the computing systems are based on service-oriented computing (SOC). This paradigm aims at replacing complex monolithic systems by a composition of interacting systems called services. A service encapsulates self-contained functionality and offers it over a well-defined and standardized interface. It allows cross-organizational collaborations in which each participant is in charge of a particular tasks leading to the development of scalable, flexible and low-cost distributed applications. Each service works as an autonomous component, performing only the tasks for which it has been implemented. As the development of such services is independent, companies can reuse a considerable amount of components, thus saving money and time. Moreover, these technologies are widely used due to their ability to provide interoperability among services from different companies since all the participants know the services offered by the others as well as how to access them.

Due to privacy concerns or commercial policy, entities participating in one of these architectures have no access to complete information, that is, he code implementing the services the particpants consume is hidden, thus being impossible to examine or verify the implementation of the consumed services. Another issue is that web services are usually *stateless*, which means that no state is stored from the clients viewpoint. However, some new applications and services have emerged, which require to capture the state of some resources. Thus, new standards to manage the state of a web service have appeared. For instance, Open Grid Services Infrastructure (OGSI) was conceived to allow designers to manage resources when using web services, and this standard became Web Services Resource Framework (WSRF) when new improvements were introduced.

Obviously, in this scenario the probability of making errors is higher than working in a monolithic scenario. Therefore, there is a clear need of apply-

ing any kind of technique to ensure the correctness of each participant and their composition. In this Thesis, we present a formal language called BPELRF and its semantics. The aim of this language is to model a set of bussiness processess implemented in the de-facto standard modelling language, WS-BPEL, but enriched with the ability to manage distributed resources. These distributed resources are managed according to the guidelines provided by the standard WSRF. Moreover, we provide a visual model of this language in terms of coloured Petri nets in order to ease uninitiated people to deal with it, and we use the well-known toolbox, CPNTools, to verify the composition of web services with distributed resources expressed in BPELRF. As usual, the process of building manually the Petri nets model of large scenarios is time-consuming and error-prone. Therefore, we have implemented a tool to support web designers that, given a BPELRF specification, it extracts automatically the coloured Petri nets of the scenario. Finally, this model can be verified using CPNTools.

On the second part of the Thesis, we extend the classical definition of Workflow nets with time features. Workflow nets were introduced by Wil van der Aalst as a formalism for the modelling, analysis and verification of business workflow processes. The formalism is based on Petri nets abstracting away most of the data while focusing on the possible flow in the system. Its intended use is in finding design errors such as the presence of deadlocks, livelocks and other anomalies in workflow processes. Such correctness criteria can be described via the notion of *soundness* that requires the option to complete the workflow, guarantees proper termination and optionally also the absence of redundant tasks.

After the seminal work on workflow nets, researchers have invested much effort in defining new soundness criteria and/or improving the expressive power of the original model by adding new features and studying the related decidability and complexity questions. In this Thesis, we define a quantitative extension of workflow nets with timing features called timed-arc Workflow nets. It allows us to argue, among others, about the execution intervals of tasks, deadlines and urgent behaviour of workflow processes. Our workflow model is based on timed-arc Petri nets where tokens carry timing information and arcs are labelled with time intervals restricting the available ages of tokens used for transition firing. Here, we consider both discrete and continuous time semantics, thus conforming a whole theory of workflow nets. Finally, all the theory presented in this

thesis have been introduced in the tool Tapaal, offering researchers a mean to model timed-arc workflow nets and to automatically verify (strong) soundness.

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Chapter 1

Introduction

1.1 Motivation

The development of software systems is becoming more complex with the appearance of new computational paradigms such as Service-Oriented Computing (SOC), Grid Computing and Cloud Computing. In these systems, the service provider needs to ensure some levels of quality and privacy to the final user in a way that had never been raised. It is therefore necessary to develop new techniques to benefit from the advantages of recent approaches, as Web service compositions. Formal models of concurrency have been widely used for the description and analysis of concurrent and distributed systems. Grid/Cloud environments are characterized by a dynamic environment due to the heterogeneity and volatility of resources. To composite web services, there are two complementary views: Choreography and Orchestration. The choreography view describes the observable interactions among services and can be defined by using specific languages such as Web Services Choreography Description Language (WS-CDL) or by using more general languages like UML Messages Sequence Charts (MSC). On the other hand, orchestration concerns the internal behaviour of a Web service in terms of invocations to other services. Web Services Business Process Execution Language (WS-BPEL) [1] is normally used to describe Web service orchestrations, so this is considered the de-facto standard language for describing Web services workflows in terms of web service compositions. Later on, a brief

introduction of WS-CDL is provided, and a deep description of WS-BPEL is introduced since it will be used as part of this work.

To facilitate additional interoperability among services, more standardization is required to deal with distributed resources. In January of 2004, several members of the *Globus Alliance* organization and the computer multinational *IBM* with the help of experts from companies such as *HP, SAP, Akamai, etc.* defined the basis architecture and the initial specification documents of a new standard for that purpose, Web Services Resource Framework (WSRF) [**?**]. Although the Web service definition does not consider the notion of state, interfaces frequently provide the user with the ability to access and manipulate states, that is, data values that persist across, and evolve as a result of Web service interactions. The messages that the services send and receive imply (or encourage programmers to infer) the existence of an associated stateful resource. It is then desirable to define Web service conventions to enable the discovery of, introspection on, and interaction with stateful resources in standard and interoperable ways [**?**].

The main motivation of the first part of the Thesis is to provide a formal semantics for WS-BPEL+WSRF to manage stateful Web services workflows by using the existing machinery in distributed systems, and specifically a well-known formalism, such as prioritised-timed coloured Petri nets, which apart of being a graphical model, but they also provide us an easier way to simulate and analyse the modelled system. Thus, our aim is not to provide just another WS-BPEL semantics. In order to deal with the integration of BPEL plus WSRF in a proper way, we have realized that it is more convenient to introduce a specific semantic model, which covers properly all the relevant aspects of WSRF such as notifications and resource time-outs. The integration of WS-BPEL and WSRF is not new; in the literature, there are a bundle of works defining this integration, but none of these works define a formal semantics in terms of Petri nets.

1.2 Objectives

Next, we describe the general and specific objectives of the Thesis.

Main Objective

The main objective of the Thesis can be splitted into two main objectives. The first one is the definition of a formal language to model Grid/Cloud Computing environments, reusing some of the web technologies presented to date. The second one is to propose a new extension of workflow nets in terms of timed-arc Petri nets, thus providing two formal models in which the time semantics is discrete or continuous. Obviously, these objectives are too general and, therefore, we list below a set of subobjectives that are required to achieve these overall objectives.

Specific Objectives

To meet this overall objectives the following specific objectives should be achieved:

- **Objective 1: State-of-the-art**
  1. Study of different formalisms for the modelling and analysis of Grid/-Cloud Computing applications using web services.
  2. Summarise the current definitions of soundness and the different extensions of workflow nets presented to date.
- **Objective 2: Technological framework definition**
  1. Study of the current techniques for modelling and implementing Web service composition and Grid/Cloud Computing applications.
  2. Analyse the different tools for modelling workflow nets as well as possible target applications of the theory presented in this Thesis.
- **Objective 3: Development of the proposal**
  1. Define the specific models, either the operational semantics or the PTCPNs semantics of the language BPELRF.
  2. Extend the current definition of workflow nets with a time semantics.
  3. Adapt the definition of soundness to this timed scenario.
  4. Develop tools within the theory presented here.

5. Analyse and evaluate both proposals.

- **Objective 4: Examples and Case studies**

  1. Propose a set of simple examples where the main features are displayed.
  2. Study a set of theoretical examples where the power of both proposals and its main aspects is characterized .
  3. Demonstrate the applicability of this work applying it to real (industry-based) case studies.

1.3 Dissertation Structure

This Thesis is organised in five different chapters as follows.

Chapter 1 makes a brief introduction of the Thesis, showing the motivation, the main objectives and the scope of it.

Chapter 2 shows the state of art of the contents included here. This chapter includes a brief description of Service-Oriented Computing (SOC) and distributed computing, e.g. Grid and Cloud computing and the use of formal methods for the analysis of web service compositions and the benefits of using formal techniques in the development of software and hardware. Moreover, a deep introduction of the standards used in this work is presented. Finally, we get into workflow nets and the possible extension of this formal model as well as its main properties.

Chapter 3 presents a formal specification language called BPELRF, which takes two well-known standards (WS-BPEL and WSRF) as basis, to model synchronous and asynchronous stateful interactions. This language is enriched with a publish-subscribe architecture, service discovery, event and fault handling and time-outs. As usual, an operational semantics for this language is defined. Moreover, we define a visual model of it in terms of coloured Petri nets and a tool to verify some properties of the specifications written in BPELRF.

In **Chapter 4** we suggest a workflow model based on timed-arc Petri nets and study the foundational problems of soundness and strong (time-bounded) soundness. We explore the decidability of these problems and compare the discrete and continuous semantics of timed-arc workflow nets.

Chapter 5 shows the main conclusions, contributions and future works of this Thesis.

Chapter 2

State of the Art

In this chapter, it will be introduced the state-of-the-art related to the specification, formalization and verfication of stateful web services and their composition as well as the use of formal methods in this topic. The aim of this chapter is to provide the reader with the basic notions about formal methods and stateful web service compositions in order to help he/she in the understanding of the Thesis. To begin with, a brief introduction of formal methods and why they are needed is presented. Second, a survey about the diffent technologies used to model web services and the different approaches to compose them are introduced and, next, the different mechanisms available to improve these web services with distributed resources. Finally, the different formal models used here are defined. On the other hand, we introduce workflow nets and why they are useful to model business processess. Some informal definition about the properties can be studied with this formal model is also provided.

2.1 Motivation

Throughout the history of computing , engineers and researchers have used different formal methods to improve the quality of hardware and software. These systems with continuous technological progress in integration techniques and programming methodologies inevitably grow in scale and complexity. Because of this complexity, the probability of error is higher and, in addition, some of

Figure 2.1: Example of systems where formal methods are (can be) used .

these errors can cause incalculable economic losses, time or even the loss of human lives. Therefore, the main aim of designers should be to provide developers with the required tools to build systems with a negligible error rate and with the lowest cost. However, this task is far from trivial since one needs to ensure the correctness of the specifications and needs to provide techniques that ease error detection and the verification of the developed models without consuming so much time of the development process. One of the ways that engineers have been used to achieve this goal is the use of formal techniques to ensure the correctness of the development process as well as the product under construction. These formal methods can be defined as the set of procedures and tools based on mathematical languages that virtually ensure the correctness of a system [3] since they increase the level of knowledge that the participants have about the system, revealing inconsistencies and ambiguities that could not be detected using other techniques, i.e., the use of formal methods provides a greater degree of refinement of the model than other methods.

In the past, the use of formal techniques in practice seemed to be utopian and unrealizable. Among other causes, the notations used to require a high mathematical background in mathematics and, therefore, they were too complicated for the uninitiated in the topic. The techniques did not allow the system

to be scalable and the existing tools were too difficult to use or understand or even there were no tools for a particular technique or formalism. In addition, case studies were not convincing enough and, therefore, developers could not appreciate the usefulness of formalization. However, in the early 90s, it started to glimpse a new way in this area. For the specification of software, the industry began to use the language Z [6] in order to obtain rigorous specifications. For hardware verification, major companies such as Intel and AMD started to use formal techniques such as *model checking* or *theorem proving* to supplement tests on simulators. This led to the description of larger case studies, which was benefitial for the advance of this area since other developers started to consider the possibility of introducing the use of formal techniques into their development processes. In Figure 2.1, one can observe different systems in which these techniques are currently used to ensure proper operation. For instance, big companies (e.g Boeing and Airbus) use formal languages to specify the requirements of the equipment as well as they use formal methods to verify the most critical systems in the aircrafts. Moreover, automotive companies verify the most critical systems (e.g. brake or airbag systems) using *model checking*.

The main advantages of using formal methods are:

- The use of mathematics as a base gives this approach a certain rigour.
- Identify ambiguity and inconsistencies.
- Facilitates the construction of consistent and *deadlock-free* systems.
- Provides customer confidence in the system.
- There are many tools that support the existing techniques.
- Find bugs early should save money.

The main disadvantages (or beliefs) that slow the progress of this area are:

- It is believed that the use of formal methods slows the development process.
- Many developers think it is difficult to work with formal specifications.
- It does not guarantee the correctness of the implemented code (only the model it is based).

- Increasing system complexity causes an exponential increase the complexity of the verification.

As commented previously, companies can use formal methods along the entire development lifecycle of a system, both hardware and software. Here, we will focus on software since this Thesis studies different standards for building software components. Next, we describe the different phases in which designers can apply any formal technique.

One of the most important part in the development of a system is the requirements specification. A specification can be seen as a technical document where the features and services needed to build a product are stated. Nevertheless, it can also include information on subsequent steps such as verification, validation, testing, etc. Therefore, this should be the first part in which the participants should apply formal methods, taking the required time to correctly specify the system since a neat and correct specification will influence the rest of the proccess. Anyway, make a proper specification does not guarantee the absence of errors because the presence of faults is an intrinsic characteristic of the systems. In this sense, the simple act of writing the document helps engineers to find errors in the early stages of the development process, helping the company to save money and time. In Figure 2.2, one can observe what is the effect (in money) of finding a bug in the different phases. As can be observed, the cost of fixing a bug increases as we advance in the lifecycle and, therefore, it is recommended to find these bugs as soon as possible. In this Thesis, we propose a formal language and its visual model to specify web service compositions with distributed resources, but this will be presented in Chapter 3.

In the classic life cycle, the verification and validation phases are performed after the implementation phase, but as we have seen in Figure 2.2, it is advisable to detect these errors as soon as possible. As expected, it is practically impossible to verify completely all the behaviour of a complex system so that the goal of researchers in this area is to check whether certain properties hold in the model. The properties of interest will be related to the classical problems of concurrency (*deadlock, mutual exclusion,...*) and some aspects directly related to the system itself such as check the adherence of it to certain time constraints. For example, in a banking system, it is mandatory to ensure that transactions

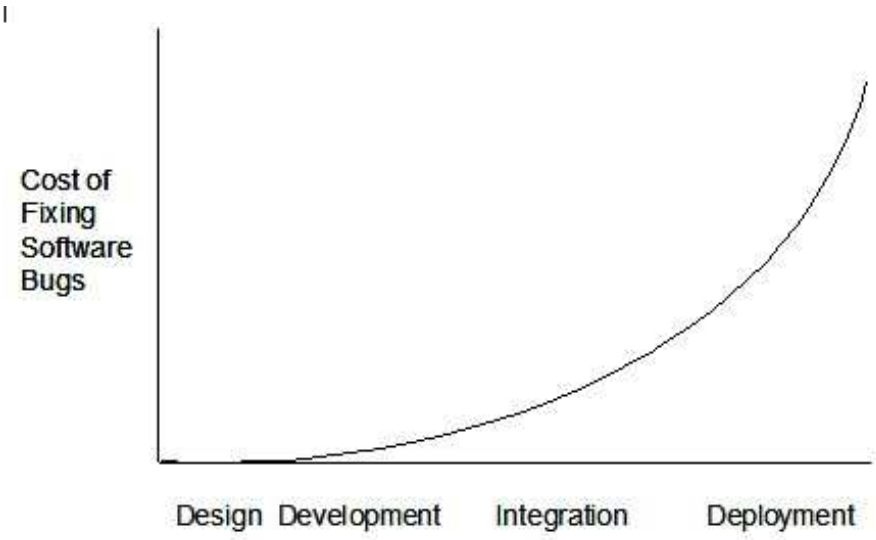

Figure 2.2: Cost evolution of fixing a bug.

meet the stipulated time for completion because if you exceed these restrictions some security issues could come out.

In this sense, one can follow two different ways to perform the verification of a system: *Human-directed proof or Automated proof*. The first one is used when you want to strengthen the knowledge of the system rather than completely ensure the correctness of it, and, therefore, it is a person who check the properties manually. This variant improves the knowledge of the system, but it is time-consuming and error-prone due to the entire process is conducted for a human being. In the second approach (*automated proof*) there are also two variants: *automated theorem proving and model checking*. The *automated theorem proving* is conducted by a program that tries to produce a formal proof of a system from scratch, giving a description of it, a set of logical axioms and a set of inference rules. On the other hand, model checking [4] is a technique for verifying finite state concurrent systems. It has a number of advantages over traditional approaches that are based on simulation, testing, and deductive reasoning. In particular, model checking is normally automatic and usually quite fast. Also, if the design contains an error, model checking will produce a counterexample that can be used to pinpoint the source of the error. Here, the specification can be expressed in propositional temporal logic propositional normally LTL [9] or CTL [11] or some of its variants, and the system is represented as a graph

of transitions between states. The main challenge in model checking is dealing with the state space explosion problem. When dealing with web systems, this problem occurs in systems with many components that can interact with each other or systems with data structures that have many different values. In such cases the number of global states can be enormous. Researchers have made considerable progress on this problem over the last ten years.

2.2 Web Services modelling

Although the Web was initially intended for the exclusive use of human beings, many experts believe that it needs to evolve (probably through modular design and construction services) to better support for the automation of many tasks. The concept of *service* provides a higher level of abstraction to organize large-scale applications and build more open environments, helping to develop applications with improved productivity and quality with respect to other approaches. As services are only a mean for building distributed applications, it is required to evaluate the different existing approaches in this area. Figure 2.3 shows an example of service-based architecture, where there are three main parts: a consumer, a provider (the servers) and a set of records, where the services are stored. The role of the providers is to publish and/or advertise the services offered in the records, where consumers can find and invoke them. Current standards that support interactions between web services provide a solid foundation for service-oriented architecture. The web architecture is a framework that can be reinforced with more powerful representations and techniques inherited from other approaches.

In this way, Service-Oriented Computing (SOC) paradigm promotes the use of services for the development of massively distributed applications, trying to achieve the creation of fast, low-cost, flexible and scalable applications [**?**]. Services are the main building block of this paradigm, being these services self-describing and platform-independent. Thanks to the use of standards for the description, publication, discovery and invocation, the services can be integrated without taking care of the low-level implementation details of each service. The aim of SOC is to make possible the creation of dynamic business processes and

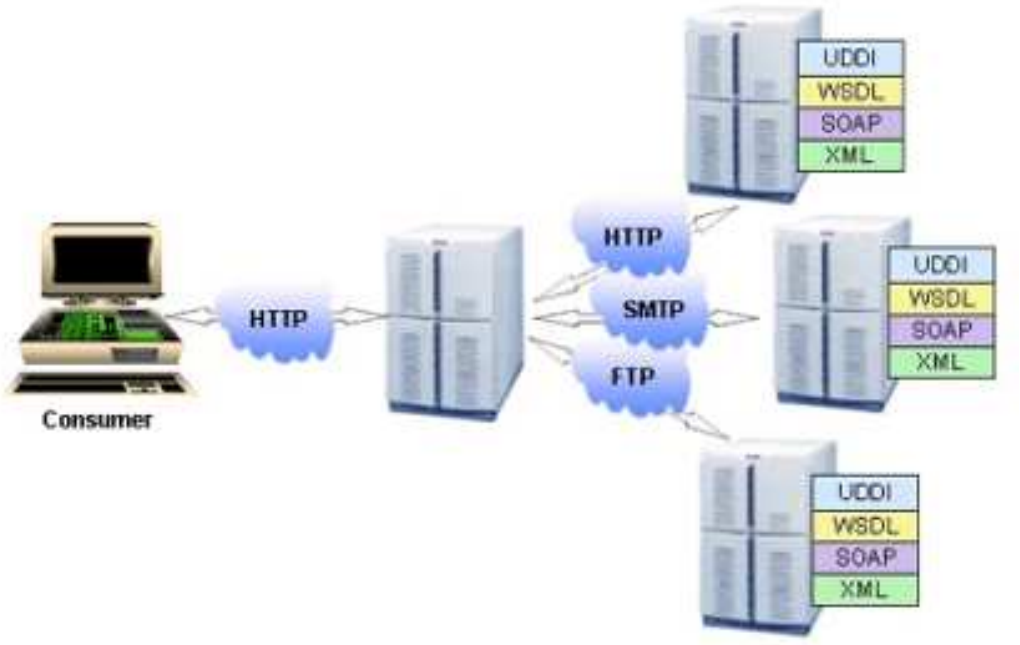

Figure 2.3: Client-server web architecture

agile applications by providing an easy way to assemble application components into a loosely coupled network of services.

To reach the goals of SOC, a Service-Oriented Architecture (SOA) is defined. SOA is a software architecture based on the utilization of services, being these services provided to the user of the application or to other services in the network. This is possible by the use of service interfaces that can be published and discovered. SOA is based on a model of roles where every service can play multiple roles. For example, a service can offer certain functionality to a user and, at the same time, being the consumer of the functionality provided by some other services. Such model reduces the complexity of applications and increases their flexibility. Although at the beginning of SOA there were several architectures aspiring to become SOA standards [**?**, **?**], the most successful one was the architecture based on Web Services.

W3C defines a Web Service (WS) in the following way:

> "A Web Service is a software system designed to support interoperable machine-to-machine interaction over a network. It has an inter-

face described in a machine-processable format (specifically WSDL). Other systems interact with the Web Service in a manner prescribed by its description using SOAP-messages, typically conveyed using HTTP with an XML serialization in conjunction with other Web-related standards."

We can see in this definition that there are two basic standards related to Web Services: Web Service Description Language (WSDL) for the definition of the service functionality and its properties [**?**], and Simple Object Access Protocol (SOAP) for the exchange of XML messages between services [**?**]. There is also an additional standard called Universal Description, Discovery and Integration (UDDI) used to create Web Service directories and to search for services in the network [**?**], but this is a bit out of date. The use of these standard protocols is the key point to improve the integration between different parties in a web service architecture.

In Figure 2.4 a possible representation of the web service architecture stack is shown. One can see that the three standards described above are only a small part of the stack. One also need protocols to define security aspects (ensuring that exchanges of information are not modified or forgotten in a verifiable manner and that parties can be authenticated), to provide reliable messaging for the exchange of information between parties, to specify the collaboration between services when we compose them, to individually describe the behaviour of each service in a business process, etc. The problem is that whereas the standards for basic services (WSDL and SOAP) are widely adopted for their respective purposes, the situation is not very clear when we talk about composing services, having multiple protocols aspiring to become a standard in this layer.

Two different approaches can be followed when we designing web service compositions. They are called *orchestration* and *choreography*. The former describes the individual business process followed by each one of the participants in the composition, while the latter describes the composition from a global viewpoint, defining the interactions (exchange of messages) happening between the parties, that is, how they collaborate in the composition. In Figure **??**, it is depicted graphically what it the role of each of them if they are compared with the

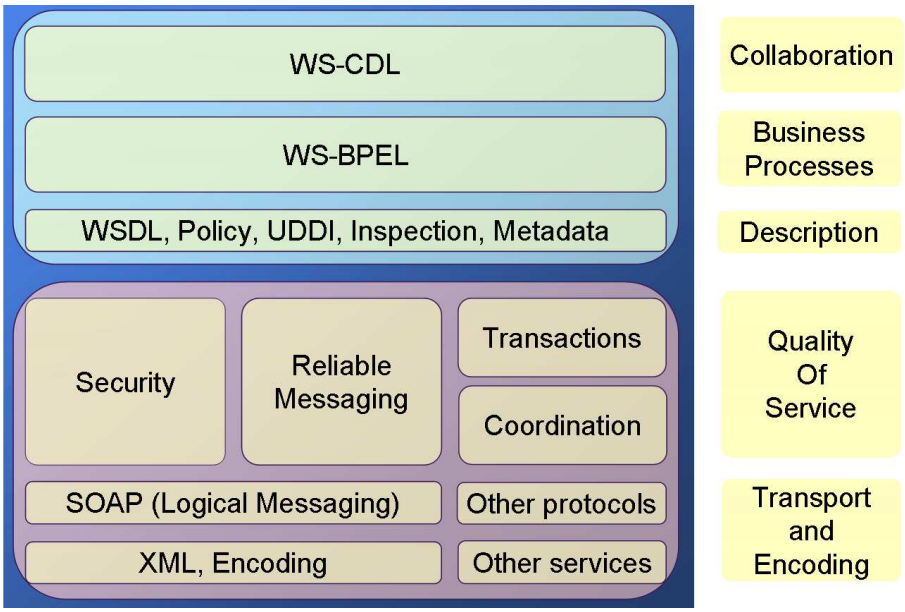

Figure 2.4: Web Service architecture stack.

musicians in an orchestra. Despite these differences, the ideal solution would be fusing both approaches in a single language and environment [**?**].

Anyway, the languages we can use in both cases should accomplish some common goals: (i) the capacity of modelling service interactions, including control flow and data constraints, (ii) the possibility of specifying exceptional behaviour, indicating which errors can happen in the execution of the composition and the way of handling these errors, and (iii) the ability to model web service compositions at a high level, without taking care of the implementation details of each one of the services.

Regarding the choreography approach, there are several languages that have been designed for that purpose. One of the most popular languages is Web Services Choreography Description Language (WS-CDL), which specifies the common and complementary observable behaviour of all participants in a composition [**?**]. It is based on XML and describes the peer-to-peer collaborations between the composite web services from a global point of view, that is, the exchange of messages to achieve a common business goal. The aim of this language is allowing the composition of any kind of web services, regardless of the platform hosting the service or the implementation language. Figure 2.6 is an

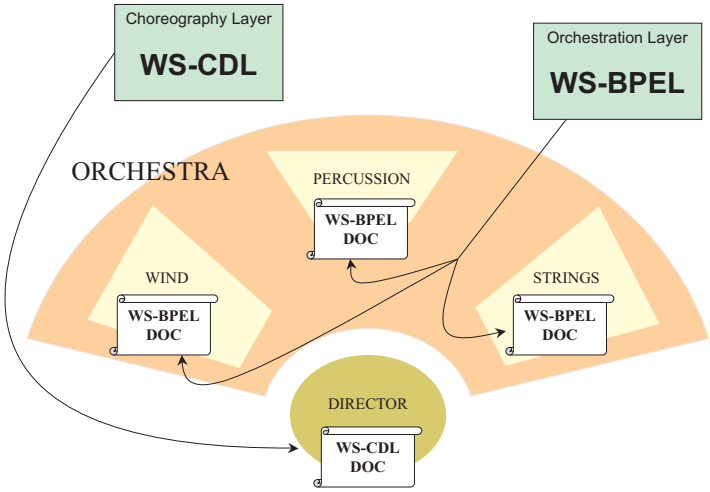

Figure 2.5: Choreography vs. Orchestration

example of how WS-CDL can be useful for the integration of different kinds of web services.

A WS-CDL document defines a hierarchy of choreographies, where there is only one top-level choreography, marked explicitly as the *root choreography*. The basic building block of a choreography is the *interaction* element. It indicates information exchanges between participants, possibly including the synchronization of some information values. These interactions are performed when one participant sends a message to another participant in the choreography. When the message exchanges complete successfully, the interaction completes normally.

We can distinguish two different kinds of *complex activities* inside a choreography: the workunit element and the ordering structures. The *workunit* element specifies a condition that must be fulfilled in order to perform some work and/or the repetition of some work. It completes successfully when the set of activities inside completes successfully. *Ordering structures* are used to combine basic activities and other complex activities in a nested way, expressing the order in which actions are performed within the choreography. There are three ordering structures: The *sequence* ordering structure expresses that the set of activities inside must be executed sequentially. The *parallel* ordering structure indicates that the set of activities inside must be executed concurrently. It completes

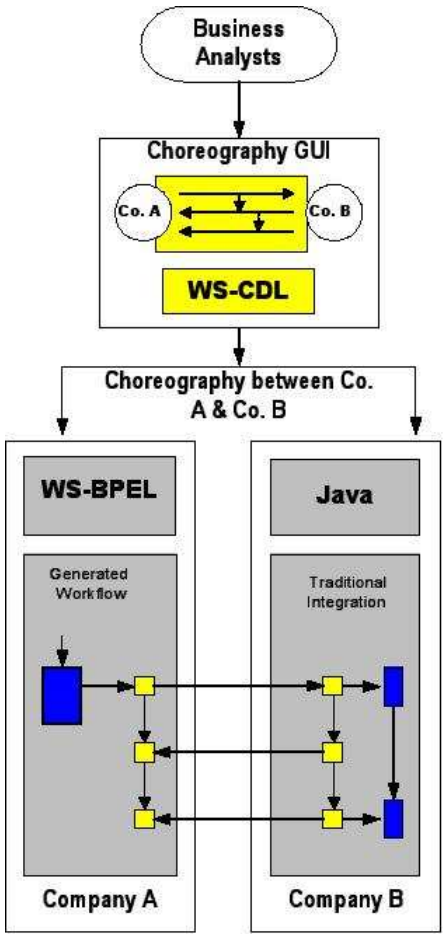

Figure 2.6: Integration of Web Services using WS-CDL.

successfully when all the concurrent activities complete successfully. And the *choice* ordering structure specifies that only one of multiple activities can be executed. If the choice have workunits inside, only the first one in lexical order with a "true" guard condition is selected. If there are other activities, there is no way to know which one is selected; it is considered as a non-observable decision.

Different types of exceptions are considered in WS-CDL. Exception workunits can be defined to handle all these exceptions. They may also be used as the mechanism to recover from the exceptions. At least one exception workunit must be defined. The guard of the workunit can be used to specify the particular type of exception we want to handle. Only one exception workunit can match each exception. If multiple exception workunits are defined, the order of evaluating them is based on the order in which the workunits have been defined. When

the matching happens, the actions of the matched workunit are executed. If no matching happens and a default exception workunit exists, then the actions of this workunit are executed. Otherwise, the exception is raised in the parent choreography. WS-CDL also allows us to define finalization actions within a choreography that can confirm or cancel the effects of this choreography, so we can use this actions for compensation.

2.2.1 WS-BPEL

In 2002, researchers and engineers of the main companies of the world (IBM, Microsoft, etc.) realised that the new and rapidly emerging process-oriented approach required the definition of a neat and precise language for describing how a set of intecting web services can be included in a business process. Traditional methods for integration and business process automation typically involve embedded logic inside of applications designed to meet a specific business need such as ERP, supply chain, or CRM. The development, testing, and deployment efforts required to change these applications make integration and process changes both costly and complex []. To address these issues, proprietary products emerged to abstract integration and process automation into a new layer of software tools. These software products liberated integration and process tasks from the underlying business systems so they could be more effectively changed, managed, and optimized. The idea and motivation behind almost each new technology and platform for enterprise application development is to provide an environment where better business applications can be developed with less effort and these business applications should closely align to the business processes, which should not be too complex, and which can be adapted to the changing nature of business processes without too much effort. Within companies, business applications have to interoperate and integrate. Integrating different applications has always been a difficult task for various functional and technology related reasons [].

The Business Process Execution Language for Web Services (BPEL4WS), for short BPEL, was first conceived in July, 2002 with the release of the BPEL4WS 1.0 specification. This first draft was initially developed by just three companies, IBM, Microsoft, and BEA. This document proposed an orchestration language in-

spired by previous variations such as Web Services Flow Language (WSFL), developed by IBM and XLANG specification language developed by Microsoft. WSFL was designed by IBM and is based on the concept of directed graphs. XLANG was designed by Microsoft and is a block-structured language. BPEL combines both approaches and provides a rich vocabulary for description of business processes. After this first attempt, other major companies such as SAP and Siebel Systems joined the former ones to write the version 1.1 of the BPEL4WS specification that was released less than a year later, in May of 2003. Fortunately, this brand new version received much more attention and vendor support, leading to a number of commercially available BPEL4WS-compliant orchestration engines []. Before publishing this release, the BPEL4WS specification was submitted to an OASIS technical committee in order to be evaluated so that the specification could be developed into an official and open standard. This technical committee was active from April 2003 to May 2007, and, during this time, a lot of contributions and improvements were received. In April 2007, WS-BPEL version 2.0 was approved as an OASIS standard. As a proof of maturity, more than 37 organizations collaborated to develop WS-BPEL, including representatives of Active Endpoints, Adobe Systems, BEA Systems, Booz Allen Hamilton, EDS, HP, Hitachi, IBM, IONA, Microsoft, NEC, Nortel, Oracle, Red Hat, Rogue Wave, SAP, Sun Microsystems, TIBCO, webMethods, and other members of OASIS []. Finally, in January 2008, another OASIS technical committee started to define a WS-BPEL extension to emcompass the definition of human interactions ("human tasks") as part of a WS-BPEL process. Figure 2.7 summarises this evolution-

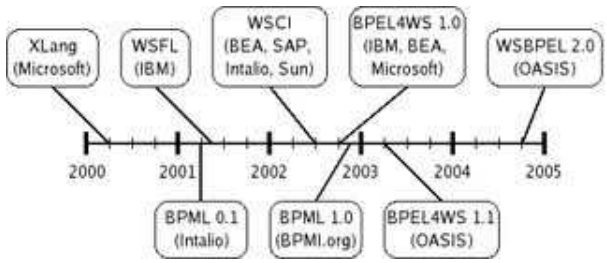

Figure 2.7: WS-BPEL evolution.

Moreover, there were established ten original design goals associated with the definition of WS-BPEL [7]:

- Define business processes that interact with external entities through web service operations defined using WSDL, and that manifest themselves as web services defined using WSDL.

- Define business processes using an XML-based language. Do not define a graphical representation of processes or provide any particular design methodology for processes.

- Define a set of web service orchestration concepts that are meant to be used by both the external (abstract) and internal (executable) views of a business process. Such a business process defines the behavior of a single autonomous entity, typically operating in interaction with other similar peer entities.

- Provide both hierarchical and graph-like control regimes, and allow their use to be blended as seamlessly as possible. This should reduce the fragmentation of the process modeling space.

- Provide data manipulation functions for the simple manipulation of data needed to define process data and control flow.

- Support an identification mechanism for process instances that allows the definition of instance identifiers at the application message level. Instance identifiers should be defined by partners and may change.

- Support the implicit creation and termination of process instances as the basic lifecycle mechanism. Advanced lifecycle operations such as "suspend" and "resume" may be added in future releases for enhanced lifecycle management.

- Define a long-running transaction model that is based on proven techniques like compensation actions and scoping to support failure recovery for parts of long-running business processes.

- Use Web Services as the model for process decomposition and assembly.

- Build on Web services standards (approved and proposed) as much as possible in a composable and modular manner.

As a result, WS-BPEL along with web services technologies provide now a standardized integration interface and a standardized language for the integration of different services as well as for the automation of some tasks. Nevertheless, web scenarios are becoming more and more complex since they highly heterogeneous, that is, a lot of different services from different companies interact jointly to perfom a particular task. In particular, it is known that business processes change relatively often due to this heterogeneity. Therefore, designers do not need only a way to compose a set of services, rather they also need a way to compose and modify them in the right order and in a relatively uncomplicated and straightforward way. Due to this, BPEL is sometimes compared to general purpose programming language, but it is not as powerful as one of the well-known programming language []. However, it is simpler and better suited for business process definition and, therefore, BPEL must be considered a supplement to modern languages rather a replacement.

After briefly introduce its history and design goals, we discuss next its technical details. BPEL is therefore an orchestration language in the sense that it is used to define the composition of services from a local viewpoint, describing the individual behaviour of each participant. Choreography is covered by other standards, such as WS-CDL (commented previously). BPEL is designed to support the description of both behavioural service interfaces and executable service-based processes [8]. A behavioural interface (known as abstract process) is a specification of the behaviour of a class of services, capturing constraints on the ordering of messages to be sent to and received from a service. An executable process defines the execution order of a set of activities (mostly communication activities), the partners involved in the process, the messages exchanged between partners, and the events and exception handling specifying the behaviour when specific events or faults occur. In Figure 2.8, we can observe an example of the typical business process of a travel agency.

According to the standard of WS-BPEL, an abstract process is a partially specified process that is not intended to be executed and it must be explicitly declared as “abstract”. As its name indicates, an abstract process may hide some of the required operational details expressed by an executable artifact. All the constructs of executables processes are made available to abstract processes and, consequently, they share the same expressive power []. Therefore, the main

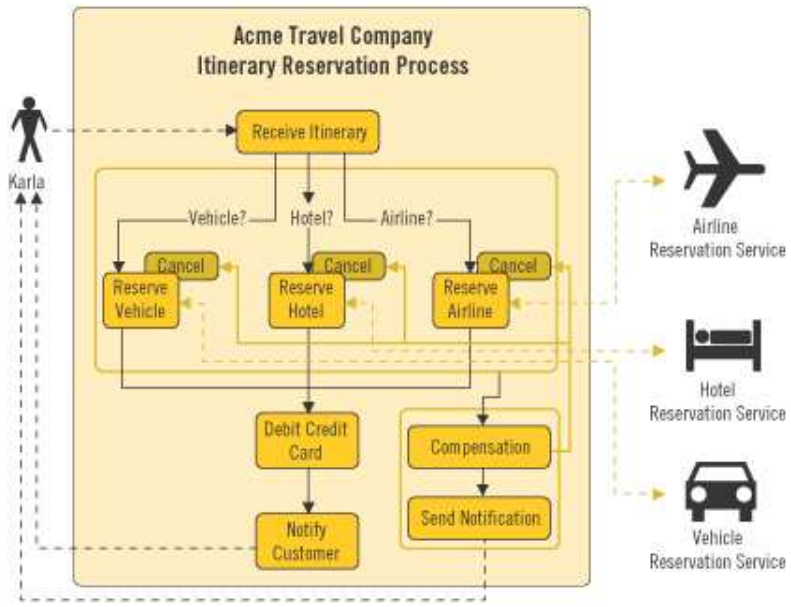

Figure 2.8: Example of a business process workflow.

different between an abstract and a executable processes is that the second one contains the exact details of business processes and, consquently, it is intended to be executed in an orchestration engine, whereas the first one serve a descriptive role, defining the message exchange between the parties involved. Specifically, an abstract process is usually use to describe the observable behavior of some or all of the services offered by an executable process and/or to define a process template that contains domain-specific best practices. Such a template can be seen as a design-time representation of the process logic, excluding execution details to be completed when mapping to an executable process. In most cases BPEL is used for executable processes []. Moreover, the definition of conceptual model in which one can define an abstract or an executable process is a key feature of WS-BPEL since the processes execute and interact with their partners in a consistent way regardless of the supporting platform or programming model used by the implementation of the hosting environment, unlocking the potential of web services because it allows the development of tools and other technologies that greatly increase the level of automation and thereby lower the cost in establishing cross enterprise automated business processes. In addition to this, abstract process ensures the level of privacy required by the companies since the implementation of the service is hidden to the other participants.

In detail, WS-BPEL is an XML-based language which supports the web services technology stack, including SOAP, WSDL, UDDI and so on. It defines a model and a grammar for describing the behavior of a business process based on interactions between the process and its partners as well as the order of these interactions. The interaction with each partner is performed through web service interfaces, and the structure of the relationship at the interface level is encapsulated in what is called a partnerLink. WS-BPEL also introduces mechanisms for dealing with business exceptions and faults. Moreover, WS-BPEL introduces a mechanism to define how activities have to be compensated in cases where exceptions occur or a partner requests reversal. A WS-BPEL process is a reusable definition that can be deployed in different ways and in different scenarios, while maintaining a uniform application-level behavior across all of them.

```
<process name="TripReservation" targetNamespace="http://jbpm.org/examples/trip"
  xmlns:tns="http://jbpm.org/examples/trip" xmlns:tic="http://jbpm.org/examples
  xmlns:xsd="http://www.w3.org/2001/XMLSchema"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xmlns:bpel="http://schemas.xmlsoap.org/ws/2003/03/business-process/"
  xmlns="http://schemas.xmlsoap.org/ws/2003/03/business-process/">

  <partnerLinks>
    <partnerLink name="traveler" partnerLinkType="tns:Traveler-Agent"
      myRole="Agent" />
    <partnerLink name="ticket" partnerLinkType="tns:Agent-Ticket"
      partnerRole="TicketIssuer" />
  </partnerLinks>

  <variables>
    <variable name="purchaseRequest" messageType="tns:purchaseRequest" />
    <variable name="cost" type="xsd:double" />
    <variable name="items" type="tns:ItemSet" />
    <variable name="cancelRequest" messageType="tns:cancelRequest" />
    <variable name="cancelResponse" messageType="tns:cancelResponse" />
    <variable name="detailRequest" messageType="tns:detailRequest" />
    <variable name="detailResponse" messageType="tns:detailResponse" />
    <variable name="dateReached" type="xsd:boolean" />
  </variables>

  <correlationSets>
    <correlationSet name="trip" properties="tns:tripLocator" />
  </correlationSets>
```

Figure 2.9: WS-BPEL code.

In Figure 2.9, we can observe a piece of the BPEL code for a booking process. BPEL processes use *variables* to temporarily store data. Variables are therefore declared on a process or on a scope within that process. Also, it provides *basic* or *structured* to declare the process logic. *Basic activities* are those which describe the elemental steps of the process behaviour []:

- The activity *assign* is used to assign data to the variables defined in the process. This activity can be used to copy data from one variable to another as well as to populate new data in a variable using expressions. As usual, expressions are constructed using variables and constants.

- The activity *empty* is devoted to be used as an activity that does nothing. For instance, one can decide to capture an exception and do nothing to handle it. Another use of *empty* is to provide a synchronization point in a parallel activity.

- The activity *wait* specifies a particular delay or deadline.

- To invoke a web service of service provider, WS-BPEL offers the activity *invoke*. Normally, this activity is used to request an operation in a service. This operation is usually a basic activity in the provider. Operations can be of two types: request-response or one-way. One-way consist of sending a message (some variables can be enclosed) so that no response is expected as part of the operation, whereas a request-response invocation requires a message back. Evidently, this response message can be used to notify the sender about a fault during the operation. A more detailed explanation will be provided in Chapter 3.

- A *receive* activity is necesary to receive the message sent in the invoke activity. messages, the portType (optional) and operation that it expects the partner to invoke. The value of the partnerRole in the partnerLink is not used when processing a ¡receive¿ activity. In addition, it specifies a variable, using the variable attribute, to store the message the operation to be requested. In many cases, this activity is the first part of the process.

- The *reply* activity is used to respond to a request previously accepted through an inbound message activity. For instance, it can be used in conjunction with the receive activity to respond to the invocation of a service. Clearly, it is only meaningful for request-response interactions, but a one-way “response” can be sent by invoking the corresponding one-way operation on the sender. Finally, it may specify a variable attribute that references the variable that contains the message data to be sent.

- The activity *throw* is used to signal an internal fault explicitly.

- The activity *exit* is used to immediately end the process instance.
- WS-BPEL provides the user with the ability to declare new activities that are not contemplated in the specification. This is done using the *extension activities*. This extension is not explicitly contemplated in the theory of this Thesis, although they are required to implement the theory in an orchestration engine.
- Finally, using the activity *rethrow* in a fault handler, it is possible to rethrow a fault. For instance, this activity is useful when the situation that causes the fault is not solved after the completion of the fault handler and, therefore, it is needed to redo this handler to check if the situation has been solved afterwards.

On the other hand, *Structured activities* encode the control-flow logic of the process. The set of structured activities defined in the standard are the following:

- The activity *sequence* includes a set of activities that are performed sequentially in the order in which they appear in the structure. It ends when the last activity in the sequence has finished.
- The activity *flow* provides concurrency and synchronization, creating a set of concurrent activities directly nested within the process and it enables synchronization dependencies between activities that are nested to it. A more detailed explanation of how this activity works is given in Chapter 3.
- The activity *if* specifies conditional behavior. As usual, the activity consists of an ordered list of one or more conditional branches defined by the "if" and optional "elseif" elements, followed by an optional "else" element.
- The activity *while* provides conditional repetitive behaviour.
- *RepeatUntil* provides the repeated execution of a contained activity. The difference with the activity while is that the inner activity is executed at least once.
- The activity *pick* waits for the occurrence of exactly one event from a set of events, and then executes the activity associated with that event. After an event has been selected, the other events are no longer accepted by

that “pick”. Moreover, a deadline for the occurrence of such events can be established in such a way if this deadline experies the pick activity ends. This structure has some similarity the choice operator in a process algebra althoudh with a predefined timeout. In WS-BPEL, it can be compared with a set of receive activities that run in parallel, where just only one can be executed, and a common deadline for the execution of these receive activities is set (to this end, the wait activity can be used).

- Lastly, the standard offeres an activity (forEach) to execute the contained activity a predefined number of times that is expressed in the definition of the activity.

Comment: Incluir foto orchesta y ventajas y desventajas choreographies and orchestations Choreography on the other hand does not rely on a central coordinator. Rather, each web service involved in the choreography knows exactly when to execute its operations and whom to interact with. Choreography is a collaborative effort focused on exchange of messages. All participants of the choreography need to be aware of the business process, operations to execute, messages to exchange, and the timing of message exchanges. The most recent answer to the integration challenge is the Service Oriented Architecture (SOA) and the web services technologies. The bottom-up view of the SOA sees different business applications exposing their functionalities through web services. Thus we can now access different functionalities of different legacy and new developed applications in a standard way (through web services). Such access to functionalities is important because typical companies have a large number of existing applications which have to be integrated.

2.3 Cloud Computing/Grid Computing

Gracias a la rpida evolucin que ha tenido la sociedad, servicios bsicos para el desarrollo de la vida cotidiana son comnmente suministrados a los ciudadanos, de tal manera, que cualquier persona puede tener acceso inmediato a ellos de forma fcil. Hoy en da, estos servicios, conocidos en el mundo anglosajn como “utility services”, engloban el suministro de agua, electricidad, gas y telfono, pero en los ltimos tiempos est cobrando fuerza una vieja idea que se intent llevar a cabo sin

xito a finales de los aos 60 y principios de los 70, el “Utility Computing”. Este nuevo paradigma de computacin es normalmente confundido con Cloud o Grid Computing, pero hay ciertos matices que los diferencian. “Utility Computing” se puede entender como el modelo de negocio que subyace en una infraestructura Cloud o Grid, es decir, puede ser entendido como el medio de cobro de servicios computacionales similar al que se hace con la electricidad, por lo que el usuario pagar slo por su consumo, mientras que los costes asociados a la produccin y distribucin de potencia de cmputo sern sufragados por las compaas suministradoras. As, las pequeas y medianas empresas podran competir en igualdad de condiciones con las grandes empresas, ya que no sera necesario hacer una gran inversin en datacenters para poder ofrecer un determinado servicio y se fomentara la creacin de empresas, ya que estos datacenters suponen una fuerte inversin inicial que muchos emprendedores no pueden acometer. Adems, el usuario final de las aplicaciones, servicios o infraestructuras tambin se beneficiara porque al reducir costes de produccin se reduce el precio de los productos. Por seguir con el smil de la energa, podemos ver el cloud computing como una gran central generadora de energa que da suministro a millones de usuarios y que evita que dichos usuarios tengan que tener su propia central en casa para poder encender sus aparatos elctricos, mientras que el “utility computing” es la forma de tarificar el gasto de los usuarios o, de una forma ms abstracta, podemos verlo como el contador que muestra el consumo energtico. Al igual que pasa con el software, los protocolos o cualquier paradigma relacionado con la informtica, Cloud Computing debe atravesar una serie de etapas para poder comprobar si toda esta publicidad que le estn dando las empresas sirve de veras para ahorrar costes y favorecer la competitividad o solo es ms una forma de aumentar ingresos o, en el caso de la investigacin, obtener nuevos fondos. En este sentido, algunos autores consideran que Cloud Computing no es mas que una nueva forma de nombrar lo que toda la vida se ha llamado Grid o Web Services y que realmente no supone ningn avance en el campo de la informtica. Este artculo tratar de presentar ms ampliamente la arquitectura y conceptos para comprender un sistema de computacin basado en la nube y mostrar las diferencias entre dos enfoques clsicos de computacin (Grid y Web Services) y Cloud. Finalmente, se propondr una serie de ideas que pueden llegar a convertirse en trabajos de investigacin en un futuro.

2.4 Introduccin

En 1943, el presidente de IBM, Thomas J. Watson, predijo:

"I think there is a world market for about five computers"

Esta frase, tan comentada en el mundo de la informtica en los ltimos tiempos, ha pasado de ser una prediccin con poco fundamento a ser una realidad en la actualidad.

Cloud Computing, el viejo sueo de ofrecer servicios de computacin como utilidad, tiene el potencial de transformar gran parte de la industra informtica, haciendo el software ms atractivo al ofrecerlo como servicio y moldeando la forma en que se disea y compra el hardware. Con este nuevo enfoque, cualquier emprendedor con buenas ideas para ofrecer servicios a travs de Internet no necesitar realizar grandes inversiones en equipamiento para llevar a cabo su proyecto ni necesitar contratar inicialmente mucho personal que gestione y mantenga dicho equipamiento. Adems, no tiene que realizar complicados estudios previos para calcular el nmero de usuarios potenciales y evitar, as, unos de los principales quebraderos de cabeza de los jefes de proyecto: el sobre-aprovisionamiento o el infra-aprovisionamiento. Estos dos conceptos junto con la elasticidad de recursos pueden ser considerados como claves en computacin en la nube, ya que el objetivo de reducir costes es directamente proporcional a la correcta estimacin de recursos en "tiempo real" y esta correcta estimacin slo se puede proporcionar si el sistema cumple la propiedad de elasticidad, es decir, que en un intervalo de tiempo relativamente corto aumentas y disminuyes los recursos dedicados a una tarea con un coste econmico bajo. Este enfoque puede hacer que, a primera vista, no se perciba la posibilidad de utilizar mtodos formales con este tipo de sistemas, puesto que normalmente se utilizan tcnicas formales en el diseo de sistemas con tiempos de respuesta crticos como sistemas de navegacin de un avin, transporte de materiales peligrosos, etc. De esta manera, se hace inviable el uso de la computacin en la nube cuando se exijan tiempos de respuesta muy bajos, ya que, por ejemplo, un sistema de navegacin de un avin no puede esperar varios minutos a que se le asignen nuevos recursos para tomar una decisin. Sin embargo, si que hay otro tipo de sistemas en los que los mtodos formales y el

cloud computing pueden converger, los sistemas de alta disponibilidad.

As, utilizando tcnicas formales se pueden disear este tipo de sistemas y verificar la ausencia de fallos en su construccin. Por ejemplo, una tienda de venta online podra pasar de tener cientos de usuarios simultneamente a miles de ellos en periodos como las vacaciones de Navidad, de manera que necesitara mucha mayor potencia de computacin si quiere satisfacer a todos los clientes y no perder ingresos ni nuevos clientes por no poder atender esa demanda. Para satisfacer esta necesidad, hara un estudio preliminar de cuantas visitas como mximo puede tener en ese perodo y comprara los datacenters necesarios para no tener problemas de congestin, lo que supone una inversin grande en infraestructura por parte de la compaa, sin embargo, una vez acaba la campaa navidea la demanda de usuarios vuelve a ser de unos cientos y la empresa se encuentra con que tiene una potencia de cmputo que no va a necesitar y, por tanto, no est amortizando econmicamente la inversin realizada. En este sentido, si la compaa en lugar de comprar los datacenters hubiese comprado capacidad de cmputo a un proveedor entonces habra amortizado en mayor medida el dinero invertido y no tendra mquinas en sus oficinas que ocupan bastante espacio y que tienen unos niveles de carga de trabajo muy bajos.

Cloud Computing se refiere tanto a las aplicaciones que se ofrecen como servicios a travs de Internet como al hardware y software que est presente en los datacenters que proveen dichos servicios. Estos servicios se han referido normalmente como Software as a Service (SaaS). El datacenter en s es lo que se considera la nube (o cloud). Desde el punto de vista del hardware, hay tres aspectos novedosos en Cloud Computing:

1. La ilusin de tener recursos ilimitados bajo demanda eliminando a los usuarios la necesidad de aprovisionarse antes de acometer una tarea.

2. La eliminacin de la inversin inicial en equipamiento permitiendo a las compaas empezar con pocos recursos e ir aumentndolos cuando las necesidades aumenten.

3. La posibilidad de pagar por el uso de recursos de computacin a corto plazo segn se necesiten (por ejemplo, procesadores por hora o capacidad de almacenamiento de datos por da) y poder liberarlos cuando no sean necesarios.

Cloud Computing podra tener el mismo impacto en la produccin de software que el que tuvieron las fundiciones de metal en la industra del hardware. En principio, las compaas fabricantes de hardware necesitaban tener sus propias instalaciones donde fabricar los componentes que componan sus productos, lo que les supona un gran esfuerzo econmico para construir y operar estas instalaciones y, por consiguiente, haca que el precio de los equipos se doblase en cada nueva generacin. Sin embargo, la aparicin de compaas que fabricasen componentes favoreci que empresas ms pequeas pudiesen entrar en el mercado del hardware, copado hasta aquel entonces por Intel o Samsung, que eran las nicas que podan hacer frente a este gran esfuerzo econmico. De manera similar, la computacin en la nube podra jugar el papel que hicieron las fundiciones, favoreciendo la competencia y evitando monopolios de grandes empresas.

Debido a que muchas empresas usan servicios software como base para su modelo de negocio, se presentan, a continuacin, los actores que formarn parte de este escenario. Los *Services Providers*(SPs) hacen accesibles los servicios a los *Service Users* por medio de interfaces que se comunican a travs de Internet. Dado que uno de los objetivos de la nube es externalizar la provisin de servicios, se necesita la aparicin de otro actor que ofrezca esta infraestructura como "servicio" llamado *Infrastructure Provider*, migrando los recursos desde los SPs al IPs y, as, los SPs pueden ganar flexibilidad y reducir costes como se puede ver en la figura 2.10.

2.5 Comparacin entre servicios web y Grid computing/Cloud computing

Como es sabido, nuestro grupo de investigacin ha centrado su investigacin en el desarrollo de una metodologa que permita construir y verificar sistemas con restricciones temporales mediante el uso de tcnicas formales. En los ltimos aos, se ha aplicado esta metodologa en el rea de los servicios web, ms conc-

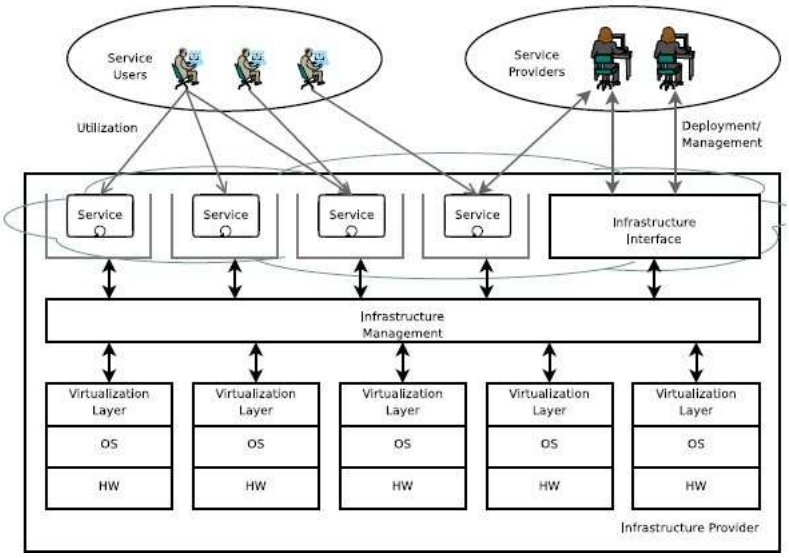

Figure 2.10: Actores en un sistema en la nube.

retamente, en que estos servicios cumplan la tarea que se les encomienda y que se coordinen automticamente para conseguir llevar a cabo un trabajo ms general. El problema que estn teniendo los servicios web es que como tuvieron un gran auge hace pocos aos, muchos grupos de investigacin centraron sus estudios en este campo y, por tanto, hay muchos investigadores proponiendo nuevas aproximaciones y sto ha llevado a que existen ciertas partes como BPEL o WS-CDL que estn bastante estudiadas. De esta manera, esta surgiendo un sistema donde los mtodos formales pueden jugar un papel muy importante y donde nuestro grupo puede beneficiarse de su amplia experiencia tanto en formalizacin como en servicios web, el cloud computing. Este nuevo paradigma, como se ha expuesto anteriormente, est viviendo su poca de plenitud en este momento y grandes empresas como Google, IBM, Microsoft han decidido dar un paso al frente y apostar fuertemente por la computacin en la nube. Adems, muchos gobiernos estn interesados en migrar sus servicios a la nube para abaratar costes y permitirles escalabilidad cuando les sea necesaria. Por ejemplo, hay que preguntarse si es necesario para la Agencia Tributaria tener grandes centros de datos cuando la demanda de servicios por parte de los ciudadanos slo crece en la poca de la declaracin de la renta. Probablemente la respuesta sea afirmativa porque s necesita almacenar todos esos datos y dar cierta confianza de que tus datos fiscales no van a caer en manos de gente con no muy buenas intenciones, pero toda la necesidad de clculo si que se puede externalizar para

ahorrar costes en equipamiento o incluso podran crear una nube privada entre todos los organismos que colaboren con la agencia pblica para compartir recursos e informacin. En este sentido, este tipo de sistemas donde la seguridad, privacidad y la disponibilidad son un requisito innegociable es donde podemos centrar parte de nuestras investigaciones e intentar mejorar alguno de los componentes de la arquitectura cloud expuesta en el apartado anterior. Por ejemplo, la mayora de grupos de investigacin desarrollan herramientas, pero la fase de pruebas o no existe o se le dedica poco tiempo. La semana pasada nos reunimos con uno de los grandes investigadores en el campo del Grid/Cloud Computing, Karim Djemame, y nos cont que el principal problema que tena era ese que no saban concretamente porque funcionaba bien su herramienta y que estaba bastante interesado en la verificacin de su herramienta.

Por otro lado, a continuacin se enumeran algunas diferencias entre servicios web y grid/cloud computing para ver donde es posible aplicar nuestra experiencia en este sistema. En primer lugar, podemos considerar que los servicios web son en s software que se ofrece como servicio (SaaS), aunque existan ciertas diferencias entre ambos enfoques, por ejemplo, la estandarizacin. Por tanto, este software podra estar compuesto de un conjunto de servicios, probablemente comunicados a travs de Internet, y que se coordinan para realizar una determinada tarea. Hasta el momento, nada nuevo, pero la principal diferencia reside en la virtualizacin, ya que los diferentes servicios que ofrece la nube se realizan en mquinas virtuales en lugar de directamente sobre un servidor como puede ser el caso del servicio web, de manera que la concurrencia en el sistema es mayor.

Otra diferencia es la persistencia de los datos. Si queremos coordinar varios servicios web para que realicen sumas la nica posibilidad de que stos puedan almacenar el resultado es guardndolo en la base de datos, sin embargo, existe una aproximacin llamada WSRF (Web Services Resources Framework) que ha sido estandarizada y que resuelve este problema. En este framework cada servicio web lleva asociado un recurso o varios del sistema de manera que puedes interactuar con el servicio y decidir a que recurso acceder. La principal ventaja que tiene es que todos los servicios se definen con WSDL (Web Services Descrip-

tion Language) y que la comunicacin, direccionamiento, etc. est estandarizado, de manera que la colaboracin entre sistemas de este tipo es sencilla. Otra ventaja es que el usuario tiene la posibilidad de decidir con que recursos interacta. As, podramos aadir una capa inferior en nuestra metodologa que permitiese la definicin de servicios web con recursos y una vez verificado que el sistema es correcto, desplegar estos servicios web en las mquinas fsicas. Este enfoque encajara perfectamente con nuestra investigacin, ya que utiliza servicios web con recursos y estos recursos tienen restricciones temporales para evitar que un usuario abarque todo el sistema.

Tambin, podemos observar que cloud computing podra verse como una capa que se colocara debajo de los servicios web, ya que se puede utilizar stos para acceder a los recursos, pero hay que resaltar que la nube no es solo ofrecer software como servicio, sino que tambin hay infraestructura y plataforma como servicio, cosa que los servicios web no pueden abarcar. Es decir, una parte del cloud computing (SaaS) puede compararse directamente con los servicios web, pero las otras dos partes no tienen nada que ver, por lo que sera como comparar el protocolo TCP/IP con la arquitectura de un PC, aunque es necesario que ambas aproximaciones (servicios web y cloud computing) converjan para el crecimiento de ambos paradigmas, igual que grid computing y servicios web convergieron en WSRF.

Por ltimo, a modo de curiosidad la principal diferencia entre un sistema grid y uno cloud reside en la virtualizacin, ya que en grid el usuario no comparte en tiempo real los recursos que tiene asignados, mientras que en cloud es indispensable la virtualizacin de recursos para conseguir dar servicio a ms clientes y conseguir ese ahorro que prometen los proveedores.

2.6 Web Services Resource Framework(WSRF)

La arquitectura que presentan los servicios web ha sido ampliamente aceptada como medio para estructurar las interacciones existentes entre los servicios que forman parte de un sistema distribuido y que colaborar para conseguir un ob-

jetivo comn. En la actualidad, los desarrolladores requieren a los entornos una mayor estandarizacin para facilitar interoperatividad adicional entre dichos servicios, pero hasta mediados de 2004 ningn grupo de investigacin o grupo de expertos se haba planteado seriamente la idea de proponer un estndar para modelar la comunicacin entre servicios web que poseen recursos persistentes asociados. As, en Enero de ese ao, varios miembros de la organizacin *Globus Alliance* y de la multinacional informtica IBM definieron, con la ayuda de expertos de empresas como HP, SAP, Akamai, etc., la especificacin de los documentos que deberan producirse en este modelo y la base de una arquitectura inicial. Estos documentos fueron enviados a la organizacin encargada de su estandarizacin, OASIS, en Marzo de 2004. En un principio, se formaron dos comits que se encargaran del estudio y desarrollo de ciertas partes de este nuevo estndar. Por un lado, estaba el *WSRF Technical Committee* que gestionaba cuatro especificaciones: *WS-ResourceProperties, WS-ResourceLifetime, WS-ServiceGroup, y WS-BaseFaults*. Por otro lado, el *WSN Technical Committee* se encargaba de las especificaciones: *WS-BaseNotification, WS-Topics, y WS-BrokeredNotification*.

WS-Resource Framework est inspirado en el trabajo realizado previamente por el *Global Grid Forum's Open Grid Services Infrastructure (OGSI) Working Group* [10]. Ms concretamente, puede ser visto como una sencilla refactorizacin de los conceptos e interfaces desarrollados en la especificacin *OGSI V1.0*, de manera que explota los recientes desarrollos en el rea de los servicios web (por ejemplo, WS-Addressing).

El objetivo de este trabajo es introducir los conceptos fundamentales para la gestin y destruccin de servicios web persistentes, es decir, servicios web que llevan asociados recursos donde guardar los estados de los mismos, ya que hasta la aparicin de esta aproximacin, los servicios web eran considerados "*stateless*" y, por tanto, no podan almacenar temporalmente datos o resultados de sus operaciones de una manera sencilla para el usuario, ya que era necesario almacenarlos en una base de datos ajena al servicio. En este enfoque, es necesario codificar la relacin entre el servicio y el recurso en trminos de patrones utilizando una serie de tecnologas ampliamente estudiadas, como, por ejemplo, el WS-Addressing y, tambin, ser necesario hacer sus propiedades accesibles desde

el exterior a travs de un interfaz. En este sentido, llamaremos *WS-Resource* a la asociacin entre un servicio web y un recurso persistente.

2.6.1 Introduccin

WS-Resource Framework [2] es una especificacin, desarrollada por OASIS y algunas de las empresas informticas ms pioneras, cuyo propsito es definir un marco genrico para el modelado y acceso a recursos asociados a servicios web, as como las relaciones entre dichos recursos en un entorno Grid/Cloud. Esta aproximacin est compuesta por un conjunto de especificaciones que definen la representacin del WS-Resource en los trminos que especifican los mensajes intercambiados y los documentos XML relacionados. Asimismo, incluye mecanismos que describen el medio para consultar el estado de un recurso y la descripcin del servicio, que forman conjuntamente la definicin de un WS-Resource. Adems, definen los pasos necesarios para hacer el estado de un servicio web accesible a travs de su interfaz (descrita en WSDL).

Normalmente, las interfaces de los servicios web proporcionan al usuario la posibilidad de acceder y manipular el estado del mismo, como, por ejemplo, valores de datos que evolucionan por la interaccin entre varios servicios. En otras palabras, los intercambios de mensajes que se implementan en el comportamiento de los servicios tienen como objetivo permitir el acceso a estos recursos persistentes. Sin embargo, la nocin de recursos persistentes que subyace en la implementacin de los servicios no es tan evidente en la definicin de la interfaz [5]. Los mensajes que estos servicios envan y reciben implican (o animan al programador a inferir) la existencia de un tipo de recurso asociado. Por tanto, es deseable que se definan estndares que permitan el descubrimiento, creacin, introspeccin, interaccin y destruccin de dichos recursos y que la forma elegida para llevar a cabo esta misin sea lo ms interoperable posible. Estas observaciones han motivado la aparicin de la propuesta comentada anteriormente, WS-Resource, para modelar estados en el contexto de los servicios web. Un WS-Resource se define como la composicin de un servicio web y sus recursos persistentes asociados, esto es, *(i)* expresado como una asociacin de un documento XML con un tipo definido con uno o varios *portTypes* (un servicio podr jugar un

determinado rol si implementa todos los *portTypes* que comprenden ese rol) y *(ii)* direccionado y accedido de acuerdo al patrn del recurso implcito, una derivacin de las *Endpoint References* del WS-Addressing. Una *Endpoint Reference* estar compuesta por: Uniform Resource Identifier (URI), parmetros del mensaje que se envi para solicitar el envo de la *Endpoint Reference* y datos relativos a la interfaz que se usa. En este intercambio, el identificador del recurso persistente es encapsulado en una *Endpoint Reference* y usado para identificar al recurso en cualquier intercambio de mensajes entre los servicios que formen la coreografa. As, WSRF permite declarar, acceder, monitorizar y destruir WS-Resources mediante mecanismos convencionales, lo que facilita la tarea de gestin, ya que no es necesario hacer ms difcil la lgica de decisin del servicio propietario del recurso para procesar los mensajes de gestin. Estos mecanismos convencionales componen cinco especificaciones tcnicas que definen los medios por los cuales:

- Se destruye un WS-Resource, ya sea de manera sncrona con respecto a una peticin explcita de destruccin o, a travs de un mecanismo basado en tiempos (scheduled). Adems, es posible declarar unas caractersticas especficas de los recursos (WS-ResourceProperties) que podran ser utilizadas para inspeccionar y monitorizar el tiempo de vida de dicho WS-Resource (WS-ResourceLifetime).

- Se definen los tipos de WS-Resource, que estn compuestos por la interfaz de la descripcin del servicio web (WSDL) y por un documento XML de propiedades del recurso. Por otro lado, el estado del WS-Resource puede ser consultado y modificado a travs del intercambio de mensajes (WS-ResourceProperties)

- Un Endpoint Reference (WS-Addressing) puede ser renovado cuando su informacin de direccionamiento ha caducado o ha dejado de ser vlida por algn error (WS-RenewableReferences).

- Adems, se define la capacidad de implementar entornos heterogneos como colecciones de servicios web, sean o no WS-Resources (WS-ServiceGroups).

- La notificacin de errores puede ser ms estandarizada al usar tipos XML Schema para definir los fallos base y definir reglas que muestren cmo esos fallos son usados y extendidos (WS-BaseFaults).

2.6.2 WS-ResourceProperties

Como se ha comentado anteriormente, WSRF utiliza una especificacin concreta para definir las propiedades del WS-Resource. Este recurso estar compuesto por la definicin de la interfaz en WSDL y un documento XML (Resource Properties Document) que especifica las propiedades del mismo, por ejemplo, el tamao de disco, la capacidad del procesador, etc., de tal manera que si queremos acceder, modificar o actualizar este documento debemos utilizar una serie de mensajes preestablecidos en la especificacin. Las operaciones que se pueden hacer son las siguientes:

GetResourceProperty

Esta operacin como su propio nombre indica permite al servicio web que realiza la peticin recuperar el valor de una **nica** propiedad del documento de propiedades. Para aclarar ms los conceptos se define el siguiente ejemplo.

Dado el documento de propiedades:

```
...
<GenericDiskDriveProperties
xmlns: tns=``http://example.com/diskDrive'' >
  <tns:NumberOfBlocks>22</tns:NumberOfBlocks>
  <tns:BlockSize>1024</tns:BlockSize>
  <tns:Manufacturer>DrivesRUs</tns:Manufacturer>
</GenericDiskDriveProperties>
...
```

Una posible peticin puede ser:

```
...
<s12:Body>
  <wsrp:GetResourceProperty
     xmlns:tns=``http://example.com/diskDrive''>
      tns:NumberOfBlocks
  </wsrp: GetResourceProperty>
</s12:Body>...
```

GetMultipleResourceProperties

Este mtodo es equivalente al anterior, pero para acceder a ms de una propiedad del documento en el mismo mensaje, es decir, se utiliza para evitar congestionar la red. El mensaje enviado sera:

```
...
<wsrp:GetMultipleResourceProperties
 xmlns:tns=''http://example.com/diskdrive''>
 <wsrp:ResourceProperty>tns:NumberOfBlock</wsrp:ResourceProperty>
 <wsrp:ResourceProperty>tns:BlockSize</wsrp:ResourceProperty>
</wsrp:GetMultipleResourceProperties>
...
```

SetResourceProperties

Este mtodo se utiliza para realizar cambios en el documento de propiedades. Existen 3 tipos de cambios:

- Insert: Permite aadir nuevas propiedades en el documento.
- Update: Se utiliza para actualizar el valor de alguna propiedad.
- Delete: Elimina propiedades del documento.

Un posible ejemplo de peticin sera:

```
...
<s12:Body>
 <wsrpw:SetResourceProperties
        xmlns:tns=''http://example.com/diskdrive''>
   <wsrp:Update>
    <tns:NumberOfBlocks>143</tns:NumberOfBlocks>
   </wsrp:Update>

   <wsrp:Delete resourceProperty=''tns:Manufacturer''/>

   <wsrp:Insert>
    <tns:someElement>42</tns:someElement>
   </wsrp:Insert>
```

```
 </wsrp:SetResourceProperties>
</s12:Body>
...
```

El documento de propiedades quedara con el siguiente formato:

```
...
<GenericDiskDriveProperties
   xmlns:tns=''http://example.com/diskDrive''>

   <tns:NumberOfBlocks>143</tns:NumberOfBlocks>
   <tns:BlockSize>1024</tns:BlockSize>
   <tns:someElement>42</tns:someElement>

</GenericDiskDriveProperties>
...
```

QueryResourceProperties

Como su propio nombre indica, este mtodo se utiliza para realizar consultas sobre propiedades del recurso. Por ejemplo si queremos saber si el nmero de bloques es mayor que 20 y el tamao de bloque es 1024 realizaramos la siguiente consulta:

```
...
<s12:Body>
 <wsrp:QueryResourceProperties>
  <wsrp:QueryExpression
    Dialect=''http://www.w3.org/REC-xpath-19991116''>
     boolean(/*/NumberOfBlocks>20 and /*/BlockSize=1024)
  </wsrp:QueryExpression>
 </wsrp:QueryResourceProperties>
</s12:Body>
...
```

La respuesta que enva el otro servicio es:

```
...
<s12:Body>
 <wsrp:QueryResourcePropertiesResponse>
   true
 </wsrp:QueryResourcePropertiesResponse>
</s12:Body>
...
```

2.6.3 WS-Base Faults

El diseador de un servicio web normalmente utiliza interfaces definidas por otros, por lo que un mtodo que estandarizase el formato de los mensajes de notificacin de errores facilitara la labor de los desarrollares. ste es el objetivo de WS-BaseFaults. Los mensajes de fallos en WSRF tienen el siguiente formato:

```
...
<BaseFault>
  <Timestamp>xsd:dateTime</Timestamp>
  <OriginatorReference>
    wsa:EndpointReferenceType
  </OriginatorReference> ?
  <ErrorCode dialect=''anyURI''>xsd:string</ErrorCode>?
  <Description>xsd:string</Description> *
  <FaultCause>wsbf:BaseFault</FaultCause> *
</BaseFault>
...
```

donde:

- Timestamp: Hora exacta cuando el fallo ha ocurrido.
- OriginatorReference: Direccin en formato WS-Addressing del servicio que ha generado el fallo.
- ErrorCode: Cdigo de error para ser utilizado por sistemas de informacin de fallos, por ejemplo, POSIX errno.

- Description: Explicacin de la causa del fallo (en lenguaje natural).

- FaultCause: Causa tcnica del fallo.

2.6.4 WS-ServiceGroup

Esta especificacin permite crear grupos que comparten una serie de propiedades en comn, es decir, agrupar diferentes servicios web que tienen comportamientos similares.

2.6.5 WS-ResourceLifetime

El tiempo de vida de un WS-Resource se define como el perodo que transcurre entre su instanciacin y su destruccin. La misin de esta especificacin es estandarizar el proceso de destruccin de un recurso y definir mecanismos para monitorizar este ciclo de vida, pero lo que no se define es cmo crear el WS-Resource. Generalmente, en los sistemas distribuidos, los clientes slo quieren tener un recurso por un determinado intervalo de tiempo, aunque en muchos escenarios es ms apropiado para el cliente que se produzca la inmediata destruccin del recurso. Otro ejemplo claro de uso se presenta cuando el cliente quiere suscribirse a un servicio por un cierto tiempo y quiere que despus de este tiempo se destruya dicha unin. Como se coment en la introduccin, existen dos formas de destruir un recurso: inmediata, mediante un mensaje explcito o temporizada, mediante un mensaje que activa o gestiona un timer.

Destruccin inmediata

Para la destruccin inmediata slo hace falta poner $< wsrl : Destroy/ >$ dentro del cuerpo ($< Body >$) del mensaje SOAP que se enva al servicio que gestiona el recurso y dicho servicio responder con $< wsrl : DestroyResponse/ >$ dentro del cuerpo ($< Body >$) del mensaje SOAP de respuesta.

Destruccin temporizada

En este caso, el WS-Resource tiene asociado un tiempo de terminacin que define el tiempo despus del cual se espera que el recurso haya sido destruido y, razonablemente, se espera que antes del mismo el recurso est disponible. A continuacin se muestra un ejemplo de cmo determinar el tiempo de terminacin de un recurso:

```
...
  <s12:Envelope
      <ex:ResourceDisambiguator>
        uuid:ba32-8680cace43f9
      </ex:ResourceDisambiguator>
      <s12:Body>
        <wsrl:SetTerminationTime>
          <wsrl:RequestedTerminationTime>
            2001-12-31T12:00:00
          </wsrl:RequestedTerminationTime>
      </wsrl:SetTerminationTime>
      </s12:Body>
  </s12:Envelope>
...
```

Como podemos observar el servicio que solicita la destruccin puede indicar la hora de destruccin y la hora actual (para evitar desajustes por la forma de representar la zona horaria). Una vez que CurrentTime alcanza el valor TerminationTime, el recurso se destruye sin ninguna intervencin ms y se notifica al emisor del mensaje de destruccin que el recurso deja de estar disponible. Existe otro mensaje que se manda desde el receptor al emisor para comunicarle que ha recibido la peticin de cambio.

Sin embargo, puede darse la situacin de que haya ms de un servicio utilizando el recurso que vaya a destruirse por lo que el propietario del recurso puede decidir o no (se deja a libre eleccin del programador) implementar los mensajes WS-Notification para informar a los interesados que el recurso deja de estar disponible. Para llevar a cabo esta tarea debe crear este Topic:

```
...
<wstop:TopicSpace name=''ResourceLifetime''
    targetNamespace=
    http://docs.oasis-open.org/wsrf/2004/06/
    wsrf-WS-ResourceLifetime-1.2-draft-01.xsd

 <wstop:Topic name=''ResourceTermination''>
   <wstop:MessagePattern>
     <wsrp:QueryExpression
        dialect= http://www.w3.org/REC-xpath-19991116 >
         boolean(/*/TerminationNotification)
     </wsrp:QueryExpression>
 </wstop:MessagePattern>
...
```

Adems, el mensaje de notificacin asociado debe contener los siguientes campos:

```
...
<wsrl:TerminationNotification>
 <wsrl:TerminationTime>xsd:dateTime</wsrl:TerminationTime>
 <wsrl:TerminationReason>xsd:any</wsrl:TerminationReason>?
</wsrl:TerminationNotification>
...
```

donde *TerminationTime* informa de la fecha de destruccin y *TerminationReason* contiene la explicacin de la destruccin.

2.7 WS-Notification

Esta especificacin permite a un *NotificationProducer* enviar un mensaje de notificacin a un *NotificationConsumer* de dos maneras diferentes:

1. El *NotificationProducer* enva un mensaje de notificacin al *NotificationConsumer* sin seguir ningn formalismo.

2. El *NotificationProducer* utiliza el formalismo que se describe a continuacin para enviar las notificaciones.

La opcin a utilizar la elegir el suscriptor cuando mande la peticin de suscripcin. En este sentido, la segunda opcin permite al usuario recibir un amplio rango de mensajes de notificacin, ya que la informacin que se enva en estos mensajes se obtiene de un rbol de Topics (temas) y, por tanto, se permite enviar subrboles en un mismo mensaje para informar de diferentes Topics. En la Figura 2.11 vemos un ejemplo:

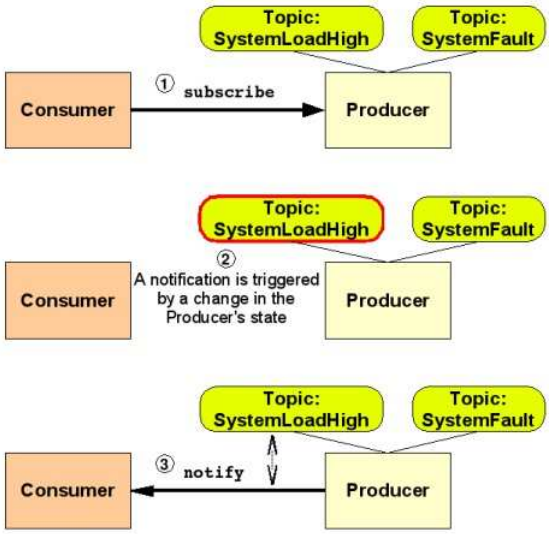

Figure 2.11: Ejemplo de uso de WS-Notification sin broker.

Este caso muestra un ejemplo de interaccin entre un consumidor y un productor de notificaciones, en el caso de que el suscriptor y el consumidor sean la misma entidad. El sistema es simple ya que tenemos un consumidor y un productor que publica 2 topics: SystemLoadHigh y SystemFault. Los pasos necesarios son:

1. En primer lugar, el consumidor se suscribe al topic SystemLoadHigh, por lo que internamente se crea un *Subscription resource* con la informacin de la suscripcin. El productor debe implementar un mtodo *Subscribe* y el consumidor un mtodo *Notify*.

2. Despus, el productor debe enviar una notificacin cuando el sistema sobrepase una determinada carga de trabajo. Por ejemplo, nuestro sistema enviar notificaciones cuando la carga de trabajo sea mayor de 50%.

3. Por ltimo, el productor enva la notificacin invocando la operacin *Notify* en el consumidor.

Un ejemplo de mensaje *Notify* es:

```
...
<wsnt:Notify>
    <wsntw:NotificationMessage>
     <wsnt:Topic Dialect= xsd:anyURI >
        {any}
     </wsnt:Topic>
     <wsnt:ProducerReference>?
      wsa:EndpointReference
     </wsnt:ProducerReference>
     <wsnt:Message>xsd:any</wsnt:Message>
    <wsnt:NotificationMessage>+
</wsnt:Notify>
...
```

Como podemos observar el mensaje *Notify* contiene uno o varios mensajes de notificacin (*NotificationMessages*). Los campos dentro de stos son:

- Topic: La informacin del topic que se enva.
- Dialect: El dialecto usado para expresar el topic anterior, es decir, el lenguaje utilizado para expresarlo.
- ProducerReference: Direccin del productor.
- Message: Una copia de la carga til (payload) del mensaje actual.

A continuacin, se muestra el mensaje que manda el suscriptor para registrar su inters en uno o ms topics:

```
...
<wsnt:Subscribe>
```

```
  <wsnt:ConsumerReference>
    wsa:endpointReference
  </wsnt: ConsumerReference>
  <wsnt:TopicExpression Dialect = xsd:anyURI >
    {any}
  </wsnt:TopicExpression>
  <wsnt:UseNotify>xsd:boolean</wsnt:UseNotify>?
  <wsnt:Precondition>wsrp:QueryExpression</Precondition>?
  <wsnt:Selector>wsrp:QueryExpression</wsnt:Selector>?
  <wsnt:SubscriptionPolicy>{any}</wsnt:SubscriptionPolicy>?
  <wsnt:InitialTerminationTime>
    xsd:dateTime
  </wsnt:InitialTerminationTime>?
</wsnt:Subscribe>

...
```

Los conceptos importantes en este mensaje son *UseNotify* que se utiliza para decidir si el mensaje de notificacin sigue el formalismo WS-Notification o se manda sin formato, *Precondition* que es la condicin que genera mensajes de notificacin, es decir, si se cumple esta condicin se generan mensajes, pero debe cumplirse tambin la condicin *selector* para enviarlos a los destinatarios que es la que se usa para decidir si se transmiten o no los mensajes generados. Adems, *SubscriptionPolicy* se podra utilizar para controlar el ratio de envo de mensajes(por ejemplo, no ms de 3 por segundo) y *InitialTerminationTime* contiene una sugerencia del tiempo de vida de la suscripcin. WSRF tambin incluye mensajes para detener la suscripcin, reanudarla o para que un servicio que acaba de unirse a una suscripcin pueda obtener un historial de notificaciones sobre un determinado topic.

2.7.1 WS-BrokeredNotification

Un *NotificationBroker* es un intermediario que, entre otras cosas, permite el envo de mensajes entre uno o varios *Publishers* y uno o varios *NotificationConsumers*. La misin del *Publisher* es observar ciertas situaciones y crear mensajes de notificacin para informar de esas situaciones, mientras que el broker es el encargado

de distribuir estos mensajes.

En este caso, se pueden dar tres relaciones entre las partes: *simple publishing*, *composable publishing* y *demand-based publishing*. En el primer caso, el *Publisher* es el encargado de observar las situaciones y notificarlas al broker que ser el encargado de transmitirlas a los interesados. En el segundo caso, el papel del *Publisher* lo realizar una entidad que implementa una serie de servicios especificados en WS-Notification (NotificationProducer). En este caso, el mensaje de notificacin puede llegar a otros consumidores que estuviesen suscritos al productor. En ambos casos, el broker puede pedir al *Publisher* que se registre para poder publicar mensajes sobre un topic determinado. El ltimo enfoque (*demand-based publishing*) requiere que el *Publisher* sea un *NotificationProducer* y, as, acepte mensajes de suscripcin. El objetivo es reducir el nmero de mensajes de notificacin haciendo que stos solo se manden cuando se soliciten expresamente.

2.7.2 Formal models of concurrency

2.8 Summary

This chapter has described the state of the art of Service-Oriented Computing (SOC), the formalization of Web Service compositions, and the specification of electronic contracts (e-contracts).

The development of systems based on Web Services allows the creation of fast, low-cost, flexible and scalable applications, where the integration is possible thanks to the definition of multiple standard protocols (WSDL, SOAP, UDDI). However, the correct composition of Web Services is still an open problem, where different approaches can be followed, such as orchestration (BPEL) and choreography (WS-CDL, WSCI, OWL-S). The formal analysis of Web Service compositions by means of formal methods is therefore necessary to guarantee the correct composition.

Several formal techniques can be used for the analysis of Web Service compositions, being model checking one of the most popular. This is an automated technique consisting of the construction of a finite-state model of the system

to check if some properties are satisfied. Different specification formalisms can be used in model checking (process algebras, Petri nets, automata) and there are several tools supporting each one of these formalisms (CWB-NC, CPN Tools, UPPAAL).

Chapter 3

BPELRF

3.1 Introduction

The development of software systems is becoming more complex with the appearance of new computational paradigms such as Service-Oriented Computing (SOC), Grid Computing and Cloud Computing. Grid/Cloud environments are characterized by a dynamic environment due to the heterogeneity and volatility of resources. In these systems, the service provider needs to ensure some levels of quality and privacy to the final user in a way that had never been raised. It is therefore necessary to develop new techniques to benefit from the advantages of recent approaches, such as Web service compositions. There are two complementary views to composite Web services: Choreography and Orchestration. The choreography view describes the observable interactions among services and it can be defined by using specific languages such as Web Services Choreography Description Language (WS-CDL) or by using more general languages like UML Messages Sequence Charts (MSC). On the other hand, orchestration concerns the internal behaviour of a Web service in terms of invocations to other services. Web Services Business Process Execution Language (WS-BPEL) [**?**] is in general used to describe Web service orchestrations, and, consequently, this is considered the de-facto standard language for describing Web services in terms of Web service compositions.

In addition, complex Web systems are composed by smaller services where each one carries out different tasks. Thus, to model such systems, specification languages should offer designers the constructions required to compose and discovery those basic services. Web service compositions could be modelled by using one of the two standards previously presented (WS-CDL or WS-BPEL). Service discovery is the process of finding a suitable Web service for a given task, and, normally, its definition is implementation-dependent.

While Web service implementations are typically stateless, their interfaces frequently provide users with the ability to access and manipulate states, i.e., data values that persist across, and evolve as a result of Web service interactions. In other words, the message exchanges that Web services implement are frequently intended to enable access to stateful resources. Besides, the messages that the services send and receive imply (or programmers infer) the existence of an associated resource type. Therefore, it is desirable to define Web service conventions to enable the discovery of, introspection on, and interaction with stateful resources in standard and interoperable ways. Most important, such an approach improves the robustness of design time selection of services during application assembly, and runtime binding to specific resource instances [**?**]. To facilitate additional interoperability among services, more standardization is required to deal with distributed resources. In January of 2004, several members of the *Globus Alliance* organization and the computer multinational *IBM* with the help of experts from companies such as *HP, SAP, Akamai, etc.* defined the basis architecture and the initial specification documents of a new standard for that purpose, Web Services Resource Framework (WSRF) [**?**].

Likewise, it is important to define a mechanism to state how the users are notified when important situations occur. To this end, a publish/subscribe architecture might be implemented, which is based on information preferences expressed in advance. Thus, whenever new content is available on one resource, the publisher would send that information to the subscriber. As far as this work is concerned, services might express its disposition to receive notifications when certain conditions hold. As WSRF specifications encourage, the present work utilizes WS-Notification as basis to cope with publish-subscribe architecture.

After introducing the relevant concepts, let us remark the main contributions of this work. The integration of WS-BPEL and WSRF is not new, since, in the

literature, one can find some works defining this integration from a technical point of view. Some of these works will be presented in the Related Work section. Surprisingly, to the best of our knowledge, this is the first work, which taking as a starting point WSRF and WS-BPEL, defines a complete and formal language to model and analyse stateful Web service compositions. In addition to this, the necessary formal machinery to build a publish-subscribe architecture is also provided here improving the expressiveness of the language, and a formal primitive to discover new services is defined. It is worthwhile to mention that the aim of this paper is not to provide yet another WS-BPEL semantics since WS-BPEL has received much attention in recent years when many operational semantics for it have arisen. As opposed to this, the main aim here is to gather the benefits of putting together WS-BPEL and WSRF to manage stateful Web services workflows by using existing formalisms in distributed systems. Additionally, in order to deal with WSRF in a proper way, we have realised that it would be better to consider a semantic model with the appropriate "tools" to cope with all the relevant aspects of WSRF such as notifications and resources timeouts. To particularise and motivate our approach, we introduce now an ideal scenario. The scenario, where our approach might be applicable, is a *group buying*, also known as collective buying. This scenario consists of a group of sellers and buyers, where offers are interpreted as resources created by sellers. Buyers subscribe to those offers, and they are notified when the offers/resources meet their expectations. This simple scenario will allow us to show readers how the situation can be managed with what we consider a very simple and succinct language. The rest of the paper is organised as follows. In Section 3.2, we present the basic concepts for a better understanding of this paper and some related works. In Section 3.3, we define the language itself and its operational semantics, whereas, in Section 3.7, we illustrate by means of a case study how it works. Finally, Section **??** presents some conclusions and possible future directions to improve the present work.

3.2 Background and Related Work

Overview of BPEL/WSRF. WSRF [**?**] is a resource specification language developed by OASIS and some of the most pioneering computer companies, whose

purpose is to define a generic framework for modelling Web services with stateful resources (WS-Resource), as well as the relationships among these services in a Grid/Cloud environment. This approach consists of a set of specifications that define the representation of the WS-Resource in the terms that specify the messages exchanged and the related XML documents. These specifications allow the programmer to declare and implement the association between a service and one or more resources. It also includes mechanisms to describe the means to check the status and the service description of a resource, which together form the definition of a WS-Resource. This WS-Resource is accessible through its unique identifier, *EndPoint Reference (EPR)*, which is defined by using WS-Addressing.

On the other hand, Web services are becoming more and more important as a platform for Business-to-Business integration. Web service compositions have appeared as a natural and elegant way to provide new value-added services as a combination of several established Web services. Services provided by different suppliers can act together to provide another service; in fact, they can be written in different languages and can be executed on different platforms. As we noticed in the introduction, we can use Web service compositions as a way to construct Web service systems where each service is an autonomous entity which can offer a series of operations to the other services conforming a whole system. In this way, it is fairly necessary to establish a consistent manner to coordinate the system participants since each of them may use a different approach, and, consequently, it is common to use specific languages such as WS-BPEL to manage the system workflow. WS-BPEL, for short BPEL, is an OASIS orchestration language to specify actions within Web service business processes. These actions are represented by the execution of two types of activities (*basic* and *structured*) that perform the process logic. *Basic activities* are those which describe elemental steps of the process behaviour and *structured activities* encode control-flow logic, and can therefore contain other basic and/or structured activities recursively [**?**].

The WSRF elements considered in our language are[1]:

- **WS-ResourceProperties**: There is a explicit specification to define WS-Resource properties, based on a Resource Properties Document (RPD), which

[1] In WSRF there are some additional technical elements to increase the modelling power that due to its technical nature are not considered in our framework.

defines the properties of the associated resource (disk size, processor capacity, etc.). Nevertheless, for simplicity, we only consider a single property for each resource, which is an integer value. Among the operations allowed by the standard are *GetResourceProperty* and *SetResourceProperty*, which are used to manipulate the resource property values.

- **WS-ResourceLifetime**: The WSRF specification does not provide a standard way to create resources. However, resources have an associated lifetime, which means that once this time has elapsed, the resource is considered to be destroyed, and the subscribers are correspondingly notified. We have then included, for completeness, an operation to publish resources, *publishResource*, in which the initial value of the resource, its lifetime, a textual identifier in order to allow users to discover it, and the activity that must be launched upon its destruction are indicated. We also have an operation in order to modify the current resource lifetime, *setTimeout*.

- **WS-Notification**: Clients can subscribe to WSRF resources in order to be notified about some topics (resource conditions). We therefore include the *subscribe* operator for a customer to subscribe to a resource, indicating the condition under which it must be notified, and the activity that must be executed upon that event.

Related Work. WS-BPEL has been extensively studied with many formalisms, such as Petri nets, Finite State Machines and process algebras, but there are only a few works considering WS-BPEL enriched with WSRF, and they only show a description of this union, without a formalization of the model. In [**?**] Slomiski uses BPEL4WS in Grid environments and discusses the benefits and challenges of extensibility in the particular case of OGSI workflows combined with WSRF-based Grids. Other two works centered around Grid environments are [**?**] and [**?**]. The first justifies the use of BPEL extensibility to allow the combination of different GRIDs, whereas Ezenwoye et al. [**?**] share their experience on BPEL to integrate, create and manage WS-Resources that implement the factory/instance pattern.

On the other hand, Ouyang et al. [**?**] define the necessary elements for translating BPEL processes into Petri nets. Thus, they cover all the important aspects

in the standard such as exception handling, dead path elimination and so on. The model they consider differs from ours in that we formalize the whole system as a composition of orchestrators with resources associated, whereas they describe the system as a general scope with nested sub-scopes leaving aside the possibility of administering resources. Furthermore, we have also formalized the event handling and notification mechanisms. Another extensive semantics for BPEL 2.0 is presented in [**?**] by Dumas et al, which introduces two new interesting improvements. They define several patterns to simplify some huge nets and introduce the semantics for the WS-BPEL 2.0 new patterns. Related to π-calculus semantics, Dragoni and Mazzara [**?**] propose a theoretical scheme focused on dependable composition for the WS-BPEL recovery framework. In this approach, the recovery framework is simplified and analysed via a conservative extension of π-calculus. The aim of this approach clearly differs from ours, but it helps us to have a better understanding of the WS-BPEL recovery framework. Other work focused on the BPEL recovery framework is [**?**]. Although this is more focused in the compensation handler, they describe the corresponding rules that manage a Web service composition. Our work is therefore quite complete as we define rules for nearly all possible activities. In addition, we also consider time constraints. Finally, we would like to highlight the works of Farahbod et al. [**?**] and Busi et al. [**?**]. In the first one, the authors extract an abstract operational semantics for BPEL based on abstract state machines (ASM) defining the framework BPEL$_{AM}$ to manage the agents who perform the workflow activities. In this approach time constraints are considered, but they do not formalize the timed model. On the other hand, the goal of the latter one is fairly similar to ours. They also define a π-calculus operational semantics for BPEL and describe a conformance notion. They present all the machinery to model Web service compositions (choreographies and orchestrations). The main difference with our work is that we deal with distributed resources. In a similar fashion Luchi and Mazzara in [**?**] presents other π-calculus operational semantic, $web\pi_\infty$, which is centred on the idea of event notification as the unique error handling mechanism. It is clear that this proposal differs from ours since they focus their attention in the error handling mechanism, however their claiming of simplifying the error handling using only the notification mechanism can be performed in our proposal since this is the mechanism used in the resource framework and therefore a technique shared by WS-BPEL and WS-RF. For fur-

ther details about the formalization of service oriented languages we would like to encourage the reader to review the works presented at the SENSORIA project in [**?**]. Here, an extensive work is presented from different international research groups aimed by the common goal of providing a rigorous software engineering view point for service-oriented system using as a cornerstone the formal specification of Web Services and WS-BPEL in particular. Works such as SOCK [**?**], CaSPiS [**?**], COWS [**?**], B-lite [**?**] or Orc [**?**] are either presented or reviewed. The first one, SOCK (Service Oriented Computing Kernel [**?**]), is a formal calculus which aims at characterizing the basic features of Service Oriented Computing and takes its inspiration from WS-BPEL, considered by the authors as the "de facto" standard for Web Service technology. The second one, CaSPiS (Calculus of Services with Pipelines and Sessions [**?**]) uses the Java framework IMC. Authors take advantage of the already built-in IMC features such us session oriented and pattern matching communication mechanisms easing the task of implementing in Java all CaSPiS abstractions. Other one, COWS (Calculus for Orchestration of Web Services [**?**]), is a new foundational language for SOC whose design has been influenced by WS-BPEL. COWS combines a number of elements from process calculi, e.g. asynchronous communication, polyadic synchronization, pattern matching, protection, delimited receiving and killing activities.

3.3 Syntax and semantics of BPEL+RF

We use the following notation: *ORCH* is the set of orchestrators in the system, *VAR* is the set of integer variable names, *PL* is the set of necessary partnerlinks, *OPS* is the set of operations names that can be performed, *EPRS* is the set of resource identifiers ($EPRS \subseteq \mathbb{N}$), and *A* is the set of basic or structured activities that can form the body of a process. The specific algebraic language that we use for the activities is defined by the following BNF-notation:

$$A ::= throw \mid receive(pl, op, v) \mid invoke(pl, op, v_1) \mid exit \mid reply(pl, op, v) \mid$$
$$\overline{reply}(pl, op, v_2) \mid assign(expr, v_1) \mid empty \mid \ A\,;A \ \mid A \parallel A \mid while(cond, A) \mid$$
$$wait(timeout) \mid pick(\{(pl_i, op_i, v_i, A_i)\}_{i=1}^{n}, A, timeout) \mid getProp(vEPR, v_1) \mid$$
$$getTimeout(vEPR, v_1) \mid publishResource(O, val, timeout, tag, vEPR, A) \mid discover(tag, vEPR) \mid$$
$$setProp(vEPR, expr) \mid setTimeout(vEPR, timeout) \mid subscribe(O, vEPR, cond', A)$$

where $O \in ORCH, pl, pl_i \in PL, op, op_i \in OPS, timeout \in \mathbb{N}$, *expr* is an arithmetic expression constructed by using the variables in *VAR* and integers; v, v_1, v_2, v_i range over *VAR*, *tag* is a string used to identify and discover resources that match a certain pattern, and $val \in \mathbb{Z}$. A variable $vEPR$ is used to store temporarily the resource identifier (*EPR*). A condition *cond* is a predicate constructed by using conjunctions, disjunctions, and negations over the set of variables *VAR* and integers, whereas *cond'* is a predicate constructed by using the variable *vEPR*, as representative of the resource value, and integers.
BPEL basic activities leveraged in our model are: *invoke* to request services offered by service providers, *receive* and *reply* to provide services to partners, *throw* to signal an internal fault explicitly, *wait* to specify a delay, *empty* to do nothing, *exit* to end the business process and *assign*, which is used to assign a variable value. The *structured activities* are: *sequence* (represented here as ;), which contains two activities that are performed sequentially, *while* to provide a (conditional) repeated execution of one activity, *pick* that waits for the occurrence of exactly one event from a set of events (including an alarm event) executing then the activity associated with that event, and, finally, *flow* ($\|$ operator in our syntax) to express concurrency. Another family of control flow constructs in BPEL includes event, fault and compensation handlers. An event handler is enabled when its associated event occurs, being executed concurrently with the main orchestrator activity. Fault handlers are performed when some failure has occurred, so the control is transferred to them. In this work, we only cover the fault and event handling, leaving compensation as a matter of future research. Besides, we do not take into consideration other advanced constructions such as correlation sets, dynamic partnerlinks or instance creation. However, an important aspect in current services technology is that of publishing and discovering of resources, which is considered in our framework. The correspondence among the syntax of WS-BPEL, WSRF, WS-Notification and our model is shown in Table 3.6. An orchestration is here defined as a pair $O = (A, A_f)$, where A and A_f are activities defined by the previous syntax. Specifically, A represents the normal workflow (and possible event handling activities which run in parallel with it), and A_f is the orchestrator fault handling activity.

Before we begin, we introduce some notations and definitions needed to describe the operational semantics.

Definition 1 State

We define a state as a pair s=(σ, ρ), where σ represents the variable values in the system and ρ captures the global resource state. We characterise σ as a global function in $\mathbb{Z}^{\text{VAR}}$, but, in practice, each orchestrator will manage its own local variables. Furthermore, $\rho = \{(O_i, EPR_i, v_i, Subs_i,\ t_i, tag_i, A_{e_i})\}_{i=1}^{r}$, where r is the number of resources in the system. Each resource has an owner (publisher), O_i, a unique identifier, EPR_i, and, at each state, a particular value, v_i, and a lifetime, t_i, initialized with the activity *publishResource*, which can be changed by using the function *setTimeout*. A_{e_i} is the activity that must be run when it expires, whereas tag_i is used as a textual description for discovery purposes. The resources in ρ are therefore published by means of the *publishResource* activity, and potential subscribers must discover the resource identifier (EPR) by using the *discover* activity. Moreover, $Subs_i = \{(O_{i_j}, cond'_{i_j}, A_{e_{i_j}})\}_{j=1}^{s_i}$, $i \in \{1, ..., r\}$, is the set of resource subscribers, their associated delivery conditions and the event handling activity $A_{e_{i_j}}$ that must be thrown in the case that $cond'_{i_j}$ holds; s_i is the number of orchestrators currently subscribed to this resource and $O_{i_j} \in ORCH$ are the subscriber identifiers.

Notation. Along the following lines, we introduce some notation used in the operational semantics. Given a state $s = (\sigma, \rho)$, a variable v and an expression e, we denote by $s' = (\sigma[e/v], \rho)$ the state obtained from s by changing the value of v for the evaluation of e, and $s^+ = (\sigma, \rho')$, where $\rho' = \{(O_i, EPR_i, v_i, Subs_i, t_i - 1, tag_i, A_{e_i}) |\ t_i > 1\}_{i=1}^{r}$. Let the function *Subs(s)*, which return the state *s* removing from each $Subs_i$ those subscriptions whose associated condition has held at *s*. We omit its formal definition since it is straightforward.

A partnerlink is here considered as a pair (O_i, O_j) representing the two roles in communication: sender and receiver. Furthermore, $\sigma(vEPR_i) \in \rho$ and $tag_i \in \rho$ will denote that there is a tuple $(O_i, EPR_i, v_i, Subs_i, t_i, tag_i, A_{e_i}) \in \rho$, where $\sigma(vEPR_i) = EPR_i$. Given a predicate $cond$, we use the function $cond(s)$ to mean the resulting value of this predicate at the current state *s*, $sel(\rho, tag)$ to return a randomly selected $EPR \in \rho$ among those whose tag attribute is *tag* , $val(\rho, tag)$ to return the current value of the resource, $time(\rho, vEPR)$ to return its lifetime and, finally, *getEPR()* to generate non-repeated resource identifiers. Let $\sigma(vEPR) = EPR$, $\rho[w/vEPR]_1$ is used to denote that the new value in ρ of the resource EPR is w, $\rho[t/vEPR]_2$ denotes a change of the resource lifetime, and the function $Add\_subs(\rho, vEPR_i, O_{i_j}, cond'_{i_j}, A_{e_{i_j}})$

denotes that $(O_{i_j}, cond'_{i_j}, A_{e_{i_j}})$ is added to the subscribers of the resource $EPR_i \in \rho$ or $cond' = cond'_{i_j}$ in the case that O_{i_j} was already in $Subs_i$. At the same time, we need an additional function to launch the corresponding activities when the subscriber condition holds at the current state s. Let s=(σ, ρ) with $\rho = \{(O, EPR_i, v_i, Subs_i, t_i, tag_i, A_{e_i})\}_{i=1}^{r}$, we define the function $N(O, s) = ||\{A_{e_{i_j}} | (O_{i_j}, cond'_{i_j}, A_{e_{i_j}}) \in Subs_i,\ O_i = O, cond'_{i_j}(s) = true\}_{i=1}^{r}$, with $j \in \{1, ..., s_i\}$.

The operational semantics for this language is defined at three levels, the internal one corresponds to the evolution of one activity as a single entity. In the second one, we define the transition rules which establish the orchestrator evolution, whereas the third level corresponds to the composition of different orchestrators and resources to conform a choreography.

Definition 2 Activity Operational semantics
We define the activity operational semantics by using two types of transition:

1. (A,s)$\xrightarrow{a}$ (A', s'), a $\in$ Act (Action transitions).
2. (A,s)$\rightarrow_1$ (A', s^+) (Delay transitions).

where Act is the set of actions that can be performed. This set can be easily deduced from the rules in Table 3.2.

Notice that we have included a τ-action that represents an empty movement in order to represent the unobservable behaviour. *Action transitions* capture a state change by the execution of an action $a \in Act$, which can be empty (τ). *Delay transitions* capture how the system state changes when one time unit has elapsed. In Tables 3.2, 3.3 we show the rules for these transitions.

Next, we only introduce a short explanation of some rules of Table 3.2. As can be observed, for the basic activities (*throw, exit, invoke, receive, reply, ...*), when the corresponding action is performed we reach the *empty* activity. With regard to the communication among services, our language is endowed with five activities to carry out this task. The model we use here is based on the invoke and receive (or pick) operations, as well as the reply activity that uses a server to reply to a client. We have also added a barred version of the reply activity to synchronise with the response from the client.

We have therefore introduced this last activity in our semantics to deal with the synchronous or asynchronous nature of the invoke activity (one-way or request-response operation, respectively), so the reply activity is optional in the syntax depicted in Table 3.6. Below, a toy example is depicted to explain how it works.

Example 3.3.1
In this example, there are two actors: a customer and a seller. The customer contacts a seller in order to gather information about a specific product identified by *id1*. The seller checks the stock and send the requested information to the customer. Let the orchestrations $O_c = (A_c, empty)$ and $O_s = (A_s, empty)$, the BPEL-RF code for the primary activity of both participants is:

$A_c = invoke(pl_1, info, id1); \overline{reply}(pl_1, info, id3)$

$A_s = receive(pl_2, info, id2); reply(pl_1, info, id4)$

According to rules **invoke**, **receive**, **reply** and $\overline{\text{reply}}$ in Table 3.2, the customer sends $\sigma(id1)$, which represents the product identifier, and starts the activity $\overline{reply}$ to receive the response in *id3*. Seller stores product identifier in its variable *id2*, and, therefore, $s' = (\sigma[m/id2], \rho)$, with $m = \sigma(id1)$. Finally, seller sends the product information $\sigma(id4)$ to the customer, which stores it in *id3*, leading to $s'' = (\sigma[m/id3], \rho)$.

Rules for the sequence and parallel operators are straightforward, but notice that when one of the arguments performs either the *throw* action or the *exit* action, the composite activity also performs this action conducting the workflow to the empty activity (rules **Seq3**, **Par3** and **Par4**). As regards resource, rule **publishResource** states that the resource and its information is added to the resource set, whereas the resource identifier (e) for this newly created resource is stored in variable vEPR, resulting in the new state $s' = (\sigma[e/vEPR], \rho \cup \{O, e, val, \emptyset, t, tag, A\})$. Time elapsing is captured by rules in Table 3.3, notice that the activities for which the passage of time is allowed are *wait, empty, receive, invoke* and *pick*.

At the orchestrator level (Table 3.4), we will require to identify the orchestrator that executes the activity as well as its mode of operation, which can be normal or failure. A superscript *m* is used to indicate the current operation mode, which can be either empty (normal) or 'f' (failure). An orchestrator enters into the failure mode when an exception has occurred. In the case of a double exception, the orchestrator terminates its execution as rule **ORCH3** in Table 3.4 captures.

Definition 3 Orchestration Operational semantics
The transitions in this level have the following form:

1. $(O : (A, s)^m) \xrightarrow{a} (O : (A', s')^{m'})$, a ∈ Act.
2. $(O : (A, s)^m) \rightarrow_1 (O : (A', s^+)^m)$.

where $O = (A, A_f)$.

Finally, the outermost semantic level corresponds to the choreography level, which is defined upon the two previously levels. In Table 3.5, we define the corresponding transition rules for the choreography semantics. Observe that Table 3.5 includes rules with negatives premises, which, in principle, could pose decidability problems. Nevertheless, these premises are all observable from the syntax of the involved terms.

Definition 4 Choreography operational semantics
A choreography is defined as a set of orchestrators that run in parallel exchanging messages: $C = \{O_i\}_{i=1}^{c}$, where c is the number of orchestrators presented in the choreography. A *choreography state* is then defined as follows: $S_c = \{(O_i : (A_i, s)^{m_i})\}_{i=1}^{c}$, where A_i is the activity being performed by O_i, m_i its *mode*, and s is the current global state.

Definition 5 Labelled transition system

For a choreography C, we define the semantics of C as the labelled transition system obtained by the application of rules in Table 3.5, starting at the state s_{0_c}:

$$lts(C) = (\mathcal{Q}, s_{0_c}, \rightarrow)$$

where $\mathcal{Q}$ is the set of reachable choreography states, s_{0_c} is the initial state where all the variables in σ are initialised to 0 and ρ is empty, and $\rightarrow = \rightarrow_1 \cup \{\xrightarrow{a} \mid$ for all basic activity a, or $a = \tau\}$.

3.4 Case Study: Automatic management system for stock market investments

The case study concerns a typical automatic management system for stock market investments, which consists of *3* participants: the online stock market system and *2* interested investors, A_1 and A_2. Here, the resource will be the stocks of a company (a bank, for instance) that the investors want to buy just in case the price falls below an established limit. This threshold is fixed previously by means of subscriptions, i.e., an investor subscribes to the resource (the stocks) with a certain guard (the value of the stocks he/she want to pay for it). The lifetime *lft* will be determined by the stock market system and the resource price will be fluctuating to simulate the rises/drops of the stocks. We do not take into account the stock buy process since our aim is to model an investors' information system. Thus, the participants will be notified either when their bids hold or the resource lifetime expires. Let us consider the choreography $C = (O_{sys}, O_1, O_2)$, where $O_k = (PL_k, Var_k, A_k, A_{f_k}, \mathcal{A}_{e_k}), A_{f_k} = exit$, k=sys, 1, 2;
$Var_{sys} = \{at, vEPR, epr\}$, $Var_i = \{epr_i, vEPR_i, at_i\}, i = 1, 2$. Hence, variables epr, epr_1, epr_2 are used to store the identifier of the resource in each of the participants, whereas variables $vEPR, vEPR_1, vEPR_2$ contain its value. Obviously, epr is initialized internally when the resource is *published*, and epr_1 and epr_2 are *discovered* by the buyers. Finally, at, at_1, at_2 control the period of time in which the auction is active. Suppose that all the variables are initially 0:

$Asys = assign(24, at); publishResource(1000, 24,$ "bank", $empty); while(actualTime() <= at, Abid)$

$Abid = getProp(epr, \text{“value”}, vEPR); assign(vEPR + bid(), vEPR); setProp(epr, vEPR); wait(1, 2)$

$A_1 = discover(\text{“bank”}, epr_1); getProp(epr_1, \text{“timeout”}, at_1); subscribe(O_1, epr_1, value < 980,$
$invoke(pl_1, buy, vEPR)); pick((pl_1, buy, vEPR_1, empty), empty, at_1)$

$A_2 = discover(\text{“bank”}, epr_2); getProp(epr_2, \text{“timeout”}, at_2); subscribe(O_2, epr_2, value < 990,$
$invoke(pl_2, buy, vEPR)); pick((pl_2, buy, vEPR_2, empty), empty, at_2)$

Here, the function *bid* is used to increase/decrease the stocks value simulating the fluctuation of the stocks price.

3.4.1 Related Work

WS-BPEL has been extensively studied with many formalisms, such as Petri nets, Finite State Machines and process algebras, but there are only a few works considering WS-BPEL enriched with WSRF, and they only show a description of this union, without a formalization of the model. In [**?**] Slomiski uses BPEL4WS in Grid environments and discusses the benefits and challenges of extensibility in the particular case of OGSI workflows combined with WSRF-based Grids. Other two works centred around Grid environments are [**?**] and [**?**]. The first justifies the use of BPEL extensibility to allow the combination of different GRIDs, whereas Ezenwoye et al. [**?**] share their experience on BPEL to integrate, create and manage WS-Resources that implement the factory/instance pattern.

On the other hand, Ouyang et al. [**?**] define the necessary elements for translating BPEL processes into Petri nets. Thus, they cover all the important aspects in the standard such as exception handling, dead path elimination and so on. The model they consider differs from ours in that we formalize the whole system as a composition of orchestrators with resources associated, whereas they describe the system as a general scope with nested sub-scopes leaving aside the possibility of administering resources. Furthermore, we have also formalized the event handling and notification mechanisms. Another extensive semantics for BPEL 2.0 is presented in [**?**] by Dumas et al, which introduces two new interesting improvements. They define several patterns to simplify some huge nets and introduce the semantics for the WS-BPEL 2.0 new patterns. Related to π-calculus semantics, Dragoni and Mazzara [**?**] propose a theoretical scheme focused on dependable composition for the WS-BPEL recovery framework. In this approach, the recovery framework is simplified and analysed via a conserva-

tive extension of π-calculus. The aim of this approach clearly differs from ours, but it helps us to have a better understanding of the WS-BPEL recovery framework. Other work focused on the BPEL recovery framework is [**?**]. Although this is more focused in the compensation handler, they describe the corresponding rules that manage a Web service composition. Our work is therefore quite complete as we define rules for nearly all possible activities. In addition, we also consider time constraints. Finally, we would like to highlight the works of Farahbod et al. [**?**] and Busi et al. [**?**]. In the first one, the authors extract an abstract operational semantics for BPEL based on abstract state machines (ASM) defining the framework BPEL$_{AM}$ to manage the agents who perform the workflow activities. In this approach time constraints are considered, but they do not formalize the timed model. On the other hand, the goal of the latter one is fairly similar to ours. They also define a π-calculus operational semantics for BPEL and describe a conformance notion. They present all the machinery to model Web service compositions (choreographies and orchestrations). The main difference with our work is that we deal with distributed resources.

For further details about the formalization of service oriented languages we would like to encourage the reader to review the works presented at the SENSORIA project in [**?**]. Here, an extensive work is presented from different international research groups aimed by the common goal of providing a rigorous software engineering view point for service-oriented system using as a cornerstone the formal specification of Web Services and WS-BPEL in particular.

3.5 Prioritised-Timed Coloured Petri Nets

In this section we introduce the specific model of prioritised-timed coloured Petri net that we consider for the translation.

3.6 Prioritised-Timed Coloured Petri Net Semantics for WS-BPEL+WSRF

3.6.1 Prioritised-Timed Coloured Petri Nets

We use prioritised-timed coloured Petri nets, which are a prioritised-timed extension of coloured Petri nets [**?**], the well-known model supported by CPN Tools[2].

Definition 6

(Prioritised-Timed Coloured Petri Nets)

We define a prioritised-timed coloured Petri net (PTCPN) as a tuple $(P, T, A, V, G, E, \lambda, D, \pi)$, where[3]:

- P is a finite set of *coloured places*. Colours used in this semantics will be introduced progressively, as we define the PTCPNs corresponding to each activity. We will use timed and untimed coloured tokens, so timed tokens will have associated a time stamp, according to the CPNTools interpretation [**?**].
- T is a finite set of *transitions* ($P \cap T = \emptyset$).
- $A \subseteq (P \times T) \cup (T \times P)$ is a set of directed *arcs*.
- V is a finite set of *integer variables* i.e. $Type(v)$, for all $v \in V$. We will assume that all variables have 0 as initial value.
- $G : T \longrightarrow EXPR_V$ is the *guard function*, which assigns a Boolean expression to each transition, i.e. $Type(G(t)) = Bool$. $EXPR_V$ denotes the expressions constructed using the variables in V, with the same syntax admitted by CPN Tools.
- $E : A \longrightarrow EXPR_V$ is the *arc expression function*, which assigns an expression to each arc.

[2] Official web page: http://cpntools.org/

[3] We use the classical notation on Petri nets to denote the precondition and postcondition of both places and transitions:

$$\forall x \in P \cup T : {}^\bullet x = \{y \,|\, (y, x) \in A\} \qquad x^\bullet = \{y \,|\, (x, y) \in A\}$$

- λ is the *labelling function*, defined both on places and transitions. Transitions can be labelled with either activity names or $\emptyset$. Places are labelled as *entry places*, *output places*, *error places*, *exit places*, *internal places*, *variable places* and *resource places*, which, respectively, correspond to the following labels: $\{in, ok, er, ex, i, v, r\}$. In our specific model, a PTCPN will have an only *entry place* p_{in}, such that ${}^\bullet p_{in} = \emptyset$, which will be initially marked with a single token, whose colour value will be 0. According to WS-BPEL and WSRF standards, we can distinguish between two kind of termination: *normal and abnormal*. On the one hand, the *normal* mode corresponds to the execution of a workflow without faults or without executing any *exit* activity. Thus, in our net model, there is an *output place* p_{ok}, such that $p_{ok}^\bullet = \emptyset$, which will be marked with one token of colour 0 when the workflow ends normally. On the other hand, a workflow can finish abnormally by means of the execution of an explicit activity (exit or throw) as well as the occurrence of an internal fault in the system. Each PTCPN has also a single *error place* p_{er}, which will become marked with one token of colour 0 in the event of a failure, then starting the fault handling activity. In a similar way, the *exit place* will be marked when the *exit* is executed by an orchestrator.

  Variable places are denoted by p_v, to mean that they capture the value of variable v. They contain a single token, whose colour is the variable value. For any resource *r* in the system we will have two complementary resource places, p_{r_i}, p_{r_a}. The first one will be marked with one token when the resource has not been instantiated or has been released (due to a time-out expiration), whereas the second one becomes marked when the resource is created, its token colour being a tuple representing the resource identifier (EPR), lifetime, value, list of subscribers and activity to be executed upon the time-out expiration. All the remaining places will be considered as *internal*.

- $D : T \longrightarrow \mathbb{N} \times \mathbb{N}$*(delay function)*, which associates a time interval to each transition. For $D(t) = [d_1, d_2]$, this means that the time delay associated to t can be any value in this interval, all of them with the same probability.

- $\pi : T \longrightarrow \mathbb{N}$ is the *priority function*, which assigns a priority level to each transition.

Markings of PTCPNs are defined in the same way supported by CPNTools, as well as the semantics of PTCPNs, so due to the lack of space we omit the formal definitions. The interested reader may see for instance [**?**].

3.6.2 PTCPN Semantics for WSRF/BPEL

Before introducing the PTCPN semantics, we define the formal model that captures the integration of BPEL and WSRF.

A system for our purposes consists of a set of orchestrators that run in parallel using a set of distributed resources. Orchestrators relate with one another by invoking the services they respectively provide. This set of orchestrators and resources is here called a *choreography*. We use the following notation: *ORCH* is the set of orchestrators in the system, *Var* is the set of integer variable names, *PL* is the set of partnerlinks, *OPS* is the set of operation names that can be performed, *EPRS* is the set of resource identifiers, and *A* is the set of basic or structured activities that can form the body of a process.

An orchestrator O is defined as a tuple $O = (PL, Vars, A, A_f, \mathcal{A}_e)$, where PL are the partnerlinks this orchestrator uses to communicate with others, $Vars$ is the set of local variables of this orchestrator, A and A_f are activities of WS-BPEL and WSRF, and $\mathcal{A}_e$ is a set of activities. Specifically, A represents the normal workflow, A_f is the orchestrator fault handling activity and $\mathcal{A}_e = \{A_{e_i}\}_{i=1}^{m}$ are the event handling activities.

Activities in BPEL-WSRF follow the syntax defined by the following BNF expression (see Table 3.6 for the equivalence with the XML syntax of BPEL and WSRF):

$$
\begin{aligned}
A ::= {} & throw \mid receive(pl, op, v) \mid invoke(pl, op, v_1) \mid exit \mid \\
& reply(pl, v) \mid \overline{reply}(pl, op, v_2) \mid assign(expr, v_1) \mid empty \mid \\
& A\,;A \mid A \parallel A \mid while(cond, A) \mid wait(a, b) \mid \\
& pick(\{(pl_i, op_i, v_i, A_i)\}_{i=1}^{n}, A, timeout) \mid getProp(EPR, v) \mid \\
& createResource(EPR, val, timeout, A) \mid \\
& setProp(EPR, expr) \mid setTimeout(EPR, timeout) \mid \\
& subscribe(EPR, cond', A)
\end{aligned}
$$

where $O \in ORCH, EPR \in EPRS, pl, pl_i \in PL, op, op_i \in OPS, a, b \in \mathbb{N}, a \leq b$, $expr$ is an arithmetic expression constructed by using the variables in *Var* and

integers; v, v_1, v_2, v_i range over *Var*, and $val \in \mathbb{Z}$. A condition $cond$ is a predicate constructed by using conjunctions, disjunctions, and negations over the set of variables Var and integers, whereas $cond'$ is a predicate constructed by using the corresponding EPR (as the resource value) and integers. Notice that *setProp* and *getProp* do not contain the property name since, for simplicity, we are only considering a single property for each resource. We therefore use its EPR as representative of this property. It is worth noting that we have previously presented an operational semantics for this language in the previous work [**?**].

Let us call N_A, N_f and N_{e_i} the PTCPNs that are obtained by applying the translation to each one of these activities A, A_f, A_{e_i}, with $i \in \{1, m\}$:

$$
\begin{aligned}
N_A &= (P_a, T_a, A_a, V_a, G_a, E_a, \lambda_a, D_a) && \text{(PTCPN for } A\text{)} \\
N_f &= (P_f, T_f, A_f, V_f, G_f, E_f, \lambda_f, D_f) && \text{(PTCPN for } A_f\text{)} \\
N_{e_i} &= (P_{e_i}, T_{e_i}, A_{e_i}, V_{e_i}, G_{e_i}, E_{e_i}, \lambda_{e_i}, D_{e_i}) && \text{(PTCPN for } A_{e_i}\text{)}
\end{aligned}
$$

Let $p_{a_{in}}$, $p_{f_{in}}$ and $p_{e_{i\,in}}$ be the initial places of N_A, N_f and N_{e_i}respectively; $p_{a_{ok}}$, $p_{f_{ok}}$ and $p_{e_{i\,ok}}$ their *correct* output places, $p_{a_{er}}$, $p_{f_{er}}$ and $p_{e_{i\,er}}$ their *error* places and, finally, $p_{a_{ex}}$, $p_{f_{ex}}$ and $p_{e_{i\,ex}}$ their *exit* places. The PTCPN for the orchestrator is then constructed as indicated in Fig. 3.1. This PTCPN is then activated by putting one token 0 on $p_{a_{in}}$. However, we can have other marked places, for instance, those associated with integer variables or resources. The other places are initially unmarked. The other places are initially unmarked.

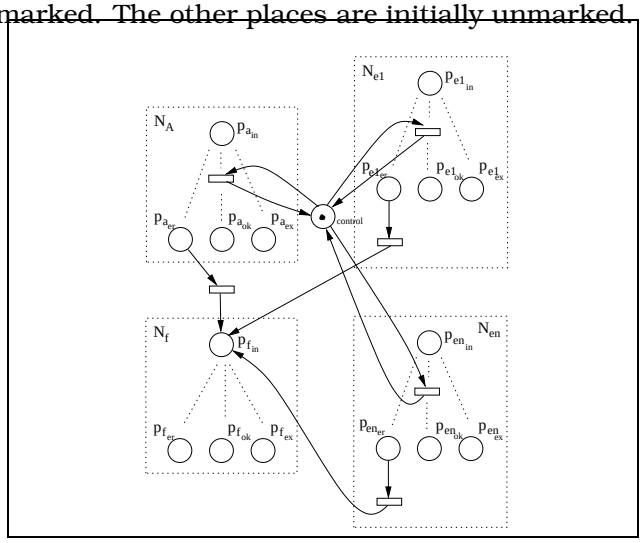

Figure 3.1: Orchestration Translation

Variables and resources: There is one place for each variable, whose token value is the current variable value. As regards resources, there are two places

associated to each resource, p_{r_i}, p_{r_a}. For any resource *r*, p_{r_a} becomes marked when the orchestrator executes the *createResource* activity, whereas the second one, p_{r_i}, is marked as far as the orchestrator does not execute the *createResource* activity. When the resource lifetime terminates, the resource is released, passing the token from p_{r_a} to p_{r_i}. Observe that we can know in advance the number of resources in the system by reading the WS-BPEL/WSRF document.

3.6.3 Basic activities

- *Throw, Empty, Assign, Exit* and *Wait* activities:
  These are translated as indicated in Fig. **??**, by means of a single transition labelled with the name of the corresponding activity linked with the corresponding terminating place. The time required to execute *assign*, *empty*, *throw* and *exit* is negligible, so that the corresponding transitions have a null delay associated. Notice that for the *assign* activity translation we use a self loop between the transition and the place associated with the variable (p_v) in order to replace its previous value by the new one, being this new value obtained from an expression (exp) consisting of variables $p_{v1}, \ldots, p_{vn}$ and integers. For the *wait* activity, we have a time interval $[a, b]$ associated, so the delay is randomly selected inside this interval.
  Notice the use of a "control" place, to arrest all possible remaining activities in the system when either throw or exit are executed. Thus, the idea is that all transitions in the net must be connected with this place, as the different illustrations show.
- *Communication activities*: The model we use is based on the invoke and receive operations, as well as the reply activity that uses a server to reply to a client. We have also added a barred version of reply to synchronise with the response from the client. We have therefore introduced this last activity in our semantics to deal with the synchronous or asynchronous nature of invoke activity (one-way or request-response operation, respectively), so the $\overline{reply}$ activity is optional in the syntax depicted in Table 3.6. Fig. **??** shows the translation for both the invoke/receive and the reply/$\overline{reply}$ pairs of activities. Part **??** of the figure corresponds to the invoke/receive translation, in which the net of the invoke activity is depicted on the left-hand-side part, whereas the receive activity is depicted on the right-hand-side part. There are two shared places, PL_{ij_s} and PL_{ij_r}, which are used to implement the synchronisation between the invocation and reception of

services. Both places are associated to the partnerlink used for this communication, denoted here by (i, j), where i and j are the orchestrator identifiers performing those activities. Notice that the value of a single variable is transmitted, which is obtained from the corresponding variable place, p_v. In the same way, the receive activity stores this value in its own variable. The interpretation of Fig. **??** is analogous.

3.6.4 Ordering structures

WS-BPEL defines structured activities for various control-flow patterns:

- Sequential control between activities is provided by <sequence>, <if>, <while>, <repeatUntil>, and the serial variant of <forEach>.
- Concurrency and synchronization between activities is provided by <flow> and the parallel variant of <forEach>.
- Deferred choice controlled by external and internal events is provided by <pick>.

The set of structured activities in WS-BPEL is not intended to be minimal [**?**], so there are cases where the semantics of one activity can be represented using another activity. Nevertheless, in order to reduce the complexity of our translation, our approach omits many derived activities only dealing with the most important ones from the modelling viewpoint, such as sequence, parallel and choice. For all these cases we provide the translation by only considering two activities. However, the generalization to a greater number of activities is straightforward in all of them.

- *Sequence*: A sequence of two activities $A_1; A_2$ (with PTCPNs N_{A_1} and N_{A_2}, respectively) is translated in a simple way (Fig. 3.2), by just collapsing in a single place (this will be an internal place of the new PTCPN) the *output* place Pok of N_{A_1}, and the *entry* place of N_{A_2}. The *entry* place of the new PTCPN will be the *entry* place of N_{A_1}. The *output* place of the new PTCPN will be the *output* place of N_{A_2}, and we also collapse the *exit*, *error* and *control* places of both PTCPNs.

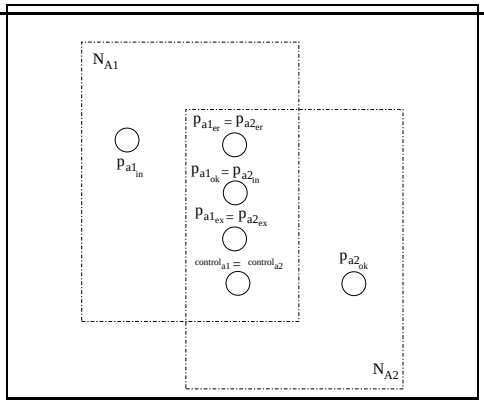

Figure 3.2: Sequence Translation

- *Parallel*: The translation for a parallel activity is depicted in Fig. 3.3, which includes two new transitions $t1$ and $t2$. The first to fork both parallel activities and the second to join them when correctly terminated. Transition $t1$ thus puts one token on the initial places of both PTCPNs, N_{A_1} and N_{A_2}, in order to activate them, and also puts one token on a new place, p_c, which is used to stop the execution of one branch when the other has failed or the exit activity is explicitly executed in one of them. This place is therefore a precondition of every transition in both PTCPNs, and it is also a postcondition of the non-failing transitions. However, in the event of a failure or an exit activity, the corresponding *throw* or *exit* transition will not put the token back on p_c, thus arresting the other parallel activity.

  Notice also that the *error* places of N_{A_1} and N_{A_2} have been joined in a single error place (p_{er}), which becomes marked with one token on the firing of one *throw* transition. In this case, the other activity cannot execute any more actions (p_c is empty), so some dead tokens would remain permanently on some places in the PTCPN. However, these tokens cannot cause any damage, since the control flow has been transferred either to the fault handling activity of the PTCPN, once the place p_{er} has become marked, or the whole system has terminated once the place p_{ex} is marked.

- *Pick* $(\{(pl_i, op_i, v_i, A_i)\}_{i=1}^{n}, A, timeout)$: The <pick> activity waits for the occurrence of exactly one event from a set of events, also establishing a timeout for this selection. The translation is depicted in Fig. 3.4 where a timer is implemented on the place *p_a* in order to enforce the firing of transition *ta* when the timeout has elapsed, thus activating N_A. Notice also the use of both timed and untimed places in this figure, respectively called *INT* and *UINT*.

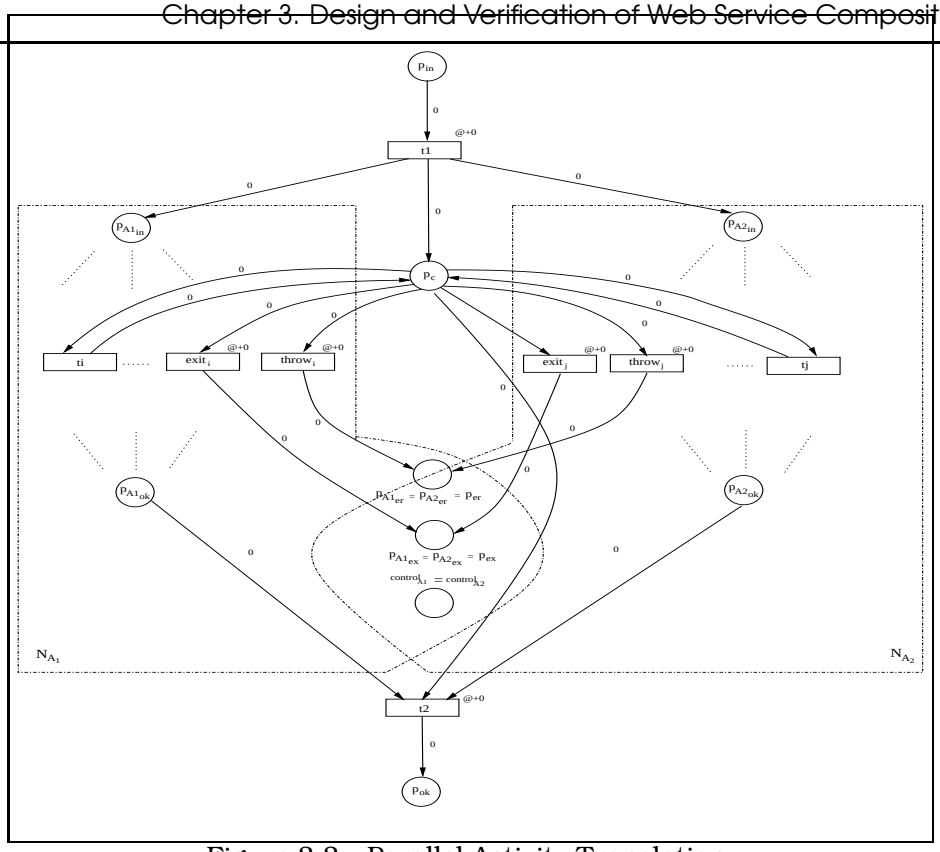

Figure 3.3: Parallel Activity Translation.

- *While* (cond,A): The machinery needed to model this construction is fairly straightforward since we only must check if the repetition condition holds or not in order to execute the contained activity or skip it. Fig. 3.5 shows this translation.

3.6.5 WSRF-compliant

Let us now see the WSRF activities, and their corresponding translations.

- *CreateResource (EPR,val,timeout,A)*: *EPR* is the resource identifier, for which we have two complementary places in Fig. 3.6, p_{r_i} and p_{r_a}, where the sub-index represents the state of the resource: i when it is inactive and a when it is active. The initial value is val, and A is the activity that must be executed when the time-out indicated as third parameter has elapsed.

  We can see in Fig. 3.6 how the transition $createResource$ removes the token from the *inactive* place, and puts a new token on the active place, whose colour contains the following information: resource identifier (EPR), its life-time (max), and its value (val). Transition $t0$ is executed when the lifetime

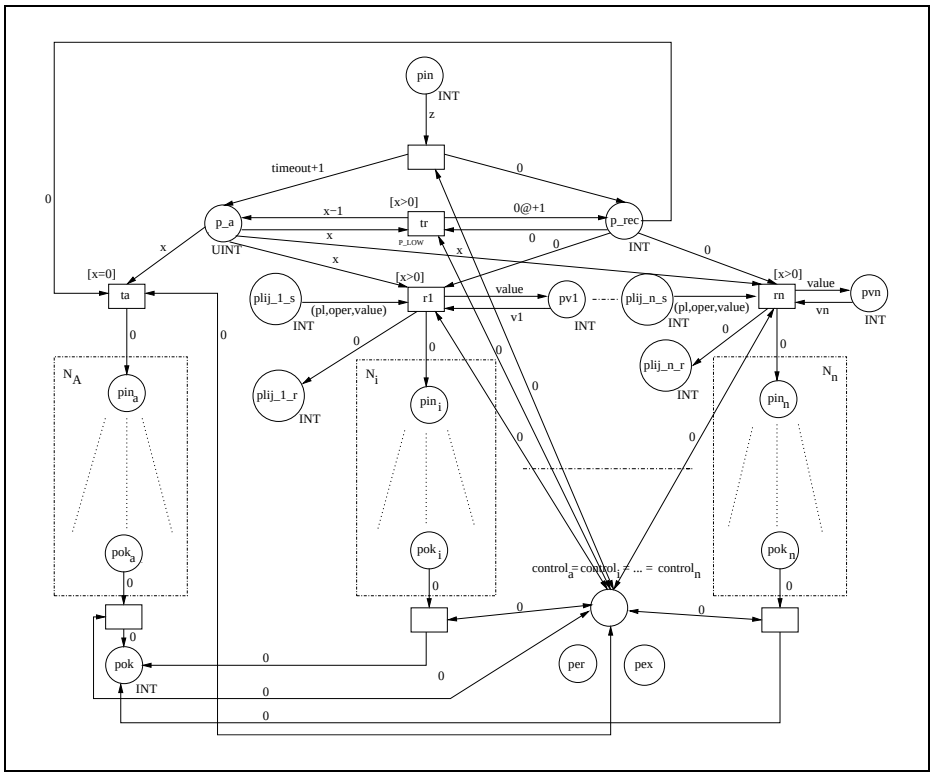

Figure 3.4: Pick Activity Translation.

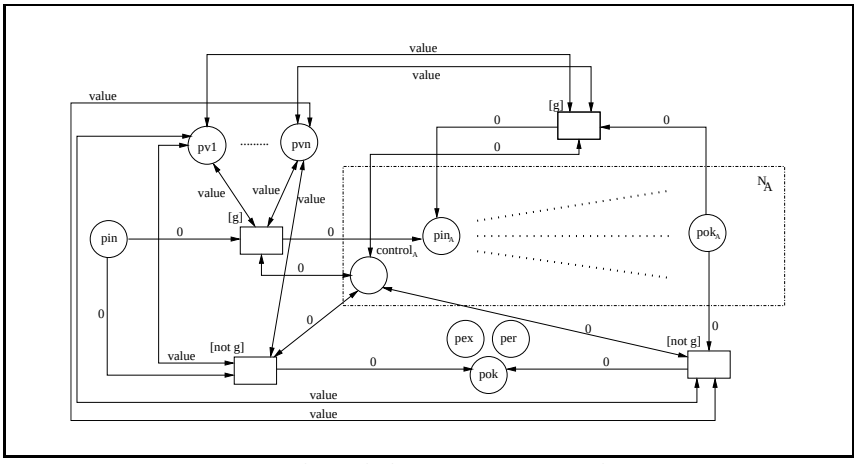

Figure 3.5: While Activity Translation.

of the resource has expired, thus removing the token from the *active* place, marking again the *inactive* place, and activating N_A. We can also see that the *active* place is linked with a number of transitions, which correspond to the subscribers (we know in advance these possible subscribers from the WS-BPEL/WSRF document). These transitions can only become enabled if the corresponding places $subs_i$ are marked by performing the correspond-

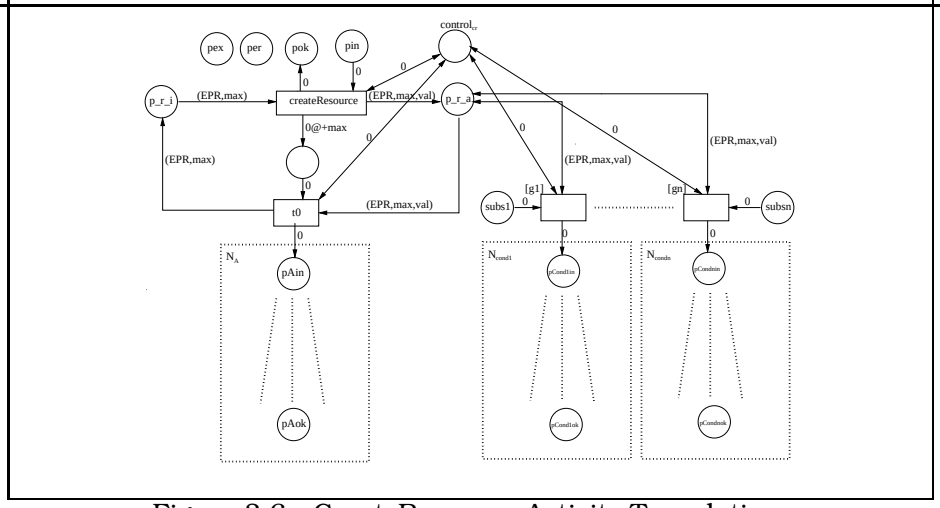

Figure 3.6: CreateResource Activity Translation.

ing activity *subscribe*. The PTCPNs $Ncond_i$ are the nets for the activities passed as parameter in the invocation of a subscribe activity.

- Subscribe (EPR,cond′,A): In this case, an orchestrator subscribes to the resource EPR, with the associated condition $cond'$, upon which the activity A must be performed. Fig. 3.7 shows this translation, where we can observe that the associated place $subs_i$ is marked in order to allow the execution of the PTCPN for the activity A if the condition g_i holds. On the contrary, if the resource is not active, we will throw the fault handling activity.

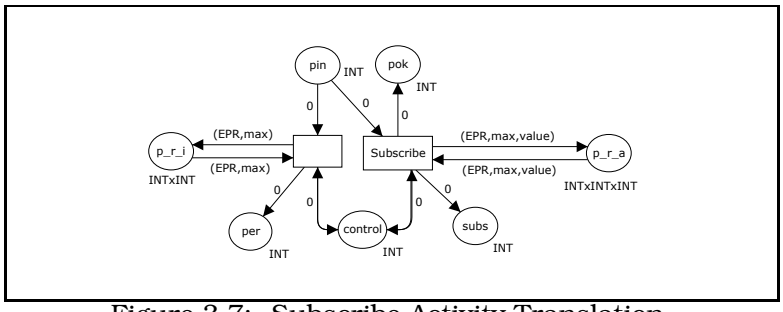

Figure 3.7: Subscribe Activity Translation.

- GetProp (EPR,v) and SetProp (EPR,expr): These are easily translated, as shown in Figs. 3.8 and 3.9, where the resource value is obtained and assigned to variable v (GetProp), or a new value is assigned to the resource (SetProp).

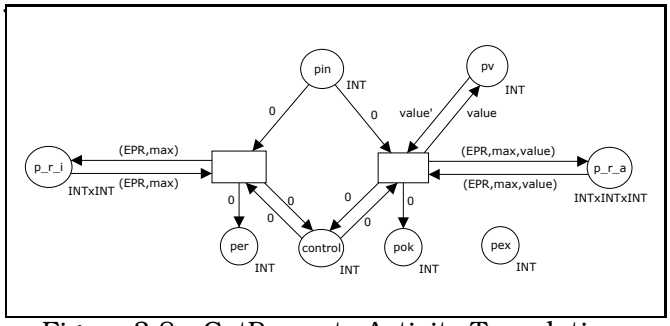

Figure 3.8: GetProperty Activity Translation.

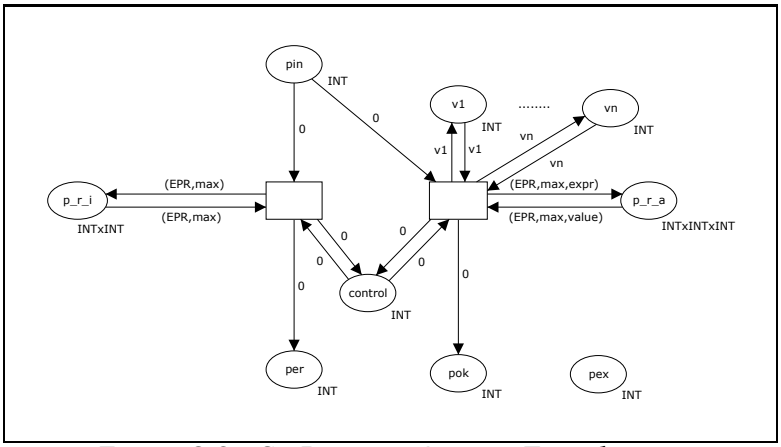

Figure 3.9: SetProperty Activity Translation.

- SetTimeout (EPR,timeout): This activity is analogous to *SetProp* activity. In this case, the resource lifetime is updated with a new value. Fig. 3.9 shows this translation.

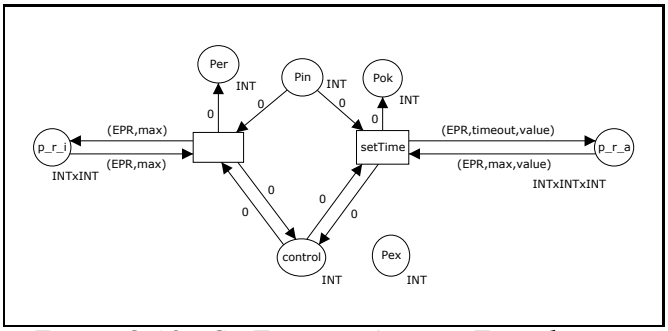

Figure 3.10: SetTimeout Activity Translation.

3.7 Case study: Online auction service

The case study concerns a typical online auction process, which consists of three participants: the online auction system and two buyers, A_1 and A_2. A seller owes a good that wants to sell to the highest possible price. Therefore, he introduces the product in an auction system for a certain time. Then, buyers (or bidders) may place bids for the product and, when time runs out, the highest bid wins. In our case, we suppose the resource is the product for auction, the value of the resource property is the current price (only the auction system can modify it), the resource subscribers will be the buyers, their subscription conditions hold when the current product value is higher than their bid, and the resource lifetime will be the time in which the auction is active. Finally, when the lifetime has expired, the auction system sends a notification to the buyers with the result of the process (the identifier of the winner, v_w) and, after that, all the processes finish. Let us consider the choreography $C = (O_{sys}, O_1, O_2)$, where $O_i = (PL_i, Var_i, A_i, A_{f_i}, \mathcal{A}_{e_i})$, i=1,2, $Var_{sys} = \{v_w, v_1, v_2, v_{EPR}, at, t\}$, $Var_1 = \{at_1, v_1, v_{w_1}\}$, $Var_2 = \{at_2, v_2, v_{w_2}\}$, $A_{f_1} = exit$, and $A_{f_2} = exit$. Variable v_{EPR} serves to temporarily store the value of the resource property before being sent; v_1, v_2, v_w, v_{w_1}, v_{w_2} are variables used for the interaction among participants, and, finally, at, at_1 and at_2 are used to control the period of time in which the auction is active. In this example, we consider a period of 10 time units. Suppose $s_{0_{sys}}, s_{0_1}$ and s_{0_2} are the initial states of O_{sys}, O_1 and O_2, respectively, and all the variables are initially 0:

$$
\begin{aligned}
A_{sys} &= assign(10, at); createResource(EPR, 25, 11, A_{not});\\
&\quad\ \ while(actualTime() <= at, A_{bid})\\
A_1 &= wait(1, 1); subscribe(O_1, EPR, EPR >= 0, A_{cond_1});\\
&\quad\ \ invoke(pl1, auction\_time_1, at1); \overline{reply}(pl1, auction\_time_1, at1);\\
&\quad\ \ while(actualTime() <= at1, A_{bid_1}); receive(pl3, bid\_finish_1, vw_1, empty)\\
A_2 &= wait(1, 1); subscribe(O_2, EPR, EPR >= 0, A_{cond_2});\\
&\quad\ \ invoke(pl2, auction\_time_2, at2); \overline{reply}(pl2, auction\_time_2, at2);\\
&\quad\ \ while(actualTime() <= at2, A_{bid_2}); receive(pl4, bid\_finish_2, vw_2, empty)\\
A_{not} &= ((invoke(pl_3, bid\_finish_1, v_w) || invoke(pl_4, bid\_finish_2, v_w))\\
A_{bid} &= getprop(EPR, v_{EPR}); pick(\\
&\quad\ \ (pl1, auction\_time1, t, reply(pl1, auction\_time1, at)),
\end{aligned}
$$

$$(pl2, auction\_time2, t, reply(pl2, auction\_time2, at)),$$
$$(pl_1, cmp, v_1, while(v_1 > v_{EPR}, assign(v1, v_{EPR});$$
$$setProp(EPR, v_{EPR}); assign(1, vw))),$$
$$(pl_2, cmp, v_2, while(v_2 > v_{EPR}, assign(v2, v_{EPR});$$
$$setProp(EPR, v_{EPR}); assign(2, vw))), empty, 1)$$
$$A_{cond_1} = getProp(EPR, v_{EPR}); invoke(pl_1, bid\_up_1, v_{EPR})$$
$$A_{cond_2} = getProp(EPR, v_{EPR}); invoke(pl_2, bid\_up_2, v_{EPR})$$
$$A_{bid_1} = receive(pl_1, bid\_up_1, v_1); assign(v_1 + random(), v_1);$$
$$invoke(pl_1, cmp, v_1); subscribe(O_1, EPR, EPR > v_1, A_{cond_1}); wait(1, 1)$$
$$A_{bid_2} = receive(pl_2, bid\_up_2, v_2); assign(v_2 + random(), v_2);$$
$$invoke(pl_2, cmp, v_2); subscribe(O_2, EPR, EPR > v_2, A_{cond_2}); wait(1, 1)$$

Regarding to the operations $auction\_time1$ and $auction\_time2$ inform buyers about the period of time in which the auction is active via variables at, $at1$ and $at2$, which are used in the while structures to control this period. The operations bid_up_1 and bid_up_2 are used to increase the current bid by adding a random amount to the corresponding variable v_i. The operation cmp is an auction system operation that receives as parameter a variable of the buyers, v_i. If the value of this variable is greater than the current value of v_{EPR}, then v_{EPR} is modified with this new value, that is, the new bid exceeds the current bid. After that, by means of the activity $setProp(EPR, v_{EPR})$, we can update the value of the resource property with the new bid. Finally, the operations bid_finish_1, bid_finish_2 update the value of v_w to inform the buyers who is the winner once the auction has expired.

In Fig. 3.11, we depict a simplified version of the PTCPN for the online auction system. The complete model can be accessed at the following web address: `http://www.dsi.uclm.es/retics/bpelrf/`. Here, we have constructed a hierarchical net relying on the notions of substitution transitions, sockets and ports offered by CPNTools [**?**]. We have then simulated and analysed the system, and we have concluded that the system finalizes successfully, that is, the output place of the system (p_ok) is reached in all the simulations. To check the consistency of the model, we have simulated the possibility of reaching an error place. For instance, if we delete the $wait(1, 1)$ sentences from activities A_1 and A_2, then it would imply that the buyers could access to the resource, that is the

bid, even before the resource has been created. This possibility would trigger the expected error. Furthermore, we have analysed the data output from an experiment consisting of 5000 simulations. From the analysis of these data, we observe that the system is fair, from the point of view of the buyers, since they have equal right to place a bid. Indeed, the average of placed bids from each buyer is similar. Other information gathered from these data shows that buyers can evenly place higher bids than their competitors.

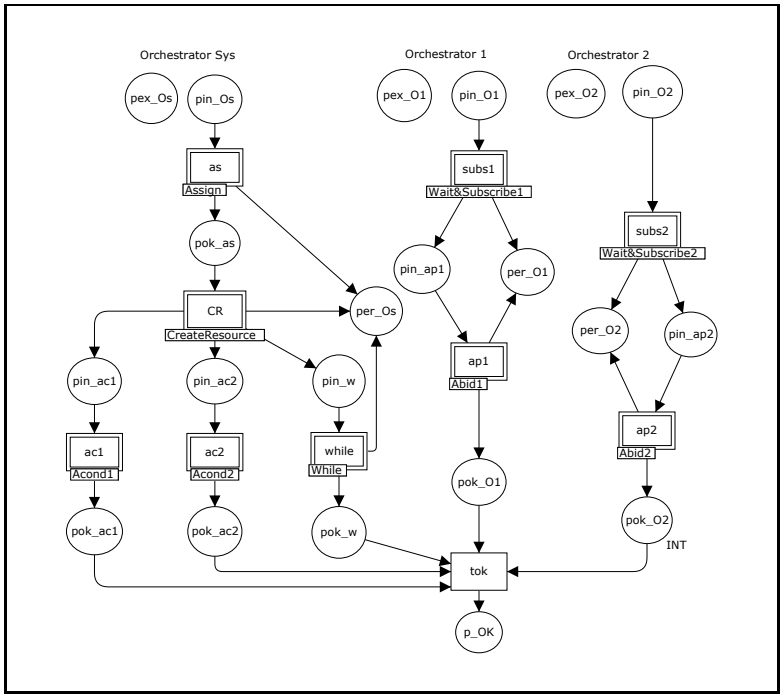

Figure 3.11: A simplified PTCPN for the online auction system.

3.8 Formal Analysis of Web Service Compositions

In last years the formal analysis of Web Service compositions has been recognized as an important problem that needs to be solved [**?**, **?**, **?**, **?**]. A strict analysis is necessary to guarantee the correct composition of the services for multiple reasons: the integration of several independent applications, the possibility of having incomplete specifications of some services, the impossibility of using traditional evaluation techniques such as software testing, . . .

The analysis of Web Service compositions usually consists of checking its specification correctness by analysing if a set of functional and non-functional

requirements are fulfilled. The behavioural requirements are especially interesting, as they specify the properties required to reach a concrete business goal. These requirements can include general properties such as deadlock freeness or correct termination, but they can also be defined explicitly, for example defining the conformance to a concrete model. This formal analysis is usually done by means of formal methods.

Formal methods [**?**] are a collection of notations and techniques for describing and analyzing systems [**?**]. They are called *formal* because they are based on mathematical theories (logics, automata, sets, ...). In formal methods we can distinguish between the *formal specification*, which describes unambiguously a system or its properties, and the *formal analysis* or *formal verification*, which serves to verify if a system satisfies its specification.

Formal methods usually cannot guarantee the correctness of the implementation and, if the specification is not correct, the verification results will also be wrong. Despite these and some other limitations, formal methods are still needed because they increase the confidence on system reliability, minimize the number of errors in the implementation and can find out errors impossible to find with other techniques such as testing.

When we are going to apply a formal method it is very important to choose the right level of abstraction in the specification of the system depending on what we want to analyze or verify. An underspecification can lead to wrong verification results because the specification is incomplete, whereas an overspecification can lead to the *state explosion problem*, making the intended analysis of the system infeasible.

Formal methods can be applied in different stages of the computer system development process, providing different information about the system in each one of these stages. The application of these methods is usually complex, being impossible without some kind of tool support. For this purpose, the language syntax of the specification must be explicit and the language semantics of the specification must be restricted. In this way, formal specifications are amenable to automate analysis and verification.

The choice of using one formal method or another depends on many factors: the problem we want to solve, the type of system, the properties we want to

check, and so on. In the case of complex systems, such as distributed concurrent systems, it is needed a combination of several techniques for the analysis.

3.9 Summary

This chapter has described a methodology called *Correct-WS* for the design and verification of Web Service compositions and a tool called WST supporting several phases of this methodology. As a proof of concept the tool has been apply to an Internet purchase process case study. The chapter ends with a brief description of some parallel works which aim is also the development of correct Web Service compositions.

Although in this chapter sequence diagrams have been used to design the service composition behaviour in a proper way, sometimes we just have an electronic contract defining all the contractually correct behaviours of the system in a more general way. In these cases we would like to have a user-friendly representation of the e-contracts but having at the same time a formal background allowing us to verify the correctness of the e-contracts. That is what Chapter **??** is focused on.

WS-BPEL/WSRF/WS-Notification Syntax	Model
<process ...> <partnerLinks> ... </partnerLinks>? <Variables> ... </Variables>? <faultHandlers> ... </faultHandlers>? <eventHandlers> ... </eventHandlers>? (activities)* </process>	(A, A_f)
<throw/>/any fault	throw
<receive partnerLink="pl" operation="op" variable="v" createInstance="no"> </receive>	receive(pl,op,v)
<reply partnerLink="pl" operation="op" variable="v"> </reply>	reply(pl,op,v)
<invoke partnerLink="pl" operation="op"inputVariable="v_1" outputVariable="v_2"?> </invoke>	invoke(pl,op,v_1); $[\overline{reply}$(pl,op,v_2)]
<empty> ... </empty>	empty
<exit> ... </exit>	exit
<assign><copy><from>expr</from><to>v_1</to></copy></assign>	assign(expr,v_1)
<wait><for>timeout</for> </wait>	wait(timeout)
<sequence> $activity_1$ $activity_2$ </sequence> <flow> $activity_1$ $activity_2$ </flow>	$\frac{A_1 \ ; \ A_2}{A_1 \parallel A_2}$
<while><condition>cond</condition>$activity_1$ </while>	while(cond,A)
<pick createInstance="no"> <onMessage partnerLink="pl" operation="op"variable="v"> $activity_1$ </onMessage> <onAlarm><for>timeout</for>$activity_1$ </onAlarm> </pick>	pick($\{(pl_i, op_i, v_i, A_i)\}_{i=1}^{n}$, A,timeout)
<invoke partnerLink="Factory"operation="CreateResource" inputVariable="O,val,timeout,tag" outputVariable="vEPR"> </invoke><assign><copy><from variable="EPR">part="ref" query="/test:CreateOut/wsa:endpointreference"</from> <to> partnerlink="Factory"</to></copy></assign>	publishResource(O,val,timeout,tag,vEPR,A)
<wsrp:GetResourceProperty> <wsa:Address>vEPR< /wsa:Address> tns:value variable_identifier1 </wsrp:GetResourceProperty>	getProp(vEPR,v_1)
<wsrp:GetResourceProperty> <wsa:Address>vEPR< /wsa:Address> tns:timeout variable_identifier1 </wsrp:GetResourceProperty>	getTimeout(vEPR,v_1)
<wsrp:SetResourceProperties> <wsa:Address>vEPR< /wsa:Address> <wsrp:Update>expression</wsrp:Update> </wsrp:SetResourceProperties>	setProp(vEPR,expr)
<wsrl:SetTerminationTime> <wsa:Address>vEPR< /wsa:Address> <wsrl:RequestedTerminationTime> timeout </wsrl:RequestedTerminationTime> </wsrl:SetTerminationTime>	setTimeout(vEPR,timeout)
<wsnt:Subscribe> <wsnt:ConsumerReference>O</wsnt: ConsumerReference> <wsnt:ProducerReference>vEPR</wsnt: ProducerReference> <wsnt:Precondition>cond′</Precondition> </wsnt:Subscribe>	subscribe(O,vEPR,cond′,A)
<wsnt:Notify> <wsnt:NotificationMessage> <wsnt:SubscriptionReference>O</wsnt:SubscriptionReference> <wsnt:ProducerReference>EPR</wsnt:ProducerReference> <wsnt:Message> ... </wsnt:Message> </wsnt:NotificationMessage> </wsnt:Notify>	Spawn the associated event handler activity
<invoke partnerLink="pl" operation="discover"inputVariable="tag1" outputVariable="vEPR"> </invoke>	discover(tag,vEPR)

Table 3.1: Conversion table

(Throw) $(throw, s) \xrightarrow{throw} (empty, s)$

(Exit) $(exit, s) \xrightarrow{exit} (empty, s)$

(Invoke) $(invoke(pl, op, v_1), s) \xrightarrow{invoke(pl,op,\sigma(v_1))} (empty, s)$

(Reply) $(\overline{reply}(pl, op, v_2), s) \xrightarrow{\overline{reply}(pl,op,m)} (empty, s')$
where $v_2 \in VAR$, $m \in \mathbb{Z}$, $pl \in PL$, $op \in OPS$, and $s' = (\sigma[m/v_2], \rho)$.

(Receive) $(receive(pl, op, v), s) \xrightarrow{receive(pl,op,m)} (empty, s')$
where $v \in VAR$, $m \in \mathbb{Z}$, $op \in OPS$, $pl \in PL$, and $s' = (\sigma[m/v], \rho)$

(Reply) $(reply(pl, op, v), s) \xrightarrow{reply(pl,op,\sigma(v))} (empty, s)$

(Assign) $(assign(expr, v_1), s) \xrightarrow{assign(expr,v_1)} (empty, s')$
where $v_1 \in VAR$, $expr$ is an arithmetic expression, and $s' = (\sigma[expr/v_1], \rho)$.

(Seq1) $$\frac{(A_1, s) \xrightarrow{a} (A_1', s'), a \neq exit, a \neq throw}{(A_1; A_2, s) \xrightarrow{a} (A_1'; A_2, s')}$$

(Seq2) $$\frac{(A_1, s) \xrightarrow{a} (empty, s'), a \neq exit, a \neq throw}{(A_1; A_2, s) \xrightarrow{a} (A_2, s')}$$

(Seq3) $$\frac{(A_1, s) \xrightarrow{a} (empty, s), (a = throw \vee a = exit)}{(A_1; A_2, s) \xrightarrow{a} (empty, s)}$$

(Par1) $$\frac{(A_1, s) \xrightarrow{a} (A_1', s'), a \neq exit, a \neq throw}{(A_1||A_2, s) \xrightarrow{a} (A_1'||A_2, s')}$$

(Par2) $$\frac{(A_2, s) \xrightarrow{a} (A_2', s'), a \neq exit, a \neq throw}{(A_1||A_2, s) \xrightarrow{a} (A_1||A_2', s')}$$

(Par3) $$\frac{(A_1, s) \xrightarrow{a} (empty, s), (a = throw \vee a = exit)}{(A_1||A_2, s) \xrightarrow{a} (empty, s)}$$

(Par4) $$\frac{(A_2, s) \xrightarrow{a} (empty, s), (a = throw \vee a = exit)}{(A_1||A_2, s) \xrightarrow{a} (empty, s)}$$

(Par5) $(empty||empty, s) \xrightarrow{\tau} (empty, s)$

(While1) $$\frac{cond(s)}{(while(cond, A), s) \xrightarrow{\tau} (A; while(cond, A), s)}$$

(While2) $$\frac{\neg cond(s)}{(while(cond, A), s) \xrightarrow{\tau} (empty, s)}$$

(Pick) $(pick(\{(pl_i, op_i, v_i, A_i)\}_{i=1}^n, A, t), s) \xrightarrow{pick(pl_i,op_i,m,A_i)} (A_i, s')$
where $t \geq 1$, $v_i \in VAR$, $m \in \mathbb{Z}$, $pl_i \in PL$, and $s' = (\sigma[m/v_i], \rho), \forall i \in \{1..n\}$.

(PublishResource) $(publishResource(O, val, t, tag, vEPR, A), s) \xrightarrow{publishResource(O,val,t,tag,e,A)} (empty, s')$
where $t \geq 1$, $O \in ORCH$, $val \in \mathbb{Z}$, $vEPR \in VAR$, $e = getEPR()$ and $s' = (\sigma[e/vEPR], \rho \cup \{O, e, val, \emptyset, t, tag, A\})$.

(GetP) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(getProp(vEPR, v_1), s) \xrightarrow{getProp(\sigma(vEPR),val(\rho,vEPR))} (empty, s')}$$
where $vEPR, v_1 \in VAR$ and $s' = (\sigma[val(\rho, vEPR)/v_1], \rho)$.

(GetT2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(getTimeout(vEPR, v_1), s) \xrightarrow{throw} (empty, s)}$$

(GetT) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(getTimeout(vEPR, v_1), s) \xrightarrow{getTimeout(\sigma(vEPR),time(\rho,vEPR))} (empty, s')}$$
where $vEPR, v_1 \in VAR$ and $s' = (\sigma[time(\rho, vEPR)/v_1], \rho)$.

(GetP2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(getProp(vEPR, v_1), s) \xrightarrow{throw} (empty, s)}$$

(SetP) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(setProp(vEPR, expr), s) \xrightarrow{setProp(\sigma(vEPR),expr)} (empty, s')}$$
where $vEPR \in VAR$ and $s' = (\sigma, \rho[expr/vEPR]_1)$.

(SetP2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(setProp(vEPR, expr), s) \xrightarrow{throw} (empty, s)}$$

(SetT) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(setTimeout(vEPR, t), s) \xrightarrow{setTimeout(\sigma(vEPR),t)} (empty, s')}$$
where $t \geq 1$, $s' = (\sigma, \rho[t/vEPR]_2)$.

(Subs2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(subscribe(O, vEPR, cond', A), s) \xrightarrow{throw} (empty, s')}$$

(Subs) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(subscribe(O, vEPR, cond', A), s) \xrightarrow{subscribe(O,\sigma(vEPR),cond',A)} (empty, s')}$$
where $s' = (\sigma, Add\_subs(\rho, vEPR, O, cond', A))$

(SetT2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(setTimeout(vEPR, t), s) \xrightarrow{throw} (empty, s)}$$

(D1) $$\frac{s = (\sigma, \rho), tag \in \rho}{(discover(tag, vEPR), s) \xrightarrow{discover(tag,sel(\rho,tag))} (empty, s')}$$
where $vEPR \in VAR$, $s' = (\sigma[sel(\rho, tag)/vEPR], \rho))$

(D2) $$\frac{s = (\sigma, \rho), tag \notin \rho}{(discover(tag, vEPR), s) \xrightarrow{discover(tag,-1)} (empty, s')}$$
where $vEPR \in VAR$, $s' = (\sigma[-1/vEPR], \rho))$

Table 3.2: Action transition rules.

(Wait1D) $$\frac{t > 1}{(wait(t), s) \rightarrow_1 (wait(t-1), s^+)}$$

(Wait2D) $(wait(1), s) \rightarrow_1 (empty, s^+)$

(SequenceD) $$\frac{(A_1, s) \rightarrow_1 (A_1', s^+)}{(A_1; A_2, s) \rightarrow_1 (A_1'; A_2, s^+)}$$

(EmptyD) $(empty, s) \rightarrow_1 (empty, s^+)$

(ParallelD) $$\frac{(A_1, s) \rightarrow_1 (A_1', s^+) \wedge (A_2, s) \rightarrow_1 (A_2', s^+)}{(A_1||A_2, s) \rightarrow_1 (A_1'||A_2', s^+)}$$

(InvokeD) $(invoke(pl, op, v_1), s) \rightarrow_1 (invoke(pl, op, v_1), s^+)$

(ReceiveD) $(receive(pl, op, v), s) \rightarrow_1 (receive(pl, op, v), s^+)$

(PickD) $(pick(\{(pl_i, op_i, v_i, A_i)\}_{i=1}^n, A, 1), s) \rightarrow_1 (A, s^+)$

(Pick2D) $$\frac{t > 1}{(pick(\{(pl_i, op_i, v_i, A_i)\}_{i=1}^n, A, t), s) \rightarrow_1 (pick(\{pl_i, op_i, v_i, A_i\}_{i=1}^n, A, t-1), s^+)}$$

Table 3.3: Delay transition rules without notifications.

$$\textbf{(ORCH1)}\ \frac{(A,s) \xrightarrow{a} (A',s'), a \neq exit, a \neq throw}{(O:(A,s)^m) \xrightarrow{a} (O:(A',s')^m)} \qquad \textbf{(ORCH2)}\ \frac{(A,s) \xrightarrow{throw} (empty,s)}{(O:(A,s)) \xrightarrow{throw} (O:(A_f,s)^f)}$$

$$\textbf{(ORCH3)}\ \frac{(A,s) \xrightarrow{throw} (empty,s)}{(O:(A,s)^f) \xrightarrow{throw} (O:(empty,s)^f)} \qquad \textbf{(ORCH4)}\ \frac{(A,s) \xrightarrow{exit} (empty,s)}{(O:(A,s)^m) \xrightarrow{exit} (O:(empty,s)^m)}$$

$$\textbf{(ORCH5)}\ \frac{(A,s) \rightarrow_1 (A',s^+)}{(O:(A,s)^m) \rightarrow_1 (O:(A',s^+)^m)}$$

Table 3.4: Action and delay transition rules for orchestrators.

$$\textbf{(Chor1)}\ \frac{(O_i:(A_i,s)^{m_i}) \xrightarrow{exit} (O_i:(empty,s)^{m_i})}{\{(O_k:(A_k,s)^{m_k})\}_{k=1}^c \xrightarrow{exit} \{(O_k:(A'_k,s)^{m_k})\}_{k=1}^c}$$
where *if* $k \neq i, A'_k = A_k$.

$$\textbf{(Chor2)}\ \frac{(O_i:(A_i,s)^{m_i}) \xrightarrow{throw} (O_i:(A'_i,s)^{m'_i})}{\{(O_k:(A_k,s)^{m_k})\}_{k=1}^c \xrightarrow{throw} \{(O_k:(A'_k,s)^{m'_k})\}_{k=1}^c}$$
where *if* $k \neq i, A'_k = A_k$, *and* $m'_k = m_k$.

$$\textbf{(Chor3)}\ \frac{(O_i:(A_i,s)^{m_i}) \xrightarrow{a} (O_i:(A'_i,s')^{m'_i}),\ a \neq exit,\ a \neq \overline{throw},\ a \neq receive,\ a \neq invoke,\ a \neq reply,\ a \neq \overline{reply},\ a \neq pick}{\{(O_k:(A_k,s)^{m_k})\}_{k=1}^c \xrightarrow{a} \{(O_k:(A'_k||N(O_k,s'),s'')^{m'_k})\}_{k=1}^c}$$
where *if* $k \neq i, A'_k = A_k, m'_k = m_k$ *and* $s'' = Subs(s')$.

$$\textbf{(Chor4)}\ \frac{(O_i:(A_i,s)^{m_i}) \rightarrow_1 (O_i:(A'_i,s^+)^{m_i}),\ \forall i \in \{1,\ldots,c\}, \text{and rules chor5, chor6, chor7 are not applicable}}{\{(O_k:(A_k,s)^{m_k})\}_{k=1}^c \rightarrow_1 \{(O_k:(A'_k,s^+)^{m_k})\}_{k=1}^c}$$

$$\textbf{(Chor5)}\ \frac{(O_i:(A_i,s)^{m_i}) \xrightarrow{invoke(pl,op,n)} (O_i:(A'_i,s)^{m_i}),\ pl=(O_i,O_j),\ (O_j:(A_j,s)^{m_j}) \xrightarrow{receive(pl,op,n)} (O_j:(A'_j,s')^{m_j})}{\{(O_k:(A_k,s)^{m_k})\}_{k=1}^c \xrightarrow{invoke(pl,op,n)} \{(O_k:(A'_k,s')^{m'_k})\}_{k=1}^c}$$
where *if* $k \neq i, k \neq j, A'_k = A_k, m'_k = m_k$.

$$\textbf{(Chor6)}\ \frac{(O_i:(A_i,s)^{m_i}) \xrightarrow{reply(pl,op,n)} (O_i:(A'_i,s)^{m_i}),\ pl=(O_i,O_j),\ (O_j:(A_j,s)^{m_j}) \xrightarrow{\overline{reply}(pl,op,n)} (O_j:(A'_j,s')^{m_j})}{\{(O_k:(A_k,s)^{m_k})\}_{k=1}^c \xrightarrow{reply(pl,op,n)} \{(O_k:(A'_k,s')^{m'_k})\}_{k=1}^c}$$
where *if* $k \neq i, k \neq j, A'_k = A_k, m'_k = m_k$.

$$\textbf{(Chor7)}\ \frac{(O_i:(A_i,s)^{m_i}) \xrightarrow{invoke(pl,op,n)} (O_i:(A'_i,s)^{m_i}),\ pl=(O_i,O_j),\ (O_j:(A_j,s)^{m_j}) \xrightarrow{pick(pl,op,n,A)} (O_j:(A'_j,s')^{m_j})}{\{(O_k:(A_k,s)^{m_k})\}_{k=1}^c \xrightarrow{invoke(pl,op,n)} \{(O_k:(A'_k,s')^{m'_k})\}_{k=1}^c}$$
where *if* $k \neq i, k \neq j, A'_k = A_k, m'_k = m_k$.

Table 3.5: Choreography transition rules.

WS-BPEL/WSRF Syntax	Model
<process ...> <partnerLinks> ... </partnerLinks>? <Variables> ... </Variables>? <faultHandlers> ... </faultHandlers>? <eventHandlers> ... </eventHandlers>? (activities)* </process>	(PL,Var,A,A_f ,A_e)
<throw/>/any fault	throw
<receive partnerLink="pl" operation="op" variable="v" createInstance="no"> </receive>	receive(pl,op,v)
<reply partnerLink="pl" variable="v"> </reply>	reply(pl,v)
<invoke partnerLink="pl" operation="op" inputVariable="v_1" outputVariable="v_2"?> </invoke>	invoke(pl,op,v_1); [$\overline{reply}$(pl,op,v_2)]
<empty> ... </empty>	empty
<exit> ... </exit>	exit
<assign><copy><from>expr</from><to>v_1 </to></copy></assign>	assign(expr,v_1)
<wait><from>a</from><to>b</to> </wait>	wait(a,b)
<sequence> $activity_1$ $activity_2$ </sequence> <flow> $activity_1$ $activity_2$ </flow>	A_1 ; A_2 $A_1 \parallel A_2$
<while><condition>cond</condition>$activity_1$ </while>	while(cond,A)
<pick createInstance="no"> <onMessage partnerLink="pl" operation="op"variable="v"> $activity_1$ </onMessage> <onAlarm><for>timeout</for>$activity_1$ </onAlarm> </pick>	pick($\{(pl_i, op_i, v_i, A_i)\}_{i=1}^{n}$, A,timeout)
<invoke partnerLink="Factory"operation="CreateResource" inputVariable="val,timeout" outputVariable="EPR"> </invoke><assign><copy><from variable="EPR">part="ref" query="/test:CreateOut/wsa:endpointreference"</from> <to> partnerlink="Factory"</to></copy></assign>	createResource(EPR,val,timeout,A)
<wsrp:GetResourceProperty> <wsa:Address>EPR< /wsa:Address> variable_identifier </wsrp:GetResourceProperty>	getProp(EPR,v)
<wsrp:SetResourceProperties> <wsa:Address>EPR< /wsa:Address> <wsrp:Update>expression</wsrp:Update> < /wsrp:SetResourceProperties>	setProp(EPR,expr)
<wsrl:SetTerminationTime> <wsa:Address>EPR< /wsa:Address> <wsrl:RequestedTerminationTime> timeout </wsrl:RequestedTerminationTime> </wsrl:SetTerminationTime>	setTimeout(EPR,timeout)
<wsnt:Subscribe> <wsnt:ProducerReference>EPR</wsnt: ProducerReference> <wsnt:Precondition>cond′ </Precondition> </wsnt:Subscribe>	subscribe(EPR,cond′,A)
<wsnt:Notify> <wsnt:NotificationMessage> <wsnt:ProducerReference>EPR</wsnt:ProducerReference> <wsnt:Message> ... </wsnt:Message> </wsnt:NotificationMessage> </wsnt:Notify>	Executes the associated event handler activity

Table 3.6: Conversion table

Chapter 4

Timed-arc workflow nets

Chapter 5

Conclusions, Contributions and Future Works

This chapter presents the conclusions of this Thesis, reviews the contributions of this work, and suggests some possible future lines of research. It also includes a list of the publications obtained as a result of this work.

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