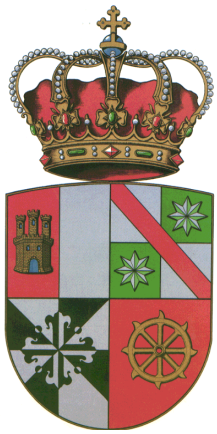
Verification and Validation of Web Service Compositions using Formal Methods



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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Abstract

Nowadays, most 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 a self-contained functionality offering it over a well-defined and standardised interface. It allows cross-organizational collaborations in which each participant is in charge of a particular task 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, the code implementing the consumed services 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), where 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 applying any

specific techniques to ensure the correctness of each participant and their composition. In this Thesis, we first present a formal language called BPELRF and its semantics. The aim of this language is to model a set of business processes 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, but abstracting away most of the data while focusing on the possible flows in the system. With the purpose of finding early 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*, which 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. These allow 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. This timed Petri net extension is currently

supported by the tool Tapaal, thus offering to researchers and users a potential 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. There are two complementary views in composite web services: 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 some 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) [5] 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.

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) [8, 3]. 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 [25].

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 are not only a graphical model, but they also provide us with 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.

The aim of the second part of the Thesis is to extend a mature formalism like Workflow nets with time features. To this end, we use timed-arc Petri nets, where each token has attached a timestamp, allowing to measure, for instance, execution times. Workflow nets are useful when designing how the participants of a business process interact and in which order. Thus, it is easy to check bottlenecks or undesirable behaviour in our processes. Moreover, we prove the decidability (or undecidability) of a fundamental property for workflow nets, soundness. This property is checked using a continuous and a discrete

time semantics. To add value to our workflow theory, we have included it into a well-known tool, Tapaal.

1.2 Objectives

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

General Objectives

Two main objectives for this Thesis have been considered. The first one is the formal definition (syntax and semantics) of a language that encapsulates the main aspects of composite web services (provided with distributed resources) from the orchestration viewpoint. The second objective 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 can be 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 are also 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 compositions and Grid/Cloud Computing applications.
  2. Analysis of 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, first the syntax, and, then, the operational semantics and the Petri nets semantics for 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 supporting 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 illustrated.
  2. Study a set of theoretical examples where the power of both proposals and its main aspects are characterized .
  3. Demonstrate the applicability of this work by 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 to the Thesis, showing the motivation, the main objectives and the scope of it.

Chapter 2 shows the state of art for 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 comprehensive introduction of the standards used in this work is presented. Next, we get into workflow nets and the possible time extension of them, as well as its main properties. Finally, we describe the basic notions of the formal models of concurrency used in the Thesis.

In **Chapter 3**, we define the extended models of concurrency used in this work. We start defining a general extension of basic Petri nets and, then, we

present two extensions of them. Some properties for the study of concurrent systems are also described. First, we introduce prioritised-timed Petri nets as they are used in the Chapter 4 as the visual formal model for the language BPELRF and, second, we define timed-arc Petri nets as they will be used as formalism to define our timed extension of workflow nets.

Chapter 4 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 that allows us to get an automatic and easy translation to CPN-Tools input model, thus permitting us to make simulation and verification of some properties.

In **Chapter 5** we suggest a timed 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.

Finally, the main conclusions, contributions and future works of this Thesis are described in **Chapter 6**.

Chapter 2

State of the Art

In this chapter, the state-of-the-art related to the specification, formalization and verification of stateful web services and their composition will be presented, 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, the different technologies used to model web services and the different approaches to compose them are introduced as well as the different mechanisms available to enrich these web services with distributed resources. Next, we will get into the technical details of workflow management systems and their relation with workflow nets and business processes. Finally, the specific formal models used here are introduced and why they are useful to model business processes. Thus, we present first some notation and the definition of basic Petri nets, and a brief introduction about process algebras (and some of the most famous cases) is shown at the end of this chapter. Next, in Chapter 3, we extend Petri nets with time features and priorities.

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

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

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 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 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 [19] 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 unrealisable. Among other causes, the notations used to require a high mathematical background in mathematics and, therefore, they were too complicated for the uninitiated people 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 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 beneficial 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).
- The increasing system complexity makes formal verification very difficult to apply, as the number of states grows exponentially.

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 process. Anyway, a proper specification does not guarantee the absence of errors, because the presence of faults is an intrinsic characteristic of systems development. 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, aiming at having a formal representation of it. This allows us to analyse the system in an automatic way.

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 the goal of researchers in this area is to check whether certain properties hold in

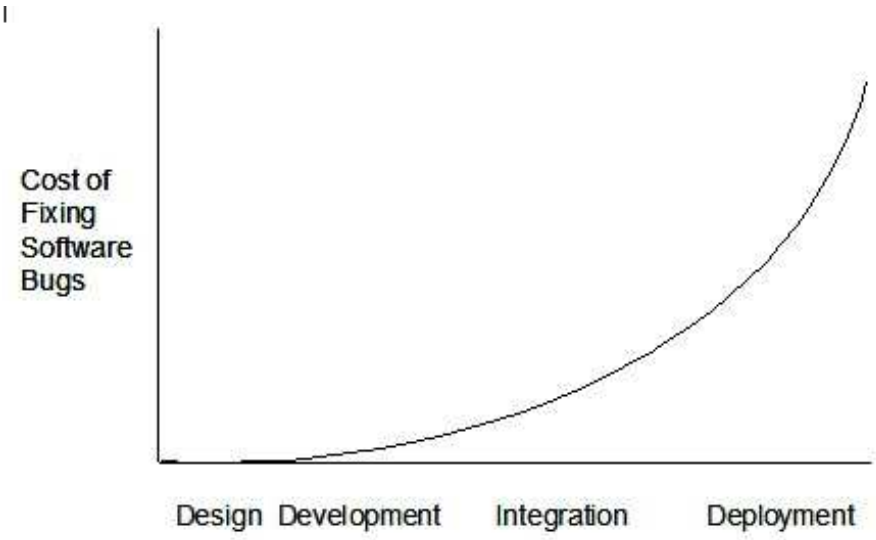


Figure 2.2: Cost evolution of fixing a bug.

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 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 [23] 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 [40] or CTL [45] 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 [37]. 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

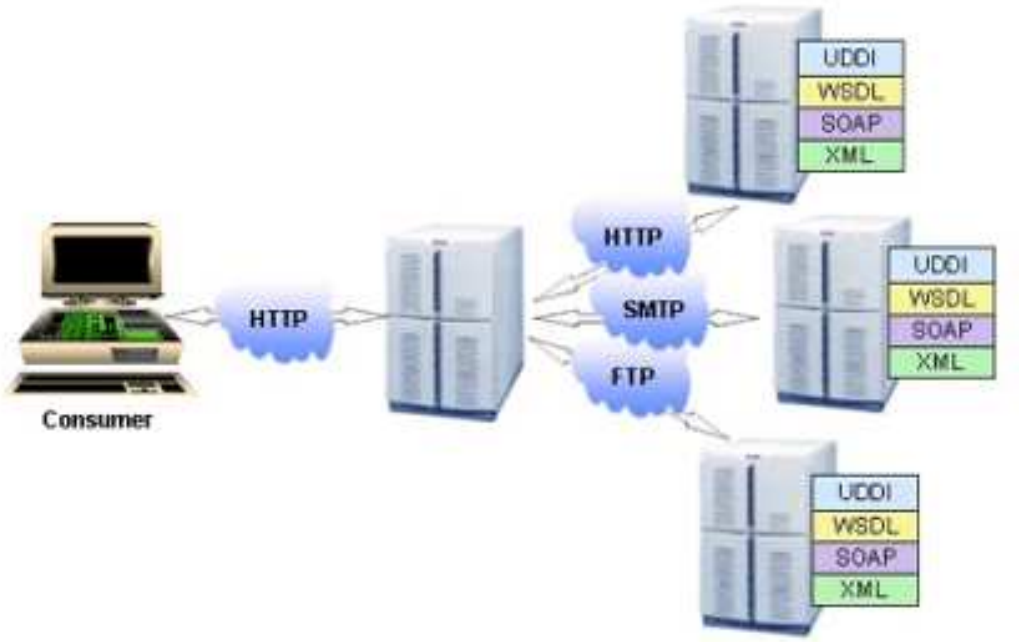


Figure 2.3: Client-server web architecture

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 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 interface 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 [17], and Simple Object Access Protocol (SOAP) for the exchange of XML messages between services [15]. 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 it [1]. 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 forged 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 designing web service compositions. These 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) taking place between the parties, that is, how they collaborate in the composition. In Figure 2.5, it is depicted graphically what it the role of each of them if they are compared with the mu-

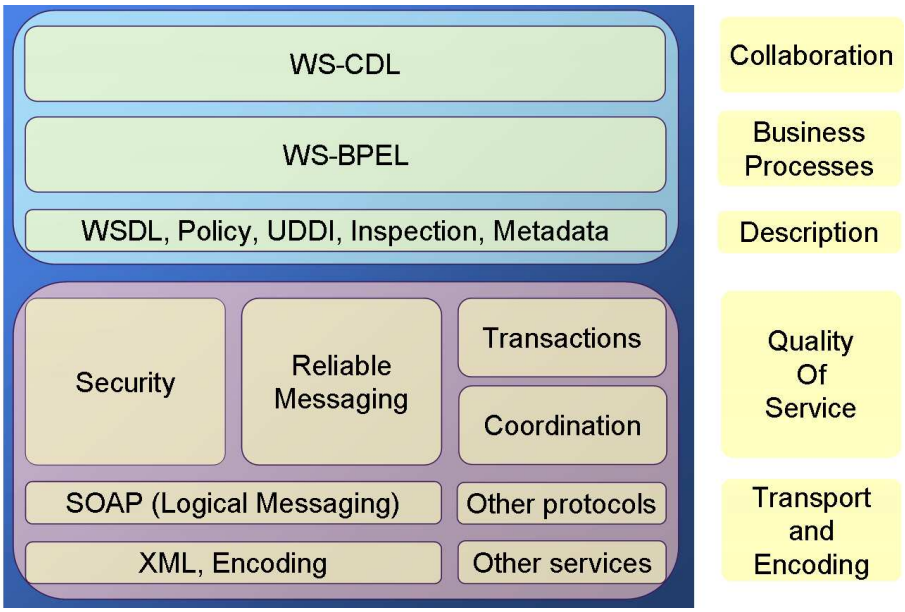


Figure 2.4: Web Service architecture stack.

sicians in an orchestra. Despite these differences, the ideal solution would be fusing both approaches in a single language and environment [37].

Furthermore, 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 [52]. 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.

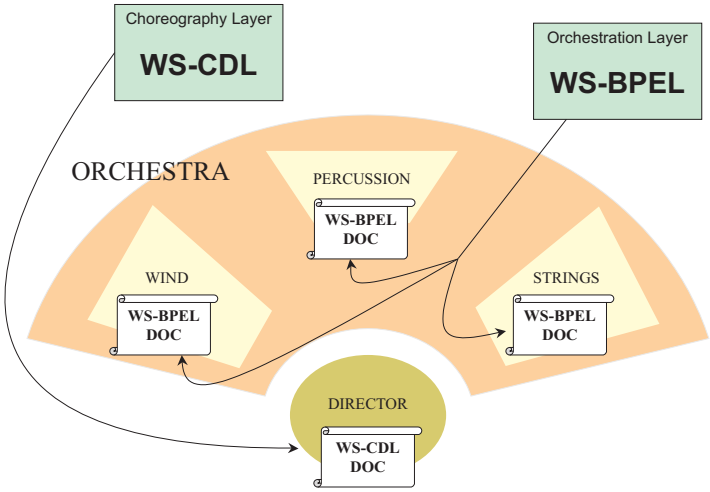


Figure 2.5: Choreography vs. Orchestration

A WS-CDL document defines a hierarchy of choreographies, where there is only one top-level 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. Next, we introduce a language (WS-BPEL), which fits in the orchestration approach, as it is used in the present Thesis.

2.2.1 WS-BPEL

In 2002, researchers and engineers from companies such as IBM, Microsoft, etc. realised that the new and rapidly emerging service-oriented approach (SOC) required the definition of a neat and precise language for describing how a set of interacting web services can be included in a business process. Traditional methods for integration and business process automation typically imply to embed the logic inside of the applications, complicating unnecessarily these applications. Moreover, this makes these applications really difficult to migrate to other platforms. The development, testing, and deployment efforts required to change these applications make integration and process changes both costly

and complex [20]. 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 that they could be more effectively changed, managed, and optimised. The idea and motivation behind almost each new technology for enterprise application development is to provide an environment where better business applications can be developed, requiring less effort. These business applications should closely align to the business processes, which should not be too complex and which should be adaptable to the changing nature of business processes without too much work. 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) [35], 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 inspired by previous languages such as Web Services Flow Language (WSFL), developed by IBM and XLANG specification language developed by Microsoft. WSFL is based on the concept of directed graphs. XLANG is a block-structured language. BPEL combines both approaches and provides a rich vocabulary for the 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. It 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 [35]. Before publishing it, the BPEL4WS specification was submitted to an OASIS technical committee in order to be evaluated so that the specification could evolve 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 [35]. Finally, in January 2008, another OASIS technical committee started to define a WS-BPEL extension to encompass the definition of human interactions ("human tasks") as part of WS-BPEL processes. Figure 2.6 summarises the evolution of WS-BPEL:

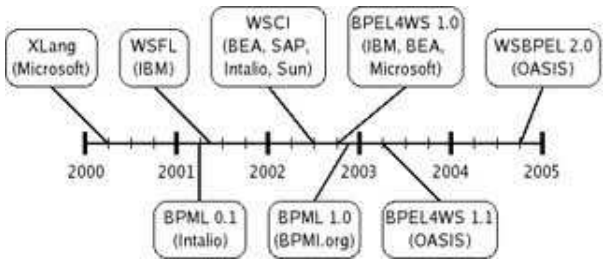


Figure 2.6: WS-BPEL evolution.

Furthermore, ten original design goals were associated with the definition of WS-BPEL [35]:

- Define business processes that interact with external entities through web service operations defined using WSDL, and that manifest themselves as web services 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 external (abstract) and internal (executable) views of a business process. Such a business process defines the behaviour of a single autonomous entity, typically operating in interaction with other similar 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 modelling space.

- Provide data manipulation functions for data process 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, based on mature techniques such as compensation 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 standardised integration interface and language for the composition of different services as well as for the automation of some tasks. Nevertheless, web scenarios are becoming more and more complex since they are highly heterogeneous, that is, a lot of different services from different companies interact jointly to perform a particular task. In particular, it is a folklore that business processes change relatively often due to this heterogeneity. Therefore, designers do not require only a way to compose a set of services, they rather 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 languages, although it is not as powerful as any of the well-known programming languages [20]. However, it is simpler and better suited for business process definition and, therefore, BPEL must be considered as a supplement to modern languages rather than a replacement.

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 [36]. 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 2.7, we can observe an example of the typical business process for a travel agency.

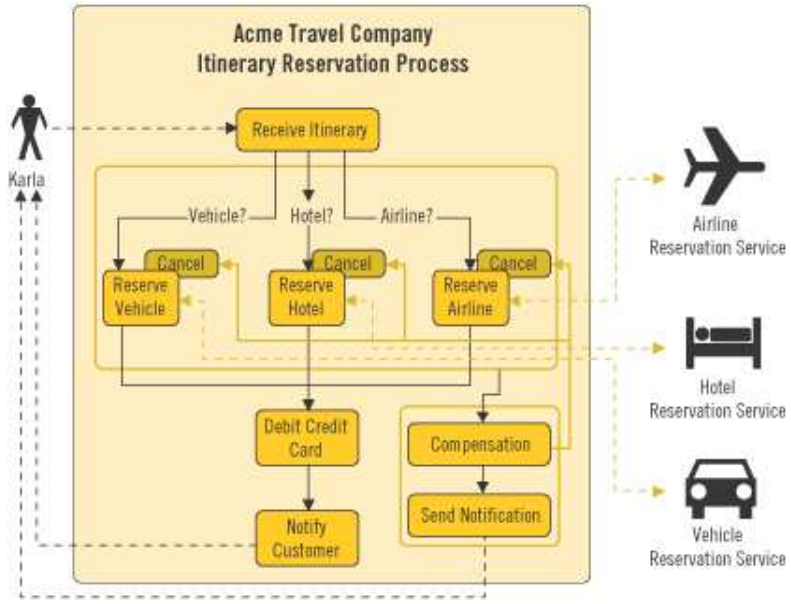


Figure 2.7: Example of a business process workflow.

According to WS-BPEL standard, 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 [35]. Therefore, the main difference between an abstract and a executable processes is that the second one contains the exact details of business processes and, consequently, it is intended to be executed in an orchestration engine, whereas the first one offers a descriptive role, defining the message exchange between the parties. Specifically, an abstract process is usually used to describe the observable behaviour

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 [35]. Moreover, the definition of a 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 hosting environment, unlocking the potential of web services. This feature allows the development of tools and other technologies that greatly increase the level of automation, decreasing the cost in establishing cross enterprise business processes. Other benefit of using abstract processes is that they ensure the level of privacy required by some companies since the service implementation is hidden to the other participants.

Furthermore, WS-BPEL is an XML-based language which supports the web services technology stack, including SOAP, WSDL, and UDDI. It defines a model and a grammar for describing the behaviour 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 those cases where exceptions occur or a partner requests to undo some activities. 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 behaviour across all of them.

In Figure 2.8, 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* activities to declare the process logic. *Basic activities* are those which describe the elemental steps of the process behaviour [35]:

```
<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 2.8: WS-BPEL code.

- The activity *assign* is used to store data into the process variables. 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* 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.

- To invoke a service, WS-BPEL offers the activity *invoke*. Normally, this activity is used to request an operation in a service and it is normally executed by the client in order to invoke an operation of the provider. Operations can be of two types: request-response or one-way. One-way activities 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 used by the server to gather the messages sent by the *invoke* activity. In many cases, this activity is the first part of the process.
- The *reply* activity is used by the server 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.
- 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.
- Finally, it is possible to rethrow a fault using the activity *rethrow* in a fault handler. For instance, this activity is useful when the situation that causes the fault is not solved after the fault handler ends and it is therefore required to rerun 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 has finished.
- The activity *flow* provides concurrency, creating a set of concurrent activities directly nested within the executing process.
- 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, and if it expires the activity ends. This structure has some similarity with the guarded choice operator in a process algebra although 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 is set (to this end, the wait activity can be used).

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

2.3 Heterogeneous Distributed Systems: Grid/Cloud Computing

In 1943, the president of IBM, Thomas J. Watson, predicted:

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

In recent times, this phrase has been widely discussed since some authors consider that it is a clear example of failed prediction. Nevertheless, with the advent of new computational paradigms such as Grid and Cloud Computing, some authors argue that it will become a reality soon. In addition, other authors consider that this phrase is completely true nowadays since five companies are monopolising the world market [7].

Thanks to the fast development of society, daily basic services such as water, electricity, gas and telephone services are commonly supplied to citizens so that everybody can have immediate access to them. Today, these services are known as "utility" services since customers are charged according to the consumption. In 1969, Leonard Kleinrock, one of the leading scientists of the American ARPANET agency, said: "Today, computer networks are in their infancy, but as they grow and become more sophisticated we will see the rise of

the *Utility computing*". It is amazing how in 1969 a scientist could already see the usefulness of computers and the advent of a distributed computing model based on providing services and paying for them. What makes this statement more fascinating is that this year is when the Internet was born. The first version only connected 2 computers worldwide, but this person was already thinking that someday the Internet could connect millions of computers into a single network. This vision of computing (based on a model of on demand service provisioning) anticipated the massive transformation of the computer industry in the XXI century. Thus, major companies such as Google, Amazon or Microsoft are introducing it in their business model.

Unfortunately, Utility Computing is often confused with Cloud and Grid Computing. It is the underlying business model for a Grid or Cloud infrastructure, i.e. it can be seen as a mean of charging customers for computing services so that users pay only for the consumption, whereas the costs associated with the production and distribution of computing services will be undertaken by the provider. As happens with revolutionary software, protocols or any computer-related paradigm, Cloud Computing must undergo a series of steps to check if all the benefits promised by service providers really help companies to save costs and enhance the competitiveness. In this sense, Larry Ellison, founder and CEO of Oracle, believes that Cloud Computing is nothing more than a new way of naming what companies have been doing so far [7]:

> "The interesting thing about Cloud Computing is that we have redefined Cloud Computing to include everything that we already do. . . I do not understand what we would do differently in the light of Cloud Computing other than change the wording of some of our ads."
> *Larry Ellison, quoted in the Wall Street Journal, September 26, 2008.*

Many researchers have tried to define the term "Cloud Computing" without reaching a standard definition. For instance, Buyya et al. [16] define a cloud system as:

> "A cloud is a parallel and distributed system consisting of a collection of virtualised and interconnected computers that have been provisioned dynamically and they are presented as a single computational

resource based on service level agreements (SLAs) established by negotiation between the service provider and the consumer."

In [51] one can find up to 21 different definitions of Cloud computing. For instance, Luis M. Vaquero et al. defines the Cloud as:

"The Cloud is a large and easy to use container of virtualized resources (such as hardware, services, development platforms . . .). These resources can be dynamically reconfigured to fit into a variable load (scale), allowing also the optimal use of these resources. This service is exploited through a pay-per-use model that is guaranteed by agreements."

Finally, the main difference between a Cloud-oriented and a Grid-oriented system relies in the virtualisation of resources. In a Grid infrastructure, users do not share in real-time the resources allocated to them, whereas in a Cloud infrastructure the virtualisation is essential to serve more users, thus getting the savings promised by providers.

Web services vs. Grid/Cloud Computing

In this section, a summary of the main differences and synergies between web services and Grid/Cloud Computing is presented since a formal language to mix both approaches is one of the parts of this Thesis. First, one can consider that web services are themselves software offered as a service (SaaS) and a system is a composition of services coordinated via the Internet cooperating to perform a certain task. Nevertheless, there are still some differences between both approaches such as standardization. Above, we have described WS-CDL and WS-BPEL standards to model web services compositions, but it is impossible to present a standard that describes the main concepts of Cloud Computing and, to some extent, of Grid Computing. One of the reasons is that Cloud and Grid are relatively new and, therefore, there has not been time to agree a standard for them. The other reason is related to commercial policies since many big companies are competing to impose its services.

Another difference is data persistence. Web services are usually "stateless", which means that no state is saved in the system after performing an operation.

The only way to save this state is to store it in a database. The main disadvantage of this approach is again the absence of agreement about a standard to do it and, therefore, this operation is completely platform dependent and it depends on the application scope. In this Thesis, we use a standard called Web Services Resources Framework (WSRF) that it is intended to solve this problem. The main advantage of it is that all the steps are standardised so that the cooperation between such systems is simple. Another advantage is that the user can decide which resources can take part in the interaction. WSRF is described in the next section.

In addition, Cloud/Grid computing could be considered as a layer to be placed on the bottom of the web services, and use them as a mean to access the resources. Thus, new standards must be defined in a similar fashion as in WSRF, but taking into account the particularities of the Cloud infrastructure. Here, we must emphasise that Cloud/Grid Computing is not only the act of offering software as a service since companies can provide infrastructure and platform as a service, which web services cannot cover.

2.4 Web Services Resource Framework

The aim of this section is to introduce the basic concepts for the management and destruction of stateful web services, i.e., web services with a set of resources associated to store the state after an operation. In this sense, we call a *WS-Resource* to the association between a web service and a persistent resource. To manage stateful web services, it is required to define the patterns used to create the relationship between the service and the resource. These patterns will reuse in most of the cases a series of widely studied technologies, e.g. WS-Addressing. Moreover, it is important to define how the properties of these resources can be accessible from outside. This is usually done through an interface.

The architecture provided by web services has been widely accepted as a means of structuring the interactions between services that are part of a distributed system. Currently, developers require a higher degree of standardization to provide additional interoperability between such services, but until mid-2004 no research group or group of experts had seriously considered the idea

of proposing a standard for modelling the communication between stateful services. Thus, in January of 2004, several members of the organization Globus Alliance and the multinational IBM, with the help of experts from companies such as HP, SAP, Akamai, etc., defined the first specification and the basis of an initial architecture of WSRF [3]. In March of 2004, these documents were sent to the OASIS organization. Initially, two committees were formed to study and develop certain parts of the recently created standard. On the one hand, it was created the *WSRF Technical Committee*, which worked on four specifications: *WS-ResourceProperties, WS-ResourceLifetime, WS-Servicegroup*, and *WS-BaseFaults*. Moreover, the *WSN Technical Committee* was responsible for the rest of the specifications: *WS-BaseNotification, WS-Topics*, and *WS-BrokeredNotification*.

WS-Resource Framework is inspired by the work previously done by Global Grid Forum's Open Grid Services Infrastructure (OGSI) Working Group [43]. More specifically, WSRF can be seen as a simple refactoring of concepts and interfaces developed in the specification *OGSI V1.0*, but exploiting recent developments in the area of web services (e.g. WS-Addressing). WSRF is a specification, whose purpose is to define a generic framework for modelling and accessing WS-Resources and the relationships between them in a Grid/Cloud environment. In detail, WSRF defines the representation of the WS-Resource, specifying the messages exchanged and the XML documents required to manage the resource. A WS-Resource is defined as (i) the combination of an XML document with a type defined by one or more *portTypes* (a service may play different roles in the same interaction) and (ii) it must be addressed and accessed according to the implied resource pattern. This pattern is a derivation of the *Endpoint References* included in the standard WS-Addressing. WS-Addressing is used to standardise the endpoint reference of a WS-Resource. This endpoint reference is the address (identifier) of the WS-Resource at a given network and it must be used to identify the resource in any exchange of messages.

Typically, web service interfaces provide users with the ability to access and manipulate its state, e.g. data values that evolve by the interaction among various services. In other words, the message exchanges that are implemented in the behaviour of the services are intended to allow persistent access to these resources. However, this notion is not as evident in the definition of the interface [30]. The messages sent and received by these services involve (or encourage

the programmer to infer) the existence of a resource. Therefore, it is desirable the definition of standards that allow the discovery, creation, manipulation and destruction of these resources. These standards should make this complex environment as interoperable as possible. Furthermore, WSRF offers mechanisms to declare, access, monitor and destroy WS-Resources by using conventional techniques, which makes it easy to run in any platform. Due to this standardization, it is not necessary to take into account the decision logic of the resource owner since WSRF sets it. Furthermore, it also includes mechanisms to describe how to check the status of a resource and how to make it accessible through its interface (described in WSDL). In detail, WSRF includes the mechanisms defining the means by which [3]:

- a WS-Resource can be destroyed, either synchronously attending to a destroy request or a time-based (scheduled) destruction, and the resource properties may be used to inspect and monitor the lifetime of a WS-Resource (WS-ResourceLifetime);
- the state of a WS-Resource can be queried and modified via web services message exchanges (using the specification WS-ResourceProperties);
- an endpoint reference (WS-Addressing) can be renewed in the event the information contained becomes invalid or stale (WS-RenewableReferences);
- a collection of heterogeneous web services can be defined, whether or not the services are WS-Resources (WS-ServiceGroups);
- fault reporting can be made more standardised through the use of a predefined XML template (WS-BaseFaults).

WS-ResourceProperties

As mentioned above, WSRF uses a particular specification language for defining the properties (attributes) of a WS-Resource. It consists of an interface in WSDL and an XML document (Resource Properties Document), which specifies its properties. For example, these properties could be the disk size, processor capacity, etc. and in the Resource Properties Document could be expressed in the following form:

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

Furthermore, some operations are available to manage this document. In WSRF, the operations for managing the properties document are:

GetResourceProperty This operation allows services to request the value of only one property of the document.

For instance, a possible request can be:

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

GetMultipleResourceProperties This method is equivalent to the last one, but it is intended to retrieve more than one property of the document. It can be used to prevent network congestion. The message would be:

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

SetResourceProperties This operation allows us to change some properties in the document. There are three kinds of changes:

- Insert: It allows us to add some new properties to the document.
- Update: It is used to update the value of a property.
- Delete: To delete a property from the document.

A possible request can have the following form:

```
...
<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>
...
```

Notice that we can introduce several operations in the same request as the previous example illustrates. After processing this request, we get the following document:

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

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

</GenericDiskDriveProperties>
...
```

QueryResourceProperties This method is used for querying resource properties. For example, to know if the number of blocks is greater than 20 and the block size is 1024, we use the following query:

```
...
<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>
...
```

The response must look like this:

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

WS-Base Faults

Normally, designers use interfaces defined by others, and, therefore, a method to standardise the format of error messages would facilitate the work of developers. This is the goal of WS-BaseFaults, where an error message has the following format:

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

where:

- Timestamp: It is the exact instant where the error happened.
- OriginatorReference: This is the endpoint reference of the service that originated the error.
- ErrorCode: Error code (e.g. POSIX errno) to be used by error handling systems .
- Description: Explanation of the cause (in natural language).
- FaultCause: Technical cause of the error.

Finally, note that it is possible to report an error without using this format.

WS-ServiceGroup

This specification allows users to create groups of services that share a number of properties in common, i.e., it is useful to group different web services with similar behaviours. This part of WSRF is not taken into account in BPELRF.

WS-ResourceLifetime

The lifetime of a WS-Resource is defined as the period between its instantiation and its destruction. The goal of this specification is to standardise the process of resource destruction and define mechanisms to monitor its lifecycle. Surprisingly, the process to create the WS-Resource is not specified. The reason is that WSRF is intended to be used in the interaction and, therefore, the internal details of each participant are hidden. Thus, WSRF meets the requirements of SOC architecture presented previously and the transition from service-oriented architecture to resource-oriented architecture is short. For technical reasons, we have included in our language BPELRF a primitive to create the resource.

Generally, in distributed systems, clients just want to use a resource for a given time interval. For instance, in subscription systems, users decide normally the duration of the subscription. Nevertheless, in some scenarios is most appropriate to provide a manner to immediately destroy the resource. Following the last example, it could happen that the client wants to interrupt its subscription and hence the immediate destruction must be provided. As discussed above, WSRF gives two ways to destroy a WS-Resource: immediate or scheduled.

Immediate destruction To activate this kind of destruction, it is only required to add the attribute $< wsrl : Destroy/ >$ inside the field $< Body >$ of the SOAP message that will be sent to the service to confirm the destruction, the receiver must send the same message including the attribute $<wsrl : DestroyResponse/>$ in the field $<Body>$ of the response SOAP message.

Scheduled destruction In this case, the WS-Resource has an associated deadline after which it is expected the resource has been destroyed. Moreover, it is reasonably expected that before this deadline the resource is available. An example of how to determine the completion time of a resource is:

```
...
  <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>
...
```

As we can see, the destruction requester may indicate the exact destruction time as well as the local time (to avoid mismatches in how to represent the time zone). Once the *TerminationTime* is reached, the resource is destroyed without any further intervention and the requester is reported that the resource is unavailable. WSRF has another message to inform the sender that the resource owner has received the destruction request. This option is not considered in our language BPELRF.

On the contrary, there may be a situation where more than one service is using the resource and, therefore, the resource owner can decide or not (this is not mandatory in WSRF) to implement a notification policy to inform other services that the resource is unavailable. The notification message must include the following fields:

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

where the attribute *TerminationTime* specifies the exact time of destruction and in the *TerminationReason* attribute it can be included the destruction reason.

The notification-based interaction pattern is a commonly used pattern for inter object communications. For example, the well-known publish/subscribe architecture uses this approach. In addition, it is increasingly being used in a web services context [3].

In conjunction with WSRF, Web Services Notification (WSN) specifications [2] are focused on the description of mechanisms to implement this notification-based pattern. As WSRF is based on web services, WSRF creators opted for the use of WS-Notification standard since the interoperability of both approaches is supposedly higher (they are based on web services).

WS-Notification is a family of specifications that uses a topic-based publish/subscribe pattern. It includes: standard message exchanges to be implemented by service providers that wish to participate in Notifications, standard message exchanges for a notification broker (allowing publication of messages from entities that are not themselves service providers), operational requirements expected of service providers and requesters that participate in notifications, and an XML model that describes the topics susceptible to generate notifications. The WS-Notification family includes three normative specifications: WS-BaseNotification, WS-BrokeredNotification, and WS-Topics.

In the notification process, there are three different steps [2]:

1. First, the observation of the situation and its characteristics. This situation represents an event of interest for some services.

2. Second, the creation of notification messages that capture the characteristics of the situation; and

3. finally, the distribution of these messages to zero or more interested parties (notification consumers).

In WS-Notification, steps 1 and 2 are not taken into account since WSRF designers did not want to restrict the means by which these stages must occur. From now on, the entity in charge of performing the stages 1 and 2 is called Publisher. Other issue is how the publisher can disseminate the notification messages. In this case, two patterns can be followed: direct or brokered.

In the direct case, the publisher implements message exchanges associated with the notification producer interface (the details of this interface are out of the scope of this Thesis) and it is responsible for accepting subscription messages and sending notification messages to interested parties. Moreover, it can choose to include in its behaviour the required logic or to delegate this task to special-

ized implementations. This last case is addressed by the WS-BaseNotification specification [2].

An example of notification message (can include one or more notification messages) is:

```
...
<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>
...
```

In the brokered case, an intermediary (broker) is responsible for disseminating messages produced by one or more publishers to zero or more notification consumers. There exists three types of relationships between the publisher and the broker: simple publishing, composable publishing and demand-based publishing.

In the simple publishing scenario, the publisher entity is responsible only for the core publisher functions - observing the situation and formatting the notification message artifact that describes the situation. The dissemination step occurs when the publisher sends the notification message to the broker. Finally, demand-based publication is intended for use in cases where observing the situation or formatting the messages is expensive, and therefore the notification should be avoided. To this end, the publisher will only send notifications to the broker if it is registered as a service interested in receiving notifications about a particular situation. Obviously, this will reduce the overload of the network [2].

In Chapter 4, we will see that the language BPELRF avoids to include the broker role, and it is indeed the owner of the resource who sends the notifications. Moreover, the subscribers must show interest by sending a subscription message directly to the resource owner within the corresponding condition, thus reducing the overload of the net. This is due to the amount of notifications in the network is reduced. More technical details will be provided in that chapter.

2.5 Workflow management

In parallel with the trend "from programming to assembling", another trend changed the way information systems were developed. This trend is the shift "from data orientation to process orientation" [22]. In the 1970s and 1980s data-driven approaches were dominating the applications market and, as a consequence, the way in which data is managed (stored, retrieved and presented) was the most important part in the development process. Thus, data modelling was the starting point for building every information system. One advantage was that robust technologies for developing data-centric information systems were developed during these years, although business processes modelling was often neglected. As a result, the logic of business processes was spread across multiple software applications and manual procedures, thereby hindering their optimization and their adaptation to changes. In addition, processes were sometimes structured to fit the constraints of the underlying information system, thus introducing inefficiencies. Nevertheless, in the last 15 years we have witnessed a shift from "data-aware" information systems to "process-aware" information systems [22]. During these years, a lot of vendors have migrated to new technologies in order to offer customers a set of applications for workflow management. Initially, these applications were called "WorkFlow Management (WFM) systems", but, nowadays, they are known as "Business Process Management (BPM) systems". Both WFM and BPM systems aim at supporting operational processes known as "workflows".

According to the organization *WorkFlow Management Coalition* (WFMC), a workflow is concerned with *"the automation of procedures where documents, information or tasks are passed between participants according to a defined set of rules to achieve, or contribute to, an overall business goal. Whilst workflow may be manually organised, in practice most workflows are normally organised within the context of an IT system to provide computerised support for the procedural automation"* [29]. In detail, a *workflow* is usually considered as "the computerized facilitation or automation of a business process, in whole or in part" [24], and it consists of a coordinated set of activities that are executed to achieve a predefined goal. Recalling the main idea for service-oriented computing, it is easy to see the relation between both definitions since both are based on a set of entities,

which can be called “services”, collaborating to achieve a common goal. Furthermore, a workflow is often defined as the assessment, analysis, modelling, definition and subsequent operational implementation of the core business processes activities of an organisation (or other business entity). Workflow technology is often an appropriate solution as it provides separation of the business procedure logic and its IT operational support, enabling subsequent changes to be incorporated into the procedural rules defining the business process [22]. This adaptability fits again in the service-oriented philosophy.

To provide users with the appropriate tools for workflow management, it was defined a reference model (see [28]) for the development of workflow (business process) management systems. These systems shall completely define, manage and execute “workflows” through the execution of software whose order of execution is driven by a computer representation of the workflow, that is, they aim at supporting the routing of activities (i.e., the flow of work) in an organization such that the work is efficiently done at the right time by the right person with the right software tool. It focuses on the structure of work processes, not on the content of individual tasks. Individual tasks are supported by specific programs. Workflow management links persons (end users, workflow participants, workflow agents) to these applications in order to accomplish the required tasks. The relation of these systems with the business process definition language presented previously is that they provide procedural automation of a business process (e.g. described in WS-BPEL) by managing the sequence of activities and the invocation of appropriate human and/or IT resources associated with the various activity steps [28].

In [28], the fundamental functional areas of a workflow management system were characterised. Thus, a workflow management system has to provide:

- The functions concerned with the definition, and possibly the modelling, of the workflow process and its constituent activities.
- The control functions concerned with managing the workflow processes in an operational environment and sequencing the various activities to be handled as part of each process.
- The means by which the participants (human users and/or IT application tools) should interact.

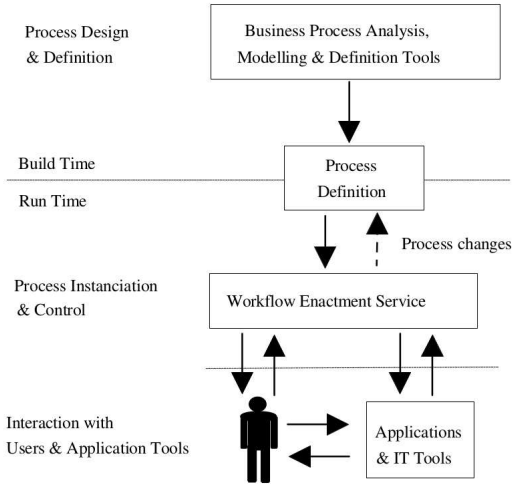


Figure 2.9: Workflow System Characteristics.

In Figure 2.9, we can see these three characteristics and their relationship. Here, it can be observed two well defined parts: *build time* and *run time*. As commented previously, formal methods have a great impact when they are applied in the early stages of the development process. Thus, in this Thesis we propose an extension of a well-known formalism (Workflow nets) that helps designers in this "design time" phase. In particular, we cover the three fundamental areas encouraged by the WorkFlow Management Coalition by providing a formalism to model workflows, some correctness properties (soundness and strong soundness) and a tool to check these properties, as well as the model evolution. Notice that the "run time part" is out of the scope of the present Thesis and, consequently, its technical details are not shown here.

In 1997, Workflow nets [47, 48] were introduced by the Dutch computer scientist Wil van der Aalst as a formalism for modelling, analysis and verification of business workflow processes, that is, as a mean to support the *build time part* of a workflow management system. As systems are moving from data-aware to process-aware, workflow nets abstract away most of the data presented in the process while focusing only on its possible flow. The aim of Van der Aalst was to provide practitioners with a formal framework that is capable of representing both the model and the possible properties. With the model, it is easy to check how the system evolves, whereas, with the properties, one can study aspects of great interest such as the presence of design errors. Among these errors, one

can check the presence of deadlocks, livelocks and other anomalies. To this end, a correctness criterion is described via the notion of *soundness* (see [50] for a summary of different soundness definitions) that requires the option to complete the workflow, guarantees proper termination and optionally also the absence of redundant tasks. In Chapter 5, we will study in depth the soundness notion and our timed extension of it.

After this 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 (see [50] for a recent overview). Thus, researchers must choose between adding expressiveness to the model, which in many cases leads to undecidability issues, or keeping the model as simple as possible in order to preserve the decidability of soundness checking algorithms. In Chapter 4, we will summarise the main extensions one can find in the literature, focusing on time extensions as they are the aim of our work.

Finally, note that workflow nets are based on Petri nets since they are an established tool for modelling and analysing processes [47]. Furthermore, the author presented in [47] the most important factors that influenced him in his decision of using Petri nets. These factors are the following:

- **Formal semantics.** A workflow process specified in terms of a Petri net has a clear and precise definition, because the semantics of the classical Petri net and several enhancements (colour, time, hierarchy) have been defined formally.

- **Graphical nature.** Petri nets are a graphical language. As a result, Petri nets are intuitive and easy to learn. The graphical nature also supports the communication with end-users.

- **Expressiveness.** Petri nets support all the primitives needed to model a workflow process. All the routing constructs present in todays workflow management systems can be modelled. Moreover, the fact that states are represented explicitly, allows for the modelling of milestones and implicit choices.

- **Properties.** In the last three decades many people have investigated the basic properties of Petri nets. The firm mathematical foundation allows for the reasoning about these properties. As a result, there is a lot of common knowledge, in the form of books and articles, about this modelling technique.

- **Analysis.** Petri nets are marked by the availability of many analysis techniques. Clearly, this is a great asset in favour of the use of Petri nets for workflow modelling. These techniques can be used to prove properties (safety properties, liveness properties, deadlock, etc.) and to calculate performance measures (response times, waiting times, occupation rates, etc.). In this way it is possible to evaluate alternative workflows using standard Petri-net-based analysis tools.

- **Vendor independent.** Petri nets provide a tool-independent framework for modelling and analysing processes. Petri nets are not based on a software package of a specific vendor and do not cease to exist if a new version is released or when one vendor takes over another vendor.

Notice that most of these arguments have been commented throughout this Thesis, reaffirming that Petri nets and their different variants are a mature and suitable formalism to model any kind of system.

2.6 Formal models of concurrency

In this section we present the formalism on which we will base throughout this Thesis to develop our specification languages. We start by presenting some notions about process algebras and some examples. Next, we introduce the basic definition of Petri nets, as well as important definitions that will help the reader to understand intuitively this work. In the next chapter, we will introduce time extensions of Petri nets as well other formal models to represent system behaviour such as labelled transition systems or timed transition systems. All these formalisms share the same characteristic, they serve as specification languages, presenting all the advantages and disadvantages presented above. The use of these specification languages allows us to perform system analysis before implementing it. Indeed, such analysis could be independent of the practical

realization of the corresponding system. Moreover, they also allow to perform the analysis of a system based on the comparison between the behaviour of the final system and the behaviour provided by the semantics of the specification language. This is known as *conformance checking*. This conformance checking is out of the scope of this Thesis, but it could be considered as future work.

The application of specification languages for the study of systems can be divided into two steps. The first one is the *representation* of the relevant system features. This representation is done using the syntax of the specification language. Notice that specification languages are usually of higher level in comparison with the languages used to develop the system. Thus, some implementation aspects are ignored. This is known as *abstraction*. Such abstraction is one of the strengths that provide these languages. Thus, abstracting away irrelevant aspects, the automatic or systematic analysis of relevant system properties can be done. In contrast, this is impracticable in we consider all the details modelled in the implementation or in the informal specification. The second step in the application of specification languages involves the manipulation of the formal specification, obtained in the previous step, to extract relevant system properties. Such manipulation is generally supported by the wide knowledge about the system provided by the semantics. This allows us to study in advance properties such as the future system evolution, the compliance with certain invariants, or the appearance of certain undesirable properties. Again, this study can consider only the properties of the obtained formal model or the comparison between specification and implementation properties.

It is worthwhile to mention that neither of the two previous steps would be, in general, fully automated. Obviously, this shall depend on the relevant features considered in the first step or in the properties to analyse in the second. However, even in case that the full automation is not possible, the power of these languages makes them an indispensable tool for the formal study of any kind of computer system. As commented previously, their power lies in the features (properties) we want to study, and, therefore, it is really important to fix first these features. For instance, in our language, we will study the communication features of the language WS-BPEL and how resource management can be conducted by using WS-BPEL and WSRF. In addition, we will study the presence of

errors such as deadlocks as well as the evolution of the system in the case of error.

In web services, one of the most important feature is the communication between services. In concurrent systems, it is modelled as the communication between processes and it is indispensable for any concurrent system. Consequently , specification languages shall pay attention to the detailed description of the communication between processes in the system. When modelling the communication, some kind of abstraction is required, implying that the internal behaviour of each process is hidden, i.e., the set of actions executed by the process is unknown. This perfectly fits again in the service-oriented philosophy commented above. In BPELRF, we will pay attention to the communication between WS-BPEL processes, implementing a client-server model by using the activities receive, reply, invoke and a barred version of the reply activity created for the language. Moreover, as we are modelling an orchestration language, each participant hides its implementation to the other participants.

However, the abstraction of the internal details of each participant will affect the communication between the processes. This is due to the actions internally performed by these processes will determine when the interaction occurs. In this way, the abstraction of not interesting details leads inevitably to the loss of some information that could be relevant for the interesting aspects we want to capture. Thus, it can be observed that in every specification language that includes special interest in modelling the communications between concurrent processes must deal with uncertainty. Specifically , communication choices occurring internally in the process result in the appearance of indeterminacy. Normally, most of the process algebras provide a special operator to deal with these choices.

As in Chapter 4 we define a specification language for web service composition, we introduce next the most relevant *ingredients* that these language must include. Despite the differences between them, the fundamental concepts are very similar, and, therefore, the basic ingredients in all of them are more or less the same. This allows us to provide a more general description in this section, although sometimes we will pay more attention to some relevant concepts. In general, every language has, at least, its syntax and its operational semantics. The first one describes the set of expressions that are permitted by the language

and, as a consequence, they are susceptible to have a specific meaning. On the other hand, the operational semantics gives us the set of rules that determine how these expressions, defined according to the syntax, evolve to other expressions. In the case of specification languages for concurrent systems, this evolution must be interpreted as a change of state due to the execution of the system, that is, the application of a operational semantics rule represents the evolution of the system over the time. Thus, system behaviour is represented by the state evolutions that may occur in it, where these evolutions are the result of the application of the rules given by the operational semantics.

The key feature of this kind of languages is that they provide a neat way to model complex global behaviours as the composition of simple behaviours of each party. This feature is fairly related with the definition of choreography and orchestration, making them a suitable artifact to model these systems. In addition, it seems reasonable that the definition of the operational semantics for such languages is therefore defined in different levels. Hence, the operational semantics should be able to describe individually the behaviour of each participant in the system and, from these individual behaviours, build the whole system. To make possible this hierarchical description of the operational semantics, the behaviour of each process has to be defined without referencing the global behaviour of the process. Thus, the behaviour of each hierarchical level can be defined from the behaviour of the lower levels. When following this approach, we say that the operational semantics is compositional. In our language BPELRF, we have defined three levels, two for describing the particular behaviour of each participant and the other one for defining the composition of these participants to conform the whole system.

In the case of process algebras, an operational semantics is usually defined as a set of rules that governs the evolution of the system. In this Thesis, we will follow the approach presented by G. Plotkin in [39]. In that work, Plotkin introduces the *structural operational semantics*. Structural Operational Semantics(SOS) provides a framework to give an operational semantics to programming and specification languages, which, because of its intuitive appeal and flexibility, has found considerable application in the theory of concurrent processes. Even though SOS is widely used in programming language semantics at large, some of its most interesting theoretical developments have taken place within concur-

rency theory. In particular, SOS has been successfully applied as a formal tool to establish result that hold for whole classes of process description languages. The concept of rule format has played a major role in the development of this general theory of process description languages, and several such formats have been proposed in the research literature [6]. As a proof of maturity, let us comment that the original paper, where Plotkin introduced structural operational semantics, has more than 3600 citations according to Google scholar or more than 1250 according to Citeseer. The rules in Plotkin-style operational semantics describe the single-step capabilities of systems and each rule has the form H/α, where H is a set of premises and α is a set of conclusions. Each rule can be interpreted as follows: " When the participants hold the premises, the global evolution, defined by the conclusion, can be done".

The basic behaviour of each participant that can be expressed in an operational semantics is known as *actions*, and, then, we will call *action* to the most basic execution in the system. With the aim of maintaining a set manageable basic actions, sometimes several communication actions are grouped in a single action. This action can be labelled with one or more parameters to identify each specific communication. Process algebras are normally enriched with a kind of special actions called "internal actions". These internal actions abstract normally an internal decision of the process that do not want to be represented explicitly in the model. Usually, a single symbol is used to represent all internal actions since it is irrelevant to distinguish between internal actions of various types. In process algebras, such internal actions are usually represented by τ.

As commented previously, the abstraction of some parts of the process introduces nondeterminism in the system. This is due to all the unpredictable factors have a direct repercussion on the system. For instance, this nondeterminism can be used to represent the freedom of concurrent processes to run asynchronously. In web service composition, a model could represent the fact that two services ready to send to send the messages a and b, respectively, could evolve as a whole sending first the message a and, then, the message b , or, on the contrary, they can send first the message b and, after that, the message a. This will depend on the freedom of such processes in that particular moment. Nevertheless, if we want the message a to be sent before the message b, then the first process shall synchronise with the sending of the message b by

the second service, and, then, both actions would occur necessarily at the same time, disappearing the freedom commented above. Nondeterminism is usually provided in process algebras by means of one (or several) specific syntactic operators, generally called parallel operators. In this case, the same operator governs both nondeterminism (due to the asynchronous evolution of the processes) and the synchronous evolution of processes (usually due to the interactions between them). In the case of finite state machines or labelled transition systems, this nondeterminism can be provided by using specific syntactic operators or by using composition rules that allow to represent the machine as a whole. This whole system is the composition of the individual machine of each participant as well as the interactions between them.

In addition to the operations introduced above, some process algebras define another operators to increase the expressive power they provide. Thus, complex scenarios can be modelled with these extension operators. For instance, most of the process algebras include a recursion operator to capture infinite behaviour. In the case of finite state machines and labelled transition system, such behaviour patterns can be partially achieved through the introduction of cycles.

Preliminaries

In this section, we will define the preliminary concepts used in this Thesis. The aim of this section is to provide the reader with a review of the elemental notions used in future sections as well as to fix the notations used throughout the Thesis. Thus, we will start presenting basic concepts such as the standard definition of Petri nets and we will continue with more technical details such as the addition of time features to this formal model.

Notation

The notation used here is the following:

1. **Numbers**

   We will denote by $\mathbb{N}_0 = \mathbb{N} \cup \{0\}$ the set of nonnegative integers including 0, and by $\mathbb{R}^{\geq 0}$ the nonnegative real numbers including 0. Obviously, $\mathbb{N}$ and $\mathbb{R}$

mean that zero is excluded from the set. Moreover, $\mathbb{N}_0^\infty = \mathbb{N}_0 \cup \{\infty\}$ is the set of natural numbers including ∞.

2. **Sets and Multisets**

   We will use the standard delimiters for sets ($\{\}$) and multisets($\{\!\{\}\!\}$). As usual, let A be a (multi)set and $R : A \longrightarrow \mathbb{N}_0$, we say that $x \in A$ iff $R(x) > 0$. Note that we abuse the notation using $x \in A$ to represent that x is an element of the multiset or the set A, and using indistinctly the general set operators (union, inclusion, etc.) for sets and multisets. The cardinality of a set (multiset) A is denoted by $|A|$. Given a set A, $\mathcal{B}(A)$ is the set of all finite multisets over A.

   For any $C_1, C_2 \in \mathcal{B}(A)$, we define:

   - $C_1 \uplus C_2 \in \mathcal{B}(A)$, where $\forall x \in A : (C_1 \uplus C_2)(x) = C_1(x) + C_2(x)$.
   - $C_1 \subseteq C_2$ if and only if $\forall x \in A : C_1(x) \leq C_2(x)$.
   - If $C_2 \subseteq C_1$ we can define the subtraction $C_1 \setminus C_2 \in \mathcal{B}(A)$, where $\forall x \in A : (C_1 \setminus C_2)(x) = C_1(x) - C_2(x)$.
   - For any $C \in \mathcal{B}(A)$, we define the first projection $\Pi_1(C) \in \mathcal{B}(\mathbb{N}_0)$, as follows: $\forall n \in \mathbb{N}_0$, $\Pi_1(C)(n) = \sum_{m \in \mathbb{N}_0} C(n, m)$.
   - For any $C \in \mathcal{B}(A)$ and $n \in \mathbb{N}_0$ we define the second projection $\Pi_2(C, n)$ as the ordered list that consists of the elements $(m_1, m_2, \ldots, m_{\Pi_1(C)(n)})$, such that $(n, m_i) \in C$, $\forall i = 1, \ldots, \Pi_1(C)(n)$ and $m_i \leq m_{i+1}$, $\forall i = 1, \ldots, \Pi_1(C)(n) - 1$.
   - For any $C_1, C_2 \in \mathcal{B}(A)$, we say that $C_1 \preceq C_2$ if and only if the following conditions hold:
     - $\Pi_1(C_1) \subseteq \Pi_1(C_2)$.
     - $\forall n \in \mathbb{N}_0$, taking $\Pi_2(C_1, n) = (m_1^1, \ldots, m_{\Pi_1(C_1)(n)}^1)$ and $\Pi_2(C_2, n) = (m_1^2, \ldots, m_{\Pi_1(C_2)(n)}^2)$, we must have $m_i^1 \geq m_i^2$, $\forall i = 1, \ldots, \Pi_1(C_1)(n)$.

     To sum up, these conditions state that for every n the total number of elements (n, m) (moving m) must be lesser in C_1 than in C_2, and for every element (n, m) in C_1 there must be a corresponding (distinct element) (n, m') in C_2, with $m \geq m'$.
   - For any $C_1, C_2 \in \mathcal{B}(A)$, with $C_1 \preceq C_2$, we define $C_2 \ominus C_1$ in the following (recursive) way:

- For $C_1 = \emptyset$ we take $C_2 \ominus C_1 = C_2$.
- For $C_1 \neq \emptyset$, let us consider that
  $C_2 = \{r_1^1.(n_1, m_1^1), \ldots, r_{i_{n_1}}^1.(n_1, m_{i_{n_1}}^1), \ldots, r_1^k.(n_k, m_1^k), \ldots, r_{i_{n_k}}^k.(n_k, m_{i_{n_k}}^k)\}$, where $n_l \neq n_j$, $\forall l \neq j$, and $m_j^l < m_{j+1}^l$, $\forall l = 1, \ldots, k$ and $\forall j = 1, \ldots, i_{n_l}$. Since $C_1 \preceq C_2$, we can take one element $(n_l, m) \in C_1$, for some $l \in \{1, \ldots, k\}$, as well as the largest index j for which $m_j^l \leq m$. We then define recursively:
  $C_2 \ominus C_1 = (\{r_1^1.(n_1, m_1^1), \ldots, r_{i_{n_1}}^1.(n_1, m_{i_{n_1}}^1), \ldots, r_1^l.(n_l, m_1^l), \ldots, (r_j^l - 1).(n_l, m_j^l),$
  $\ldots, r_{i_{n_l}}^l.(n_l, m_{i_{n_l}}^l), \ldots, r_1^k.(n_k, m_1^k), \ldots, r_{i_{n_k}}^k.(n_k, m_{i_{n_k}}^k)\}) \ominus (C_1 - \{1.(n_l, m)\})$.
  Thus, $C_2 \ominus C_1$ is obtained by removing from C_2 elements (n, m) that correspond to elements (n, m') of C_1, such that m is the largest value with $m \leq m'$.

  For instance, taking $C_1 = \{1.(2,3), 1.(2,5), 1.(1,4), 1.(7,6)\}$, and $C_2 = \{1.(2,0), 1.(2,1), 1.(2,2), 1.(1,3), 2.(7,6), 3.(3,3)\}$ it follows that $C_1 \preceq C_2$. Then, $C_2 \ominus C_1 = \{1.(2,0), 1.(7,6), 3.(3,3)\}$.

The last multiset operations are related with the definition of binding and firing for coloured Petri nets.

3. **Relations**

Let X be a set, a relation over X is a set $R \subseteq X \times X$. The domain (or the set of departure) of R, denoted by $dom(R)$, is:

$$dom(R) = \{x \in X \mid \exists y \in X \, : \, (x, y) \in R\}$$

and the codomain (or the set of destination) of R, denoted by $cod(R)$, is:

$$cod(R) = \{x \in X \mid \exists \, y \in X \, : \, (y, x) \in R\}$$

Given a relation R, the *reflexive and transitive closure* of R, R^*, is defined as follows:

$$R^* = \{(x, y) \mid x = y \vee \exists \, x_1, \ldots, x_n \text{ s.t. } (x, x_1) \in R, \ldots, (x_n, y) \in R\}$$

Moreover, the *transitive closure* of R, R^+, is given by:

$$R^+ = \{(x, y) \mid \exists \, x_1, \ldots, x_n \text{ s.t. } (x, x_1) \in R, \ldots, (x_n, y) \in R\}$$

Petri nets

Definition 1 (Basic Petri nets)
A *basic Petri net* (PN) is a triple $N = (P, T, F)$, where P and T are sets and F is a relation defined over $P \cup T$. Moreover, it has to satisfy the following constraints:

1. $P \cap T = \emptyset$ (P and T are disjoint)
2. $F \subseteq (P \times T) \cup (T \times P)$ (arcs from places to transitions and vice versa)
3. $dom(F) \cup cod(F) = P \cup T$ (no isolated places or transitions)

In a Petri net, P is known as the set of *places* of N, T is the set of *transitions* and F is a flow relation between the places in P and the transitions in T. This relation is graphically represented by arcs. In this Thesis, we suppose that P and T are finite. Petri nets can be graphically represented by means of bipartite graphs (or bigraphs), which are graphs whose vertices can be divided into two disjoint sets (P and T in this case) such that every edge connects an element from P to T, and vice versa. In the graphical representation, places are drawn as circles and transitions as rectangles or boxes. The places from which an arc runs to a transition are called the *input places* of the transition, whereas the places from which an arc runs from the transition are called the *output places*.

Let $X = P \cup T$ be a set and $x \in X$ an element of this set. The preset of x is ${}^\bullet x = \{y \in X \mid (y, x) \in F\}$, whereas the postset of x is defined as $x^\bullet = \{y \in X \mid (x, y) \in F\}$.

A net N is T-restricted iff ${}^\bullet t = t^\bullet = \emptyset$ for all $t \in T$. □

Example 2.6.1
Let $N = (P, T, F)$ be a Petri net such that:

$$P = \{p_1, p_2, p_3\}$$
$$T = \{t_1, t_2\}$$
$$F = \{(p_1, t_1), (p_2, t_1), (t_1, p_3), (p_3, t_2)\}$$

This net is depicted in Figure 2.10.

Graphically, places in a Petri net may contain a discrete number of marks called *tokens*.

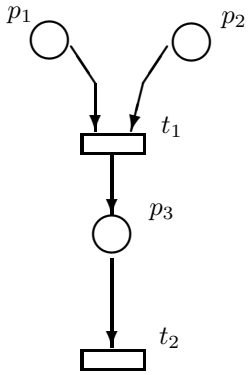


Figure 2.10: Example of a basic Petri net.

Definition 2 (Marking on basic Petri nets)
Let $N = (P, T, F)$ be a basic Petri net. The function $M : P \longrightarrow \mathbb{N}_0$ is called *the marking of* N. Then, (P, T, F, M) is called a *marked Petri net*.

Any distribution of tokens over the places will represent a configuration of the net called *marking*. The marking of a Petri net is graphically represented by drawing in each place as many dots as tokens correspond, or putting into each place the number of tokens associated with it.

Example 2.6.2
In the net of Figure 2.10, we can consider the following marking:

$$M(p_1) = 1, \;\; M(p_2) = 1, \;\; M(p_3) = 0$$

The graphical representation of this marking is shown in Figure 2.11.

The semantics of a Petri net is defined by the following *firing rule*, which represents the marking reached after firing a transition.

Definition 3 (Enabling rule)
Let $N = (P, T, F, M)$ be a marked Petri net. A transition $t \in T$ is *enabled* by the marking M, denoted by $M[t\rangle$, if for all place $p \in P$ such that $(p, t) \in F$, $M(p) > 0$.

Definition 4 (Firing rule)
The *firing* of a transition t enabled by the marking M produces a new marking on the net, M', defined as:

$$M'(p) = M(p) - W_f(p, t) + W_f(t, p) \quad \forall p \in P$$

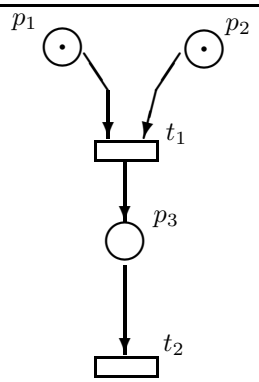


Figure 2.11: Example of a marked Petri net.

where for all $x \in (T \times P) \cup (P \times T)$, $W_f(x) = 1$ if $x \in F$ and $W_f(x) = 0$, if $x \notin F$. This is denoted by $M[t\rangle M'$.

Example 2.6.3

In Figure 2.11, the firing of the transition t_1 creates the marking M':

$$M'(p_1) = 0, \;\; M'(p_2) = 0, \;\; M'(p_3) = 1$$

Definition 5 (Concurrent enabling of transitions)

Let $N = (P, T, F, M)$ be a marked Petri net and $R \subseteq T$ a subset of transitions of N. The set of transitions R is *concurrently enabled*, denoted by $M[R\rangle$ iff $M(p) \geq \sum_{t \in R} W_f(p,t), \;\; \forall p \in P$, where $W_f(p,t)$ is defined as in the last definition.

We can also extend this definition to multisets, thus allowing multiple instances of the same transition to be fired in just one step. In this way, we say that the multiset of transitions R is enabled in M iff $M(p) \geq \sum_{t \in T} W_f(p,t) \cdot R(t)$, $\forall p \in P$.

The firing of the multiset of transitions R in M produces the new marking M' of N:

$$M'(p) = M(p) - \sum_{t \in T} (W_f(p,t) - W_f(t,p)) \cdot R(t)$$

This net evolution in just one step is denoted by $M[R\rangle M'$.

2.7 Summary

To be added.

Chapter 3

Extended Petri nets

After introducing web services (and their composition) and the basic formalisms that can be used to model and analyse them, we will focus on this chapter in defining the specific models used in this Thesis. Thus, we will present some extensions of the basic model of Petri nets and some properties that can be analysed. We will recall some notions (marking, firing, enabledness and so on) defined in the preceding chapter and we will adapt them to a particular case. This chapter is mainly divided in two parts. On the one hand, we will focus first on the definition of Coloured Petri nets since they are used in the definition of the language BPELRF, and, then, we will present timed-arc Petri nets, in its two variants (discrete and continuous), as they are the basis of the workflow model presented in the second part of the present Thesis.

Definition 6 (General Petri nets)
A general Petri net is a 5-tuple $N = (P, T, F, K, W)$, where:

1. (P, T, F) is a basic Petri net.
2. $K : P \longrightarrow \mathbb{N}_0 \cup \{\infty\}$ is a function that indicates the maximum number of tokens in each place (capacity function).
3. $W : F \longrightarrow \mathbb{N}_0$ is a function that indicates the multiplicity of the arcs (*weight of the arcs*).

When the context is clear, we will call them Petri nets. The function K can be omitted if it is infinite for all the places in the net.

Definition 7 (Firing rule for general Petri nets)
Let $N = (P, T, F, K, W)$ be a general Petri net.

1. A function $M : P \longrightarrow \mathbb{N}_0$ is a marking N iff $M(p) \leq K(p)$, for all $p \in P$.

2. A transition $t \in T$ is enabled in M, denoted by $M[t\rangle$, iff $W(p,t) \leq M(p)$ and $K(p) \leq M(p) - W(p,t) + W(t,p)$, for all $p \in P$. The firing of t produces the marking M': $M'(p) = M(p) - W(p,t) + W(t,p)$, for all $p \in P$. Again, this evolution is denoted by $M[t\rangle M'$.

3. A multiset of transitions R is enabled in M, written $M[R\rangle$, if and only if $M(p) \geq \sum_{t \in T} W(p,t) \cdot R(t)$. The firing of R, denoted by $M[R\rangle M'$, produces M':
$$M'(p) = M(p) - \sum_{t \in T} (W(p,t) - W(t,p)) \cdot R(t), \ \forall p \in P$$

Definition 8 (Occurrence Sequence)
Let $N = (P, T, F, K, W, M_0)$ be a marked Petri net.

1. $\sigma = M_0 t_1 M_1 \dots t_n M_n$ is a finite occurrence sequence of N if and only if $\forall i \in \{1, \dots, n\}$, $M_{i-1}[t_i\rangle M_i$. Occasionally, we will write $t_1 \dots t_n$, omitting the corresponding markings, since starting from M_0 it is easy to obtain the rest of the markings knowing the transitions fired. We extend the conventional notation to occurrence sequences, obtaining $M_0[\sigma\rangle M_n$. The set of occurrence sequences starting from M_0 are denoted by $L(N, M_0)$.

2. For multiple transitions, $\sigma = M_0 R_1 M_1 \dots R_n M_n$ is a finite step sequence iff $\forall i \in \{1, \dots, n\}$, $M_{i-1}[R_i\rangle M_i$. The set of finite step sequences of N starting from M_0 is denoted by $P(N, M_0)$.

3.1 Petri nets analysis

When designing a new system, the construction of a graphical model (e.g. a Petri net) of it is always helpful since it is interesting to broadly understand how this system works before building it. This also helps designers to have a deeper knowledge about how it evolves in its different steps. Nevertheless, the presence of a graphical model is not enough in many cases as the designers want the system to meet some properties of interest. For instance, the system

can be useless if it can become deadlocked in some executions. To this end, it is valuable to have tools that allow to evaluate properties in the model (and, in extension, in the real system). In finite sequential systems, it is not particularly challenging to check the fulfilment of certain statement, whereas the presence of concurrency complicates this task. Thus, the analysis of system behaviour is intended to determine the compliance of certain properties such as that the number of processes in a queue does not exceed certain threshold or that the mutual exclusion is guaranteed when accessing to a shared resource.

In Petri nets, one can use a set of powerful tools to formally analyse the compliance of such properties. With these tools, designers can check the absence of deadlocks, the reachability of a certain state, the possibility of reaching a concrete situation after performing some computations and so on. Some examples of these tools are TINA [10], CPNTools, [4], Snoopy [27] and GreatSPN [18].

Normally, these properties are divided in two categories:

3.1.1 Safety properties

A safety property asserts that *"nothing bad happens"*. Thus, they guarantee that a set of undesirable states are not reached or that the system does not execute an unwanted occurrence sequence.

The *safety properties* are the following:

1. **Reachability**. A marking M of a marked Petri net $N = (P, T, F, W, M_0)$ is *reachable* in N iff there exists an occurrence sequence $\sigma \in L(N, M_0)$ such that $M_0[\sigma\rangle M$. We will denote by $[M_0\rangle$ the set of reachable markings of N starting from M_0, and by $[M\rangle$ the set of reachable markings starting from the marking M.

2. **Boundedness**. A marked Petri net $N = (P, T, F, W, M_0)$ is *k-bounded*, for some $k \in \mathbb{N}_0$, if for all reachable marking M from M_0, it holds $M(p) \leq k$, for all $p \in P$. N is said to be safe if it is 1-bounded. A place $p \in P$ is *n-safe* if $M(p) \leq n$, for all marking M reachable from M_0.

3. **Deadlock-free**. Let $N = (P, T, F, W, M_0)$ a marked Petri net and M be a reachable marking. M is a *dead marking* if there is no $t \in T$ enabled at M. The net N is deadlock-free iff there are no dead markings.

4. **Coverability**. Let $N = (P, T, F, W, M_0)$ be a marked Petri net and M be a marking of N. M is said to be *coverable* if there exists $M' \in [M_0\rangle$ such that $M'(p) \geq M(p)$, for all $p \in P$.

3.1.2 Liveness properties

A liveness property asserts that *"something good eventually happens"*. For instance, they guarantee that, independently of the current state of the system, a specific state can eventually be reached or that a certain occurrence sequence can eventually be executed in the system.

The *liveness properties* are:

1. **Liveness**. Let $N = (P, T, F, W, M_0)$ be a marked Petri net. A transition $t \in T$ is said to be *live* if for all reachable marking $M \in [M_0\rangle$ there is an occurrence sequence σ starting from M such that $\sigma = t_1 \dots t_m$, with $t_m = t$. The net N is *live* iff all the transitions are live.

2. **Home State**. Let $N = (P, T, F, W, M_0)$ be a marked Petri net. A marking M of N is a *home state* if for all $M' \in [M_0\rangle$, $M \in [M'\rangle$.

3. **Home Space**. Let $N = (P, T, F, W, M_0)$ be a marked Petri net. The set of markings $\mathcal{M}$ is a *home-space* of N if for all marking $M' \in [M_0\rangle$ there is a marking $M'' \in \mathcal{M}$ such that $M'' \in [M'\rangle$.

4. **Cyclic**. Let $N = (P, T, F, W, M_0)$ be a marked Petri net. It is said that N is cyclic if for all marking $M \in [M_0\rangle$ there exists an occurrence sequence σ starting at M such that $M[\sigma\rangle M_0$.

3.2 Timed extensions of Petri nets

In the literature on timed extensions for Petri nets we can identify a first group of models, which assign time delays to transitions, by using either a fixed deterministic value [41, 44, 42] or choosing it from a probability distribution [33].

Other models use time intervals to establish the enabling times of transitions [34]. There are also models that include time on tokens [46, 49, 13]. In [14, 53] a summary of time extensions for Petri nets is presented.

3.2.1 Prioritized-Timed Colored Petri Nets

Next we introduce the particular model of prioritised-timed coloured Petri net considered as the graphical formalism for the language BPELRF.

We use prioritised-timed coloured Petri nets (PTCPNs), which are a prioritised-timed extension of coloured Petri nets [31]. PTCPNs are supported by CPN Tools [4], which is a toolbox developed originally by the *CPN group* at the University of Aarhus. The maintenance and extension of CPNTools are now in charge of the group *Architecture of Information Systems*, chaired by Wil van der Aalst, at Technische Universiteit Eindhoven. Priorities were also introduced in Petri nets to extend the descriptive power of the model [9, 11, 38], usually by associating priority levels with transitions and modifying the firing rule to prevent the firing of a transition when another one with higher priority is enabled. Note that this feature is really useful for describing some activities in the language BPELRF.

In PTCPNs, places have an associated colour set (data types). Each token has then an attached data value (*token colour*), which belongs to the colour to which the token is associated. We will use timed colours, for which the first component will be a non-negative integer value, representing the data value, and the second component will be the token timestamp, a natural number representing the time at which the token will be available.

There is also a discrete global clock that represents the total time elapsed in the system model. Moreover, arcs have also an associated inscription (*arc expressions*), constructed using variables, constants, operators and functions. To evaluate an arc expression we need to bind the variables that are part of the expression with their current value, that is, this binding consists of assigning a value to the variables that appear in the arc inscription. These values are then used to select the token colours that must be removed or added when firing the corresponding transition.

Arc expressions can also have associated time information both for place-transition and transition-place arcs. However, only time inscriptions are needed in output arcs, and even, when all the output arcs of a transition have the same time inscription, there is a shorthand notation in CPN Tools by which this time information is associated with the transition instead of the output arcs.

The time inscription associated with a transition is used to specify the delay that must be added to the current value of the global clock for every token generated by the firing of the transition.

Transitions can also have associated guards, which are Boolean expressions that can prevent their firing. Thus, when a transition has a guard, it must evaluate to true for the binding to be enabled, otherwise the binding is disabled and the transition cannot be fired.

Definition 9 (Prioritised-Timed Coloured Petri Nets)
A prioritised-timed coloured Petri net is a tuple $(P, T, A, \Sigma, V, G, E, \lambda, D, \pi)$, where:

- P is a finite set of *places*, with colours in the set Σ. Thus, in our case, colours will be pairs $(n, x) \in \mathbb{N}_0 \times \mathbb{N}_0$, where n is the token value and x its timestamp.
- 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*.
- Σ is a finite set of non-empty colour sets. These colour sets can be timed or untimed. For simplicity, we only use non-negative integer variables and, therefore, the colour sets are: $\mathbb{N}_0 \times \mathbb{N}_0$ for the timed version and $\mathbb{N}_0$ for the untimed version. Thus, in our case, colours will be pairs $(n, x) \in \mathbb{N}_0 \times \mathbb{N}_0$ or just n, where n is the token value and x its timestamp.
- V is a finite set of *typed variables* in Σ, i.e. $Type(v) \in \Sigma$, for all $v \in V$.
- $G : T \longrightarrow EXPR_V$ is the *guard function*, which assigns a Boolean expression to each transition, i.e. $Type(G(t)) = Bool$.
- $E : A \longrightarrow EXPR_V$ is the *arc expression function*, which assigns an expression to each arc, such that $Type(E(a)) = \mathcal{B}(\mathbb{N}_0)$, which corresponds to untimed arcs, since, as mentioned above, we only attach time delays to transitions.

- λ is the *labelling function*, defined both on places and transitions.
- $D : T \longrightarrow \mathbb{N}_0 \times \mathbb{N}_0$, which is the *delay function*, which associates a time interval to each transition. For $D(t) = [d_1, d_2]$, this means that a uniform probability function will be used when t is fired to select the specific discrete delay in that time interval. This is a particularity of CPNTools [4].
- $\pi : T \longrightarrow \mathbb{N}_0$ is the *priority function*, which assigns a priority level to each transition. In CPNTools, the lower value, the higher priority, that is, 0 is the highest priority.

In this definition, $EXPR_V$ denotes the expressions constructed using the variables in V, with the same syntax admitted by CPN Tools. Notice again that we only use here non-negative integer variables for simplicity, but our model can be easily extended to other variable types.

Definition 10 (Markings)
Given a PTCPN $N = (P, T, A, \Sigma, V, G, E, \lambda, D, \pi)$, a marking M is defined as a function $M : P \longrightarrow \mathcal{B}(\Sigma)$, which assigns a multiset of colours to each place (which can be empty).

A timed marking of a PTCPN N is a pair (M, x), where M is a marking of N and x is the current system time instant. Initial markings are those markings for which the timestamp of every token is 0, and all variable places are marked with a single token $(0, 0)$. A marked prioritized-timed coloured Petri net (MPTCPN) is then defined as a triple (N, M, x), where N is a PTCPN, and (M, x) a timed marking of it.

We define the semantics for MPTCPNs in a similar way as in [32], now taking into account that transitions have associated priorities. We first introduce the notion of *binding*, then the *enabling condition* and finally the *firing rule* for MPTCPNs.

The variables of a transition t are denoted $Var(t) \subseteq V$ and consist of the free variables appearing in the guard of the transition and in the arc expressions connected to it.

Definition 11 (Bindings)
Let $N = (P, T, A, \Sigma, V, G, E, \lambda, D, \pi)$ be a PTCPN. A *binding* of a transition $t \in T$ is

a function b that maps each variable $v \in Var(t)$ into a value $b(v) \in \Sigma$. We will denote by $B(t)$ the set of all possible bindings for the transition $t \in T$.

Given an expression $e \in EXPR_V$, we will denote by $e\langle b \rangle$ the evaluation of e for the binding b.

A *binding element* is then defined as a pair (t, b), where $t \in T$ and $b \in B(t)$. The set of all binding elements is denoted by BE.

Definition 12 (Enabling condition)
Let $N = (P, T, A, \Sigma, V, G, E, \lambda, D, \pi)$ be a PTCPN, and (M, x) a timed marking of it. We say that a binding element $(t, b) \in BE$ is *enabled* at the time instant x' in the timed marking (M, x) if and only if the following conditions are fulfilled:

1. $x' \geq x$.
2. $G(t)\langle b \rangle = true$.
3. For all $p \in {}^\bullet t$, $E(p,t)\langle b \rangle_{x'} \preceq M(p)$, where $E(p,t)\langle b \rangle_{x'}$ consists of the same colours as $E(p,t)\langle b \rangle$, but replacing their timestamp (which was 0) by x'.
4. There is no other binding element $(t', b') \in BE$ fulfilling the previous conditions such that $\pi(t') < \pi(t)$.
5. x' is the smallest time value for which there exists a binding element (t, b) fulfilling these conditions.

Definition 13 (Firing rule)
Let $N = (P, T, A, \Sigma, V, G, E, \lambda, D, \pi)$ be a PTCPN, (M, x) a timed marking of N, and an enabled binding element $(t, b) \in BE$ at instant x' in the timed marking (M, x).

The firing of (t, b) at instant x' is non-deterministic, depending on the chosen delay $d \in \mathbb{N}_0$ for the transition. This delay is randomly selected in the interval given by $D(t)$. Thus, the new timed marking (M', x') is:

$$\forall p \in P \,:\, M'(p) = M(p) \ominus E(p,t)\langle b \rangle_{x'} + E(t,p)\langle b \rangle_{d+x'}$$

Example 3.2.1
Let us consider the marked PTCPN depicted in Figure 3.1, obtained from CPN-Tools examples. Observe that timed colour tokens in CPN Tools are drawn using

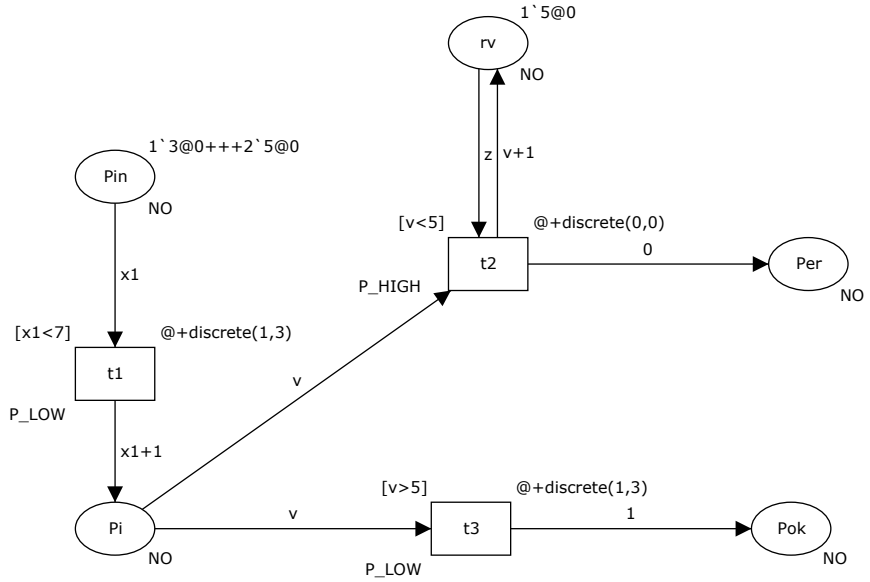


Figure 3.1: Graphical view of a PTCPN.

the notation $n`v@x$, meaning that we have n instances of a timed colour token with colour value v and *timestamp* x, which correspond to $n.(v, x)$ according to our formal notation. Besides, the symbol '+++' is there used to represent the union of timed multisets.

Thus, p_{in} is initially marked with one token of colour $(3, 0)$, and two tokens of colour $(5, 0)$, and the place rv has one token with colour $(5, 0)$. Transitions are labelled with their associated guard, time interval and priority information. Arcs are labelled with the corresponding expressions, in which no time delays appear, as we are considering that only transitions have associated time delays.

From the initial marking we can see that only transition t_1 can be fired (at instant 0), and any token of those in p_{in} can be used for that purpose. Taking $(5, 0)$ we get the binding $x = 5$, which fulfils the transition guard. The firing of t_1 with this binding removes one instance of $(5, 0)$ from p_{in}, and produces a new token on p_i. The timestamp of this new token is a discrete value in the interval $[1, 3]$ (let us say 3). Thus, considering the output arc inscription we get a token $(6, 3)$ on p_i.

Now, transition t_1 must fire again twice (until p_{in} becomes empty), due to the time constraints of this model. As a result we may obtain in p_i the following marking $\{1.(4, 3), 1.(6, 1),\ 1.(6, 3)\}$ (the timestamp values depend on the values

chosen from the interval $[1,3]$). The only transition that can be fired at this marking is t_3, because due to the time constraints we must first use the token $(6,1)$ and t_2 cannot be fired using this token. The firing of t_3 produces a new token on p_{ok}, whose colour value must be 1, and the timestamp depends again on the chosen delay in the time interval $[1,3]$. For instance, we could obtain the colour token $(1,4)$.

Two tokens now remain in p_i, with colours $(4,3)$ and $(6,3)$, and t_2 becomes the only transition enabled (due to condition (4) of Def. 12). Its firing removes the token $(4,3)$ from p_i, the token on the place rv changes to $1.(5,3)$, and creates a new token on p_{er}, with colour $(0,3)$. Finally, the remaining token $(6,3)$ on p_i only allows us to fire t_3, generating a new token on p_{ok}, with value 1 and a timestamp depending on the delay chosen for its firing.

3.2.2 Extended Timed-Arc Petri Nets

A *discrete timed transition system* (DTTS) is a triple $(S, Act, \rightarrow)$ where S is the set of states, Act is the set of actions and $\rightarrow \subseteq S \times (Act \cup \mathbb{N}_0) \times S$ is the transition relation written as $s \xrightarrow{a} s'$ whenever $(s,a,s') \in \rightarrow$. In continuous time, the transition relation is defined as $\rightarrow \subseteq S \times (Act \cup \mathbb{R}^{\geq 0}) \times S$. If $a \in Act$ then we call it a *switch transition*, if $a \in \mathbb{N}_0$ we call it a *delay transition*. We also define the set of *well-formed time intervals* by:

$$\mathcal{I} = \{[a,a] \mid [a,b] \mid [a,b) \mid (a,b] \mid (a,b) \mid [a,\infty) \mid (a,\infty) \mid a,b \in \mathbb{N}_0, a < b\}$$

Moreover, its subset:

$$\mathcal{I}^{\text{inv}} = \{[0,0] \mid [0,b] \mid [0,b) \mid [0,\infty) \mid b \in \mathbb{N}_0\}$$

is used in age invariants. Let us note that we use a discrete time semantics in our definitions to avoid the duplication for the case of continuous time. Nevertheless, it is enough to include $\mathbb{R}^{\geq 0}$ instead of $\mathbb{N}_0$ to provide a continuous time semantics.

Definition 14 (Extended timed-Arc Petri Net)
An *extended timed-arc Petri net* (ETAPN) is a 9-tuple $N = (P, T, T_{urg}, IA, OA, g, w, Type, I)$ where

- P is a finite set of *places*,
- T is a finite set of *transitions* such that $P \cap T = \emptyset$,
- $T_{urg} \subseteq T$ is the set of *urgent transitions*,
- $IA \subseteq P \times T$ is a finite set of *input arcs*,
- $OA \subseteq T \times P$ is a finite set of *output arcs*,
- $g : IA \to \mathcal{I}$ is a *time constraint function* assigning guards to input arcs,
- $w : IA \cup OA \to \mathbb{N}$ is a function assigning *weights* to input and output arcs,
- $Type : IA \cup OA \to \mathbf{Types}$ is a *type function* assigning a type to all arcs where $\mathbf{Types} = \{Normal, Inhib\} \cup \{Transport_j \mid j \in \mathbb{N}\}$ such that
  - if $Type(a) = Inhib$ then $a \in IA$ and $g(a) = [0, \infty]$,
  - if $(p, t) \in IA$ and $t \in T_{urg}$ then $g((p, t)) = [0, \infty]$,
  - if $Type((p, t)) = Transport_j$ for some $(p, t) \in IA$ then there is exactly one $(t, p') \in OA$ such that $Type((t, p')) = Transport_j$,
  - if $Type((t, p')) = Transport_j$ for some $(t, p') \in OA$ then there is exactly one $(p, t) \in IA$ such that $Type((p, t)) = Transport_j$,
  - if $Type((p, t)) = Transport_j = Type((t, p'))$ then $w((p, t)) = w((t, p'))$,
- $I : P \to \mathcal{I}^{inv}$ is a function assigning *age invariants* to places.

Remark 3.2.1
Note that for transport arcs we assume that they come in pairs (for each type $Transport_j$) so that their weights match. Also for inhibitor arcs and for input arcs to urgent transitions, we require that the guards are $[0, \infty]$. This restriction is important for some of the results presented in this Thesis and it also guarantees that we can use DBM-based algorithms in the tool TAPAAL [21].

The ETAPN model is not monotonic, meaning that adding more tokens to markings can disable time delays or transition firing. Therefore we define a subclass of ETAPN where the monotonicity breaking features are not allowed. In the literature such nets are often considered as the standard timed-arc Petri net model [12, 26] but we add the prefix monotonic for clarity reasons.

Definition 15 (Monotonic timed-arc Petri net)
A *monotonic timed-arc Petri net* (MTAPN) is an extended timed arc Petri net with no urgent transitions ($T_{urg} = \emptyset$), no age invariants ($I(p) = [0, \infty]$ for all $p \in P$) and no inhibitor arcs ($Type(a) \neq Inhib$ for all $a \in IA$).

Before giving the formal semantics of the model, let us fix some notation. We will recall some definitions presented previously, although applying them to this kind of nets. Let $N = (P, T, T_{urg}, IA, OA, g, w, Type, I)$ be an ETAPN. We denote by ${}^\bullet x \stackrel{\text{def}}{=} \{y \in P \cup T \mid (y, x) \in (IA \cup OA),\ Type((y, x)) \neq Inhib\}$ the preset of a transition or a place x. Similarly, the postset $x^\bullet$ is defined as $x^\bullet \stackrel{\text{def}}{=} \{y \in P \cup T \mid (x, y) \in (IA \cup OA)\}$. Let $\mathcal{B}(\mathbb{N}_0)$ be the set of all finite multisets over $\mathbb{N}_0$. A *marking* M on N is a function $M : P \longrightarrow \mathcal{B}(\mathbb{N}_0)$ where for every place $p \in P$ and every token $x \in M(p)$ we have $x \in I(p)$. In other words all tokens have to satisfy the age invariants. The set of all markings in the net N is denoted by $\mathcal{M}(N)$.

We write (p, x) to denote a token at a place p with the age $x \in \mathbb{N}_0$. Then $M = \{\!\{(p_1, x_1), (p_2, x_2), \ldots, (p_n, x_n)\}\!\}$ is a multiset representing a marking M with n tokens of ages x_i in places p_i. We define the size of a marking as $|M| = \sum_{p \in P} |M(p)|$ where $|M(p)|$ is the number of tokens located in the place p.

Definition 16 (Enabledness)
Let $N = (P, T, T_{urg}, IA, OA, g, w, Type, I)$ be an ETAPN. We say that a transition $t \in T$ is *enabled* in a marking M by the multiset of timed tokens
$In = \{\!\{(p, x_p^1), (p, x_p^2), \ldots, (p, x_p^{w((p,t))}) \mid p \in {}^\bullet t\}\!\} \subseteq M$ and by the multiset of tokens
$Out = \{\!\{(p', x_{p'}^1), (p', x_{p'}^2), \ldots, (p', x_{p'}^{w((t,p'))}) \mid p' \in t^\bullet\}\!\}$ if

- for all input arcs except the inhibitor arcs, the tokens from In satisfy the age guards of the arcs, i.e.

$$\forall (p, t) \in IA. Type((p, t)) \neq Inhib \Rightarrow x_p^i \in g((p, t)) \text{ for } 1 \leq i \leq w((p, t))$$

- for any inhibitor arc pointing from a place p to the transition t, the number of tokens in p is smaller than the weight of the arc, i.e.

$$\forall (p, t) \in IA. Type((p, t)) = Inhib \Rightarrow |M(p)| < w((p, t))$$

- for all input arcs and output arcs which constitute a transport arc, the age of the input token must be equal to the age of the output token and satisfy the invariant of the output place, i.e.

$$\forall(p,t) \in IA. \forall(t,p') \in OA. Type((p,t)) = Type((t,p')) = Transport_j$$
$$\Rightarrow \left(x^i_p = x^i_{p'} \wedge x^i_{p'} \in I(p')\right) \text{ for } 1 \leq i \leq w((p,t))$$

- for all normal output arcs, the age of the output token is 0, i.e.

$$\forall(t,p') \in OA. Type((t,p')) = Normal \Rightarrow x^i_{p'} = 0 \text{ for } 1 \leq i \leq w((p,t)).$$

A given ETAPN N defines a DTTS $T(N) \stackrel{\text{def}}{=} (\mathcal{M}(N), T, \rightarrow)$ where states are the markings and the transitions are as follows:

- If $t \in T$ is enabled in a marking M by the multisets of tokens In and Out then t can *fire* and produce the marking $M' = (M \setminus In) \uplus Out$ where $\uplus$ is the multiset sum operator and $\setminus$ is the multiset difference operator; we write $M \xrightarrow{t} M'$ for this switch transition.
- A time *delay* $d \in \mathbb{N}_0$ is allowed in M if
  - $(x + d) \in I(p)$ for all $p \in P$ and for all $x \in M(p)$, and
  - if $M \xrightarrow{t} M'$ for some $t \in T_{urg}$ then $d = 0$.

  By delaying d time units in M we reach the marking M' defined as $M'(p) = \{\!\{x + d \mid x \in M(p)\}\!\}$ for all $p \in P$; we write $M \xrightarrow{d} M'$ for this delay transition.

Let $\rightarrow \stackrel{\text{def}}{=} \bigcup_{t \in T} \xrightarrow{t} \cup \bigcup_{d \in \mathbb{N}_0} \xrightarrow{d}$. Again, the set of all markings reachable from a given marking M is denoted by $[M\rangle \stackrel{\text{def}}{=} \{M' \mid M \rightarrow^* M'\}$. By $M \xrightarrow{d,t} M'$ we denote that there is a marking M'' such that $M \xrightarrow{d} M'' \xrightarrow{t} M'$.

A marking M is a *deadlock* if there is no $d \in \mathbb{N}_0$ and no $t \in T$ such that $M \xrightarrow{d,t} M'$ for some marking M'. A marking M is *divergent* if for any $d \in \mathbb{N}_0$ we have $M \xrightarrow{d} M'$ for some M'.

In general, ETAPNs are infinite in two dimensions. The number of tokens in reachable markings can be unbounded and even for bounded nets the ages of tokens can be arbitrarily large.

Chapter 4

BPELRF: A language for the specification of stateful web service compositions

In this chapter, we introduce the language BPELRF. This language is intended to be used in the specification of web services compositions in which the state of each participant is required to be stored. As commented previously, web services are usually "stateless", which means that when an operation is invoked, no state is stored after performing it. Here, we introduce the concept of *stateful web services compositions*. Obviously, in this kind of compositions, the services can use a set of distributed resources to save the state of some operations. To this end, we will use the standard WSRF since it is intended to be used in conjunction with web services. Moreover, WS-BPEL language will be used to specify the interactions between web services. First, we provide the syntax and semantics of the language BPELRF. The syntax will be defined following the classical BNF notation, whereas the operational semantics is expressed following the Plotkin-style presented in [39]. The main concepts about it were introduced in Section 2.6 of Chapter 2. In the second part of the chapter, we will define a graphical model for this language by using Petri nets. Moreover, we present the tool we have developed in order to support the creation of stateful web services compositions.

After briefly introducing the content of the chapter, let us remark what are the main contributions of the language BPELRF. First, note that the integration of WS-BPEL and WSRF is not new, since, in the literature, one can find some technical works illustrating this integration. Some of these works will be presented in the Related Works section. Surprisingly, to the best of our knowledge, this is the first work, which taking as a starting point WSRF/WSN 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 (according to the standard WSN) is also provided here. This improves the expressiveness of the language BPELRF as it does not only allow to model the interactions between services, but it also includes mechanisms to manage the notification methods between these services. Furthermore, we commented in the introduction that it is really important to discover the set of services that will conform the system if the designer does not know these services beforehand. To this end, we have enriched BPELRF with a formal primitive to discover these new services, increasing again the expressive power of the language.

It is worthwhile to mention that our aim with BPELRF 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/WSN to manage stateful web services compositions 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 and WSN such as notifications and resources time-outs.

We split this chapter in two well differentiated parts. On the one hand, we present the syntax and semantics in Plotkin-style, whereas in the second part the Petri nets semantics of BPELRF is introduced. Thus, the rest of the chapter is organised as follows. Each part will be treated separately and, therefore, each of them will consist of the presentation of some related works, the semantics and a case study to illustrate how it works. Notice that the syntax will be the same for both parts and, therefore, it will be introduced only when defining the operational semantics in Plotkin-style.

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.

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 orches-

trations). 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 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. 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. Other one reviewed also in this book is B lite [**?**]. This is a lightweight language for web services orchestration designed around some of WS-BPEL peculiar features like partner links, process termination, message correlation, long-running business transactions and compensation handlers aiding to clarify some ambiguous aspects of the WS-BPEL specification. The last one, Orc [**?**], is not influenced by any other language used for orchestration purposes like WS-BPEL. The authors define the language as a novel language for distributed and concurrent programming which provides

uniform access to computational services, including distributed communication and data manipulation, through sites. Using four simple concurrency primitives, the programmer orchestrates the invocation of sites to achieve a goal, while managing timeouts, priorities, and failures. This language uses as a basic activity the information published by a site and therefore each site invocation always finishes with one or more either nested or parallel publications.

4.1 Syntax and semantics of BPELRF

In this section, we present the syntax and semantics of BPELRF. First, we introduce some notation used only in this chapter. 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 ($EPRS \subseteq \mathbb{N}_0$), 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:

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

where $O \in ORCH, pl, pl_i \in PL, op, op_i \in \ OPS, timeout \in \mathbb{N}_0$, $expr$ 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. When in a condition or in an expression appears the variable $vEPR$, we suppose that the evaluation of this variable is not the resource identifier, but the value of this resource.

WS-BPEL 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>	$A_1 \; ; \; A_2$
<flow> $activity_1$ $activity_2$ </flow>	$A_1 \parallel A_2$
<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)

Table 4.1: WS-BPEL Syntax Conversion table

BPEL basic activities included 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* ($\parallel$ 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 and our model is shown in Table 4.1, whereas the correspondence between our model and WSRF/WSN Notification syntax is depicted in Table 4.2.

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.

WSRF/WS-Notification Syntax	Model
<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 4.2: WSRF/WSN Notification Conversion table

Before we begin, we introduce some additional notation and definitions required to describe the operational semantics.

Definition 17 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. □

Along the following lines, we introduce the additional notation used only 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 we denote the elapse of one time unit by $s^+ = (\sigma, \rho')$, 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 $(O_i, EPR_i,\ v_i, Subs_i, t_i, tag_i, A_{e_i}) \in \rho$ such that $\sigma(vEPR_i) = EPR_i$. 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 re-

source 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 18 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 4.4. □

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 4.4, 4.5 we show the rules for these transitions.

Next, we only introduce a short explanation of some rules of Table 4.4. 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.

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

(Iv) $(invoke(pl, op, v_1), s) \xrightarrow{invoke(pl,op,\sigma(v_1))} (empty, s)$ **(Re)** $(receive(pl, op, v), s) \xrightarrow{receive(pl,op,m)} (empty, s')$
where $v \in VAR$, $m \in \mathbb{Z}$, $op \in OPS$, $pl \in PL$, and $s' = (\sigma[m/v], \rho)$

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

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

(Wh1) $$\frac{cond(s)}{(while(cond, A), s) \xrightarrow{\tau} (A; while(cond, A), s)}$$

(Wh2) $$\frac{\neg cond(s)}{(while(cond, A), s) \xrightarrow{\tau} (empty, s)}$$

(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 $s' = (\sigma[m/v_i], \rho)$, $\forall i \in \{1..n\}$.

Table 4.3: Action transition rules.

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), and, therefore, the reply activity is optional in the syntax depicted in Table 4.1. Below, a toy example is depicted to explain how it works.

Example 4.1.1

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 4.4, 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 $s'' = (\sigma[m/id3], \rho)$.

(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 $s' = (\sigma[e/vEPR], \rho \cup \{O, e, val, \emptyset, t, tag, A\})$.

(GetProperty) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(getProp(vEPR, v_1), s) \xrightarrow{getProp(\sigma(vEPR),val(\rho,vEPR))} (empty, s')}$$

(GetProperty2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(getProp(vEPR, v_1), s) \xrightarrow{throw} (empty, s)}$$
where $vEPR, v_1 \in VAR$ and $s' = (\sigma[time(\rho, vEPR)/v_1], \rho)$.

(GetTimeout) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(getTimeout(vEPR, v_1), s) \xrightarrow{getTimeout(\sigma(vEPR),time(\rho,vEPR))} (empty, s')}$$

(GetTimeout2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(getTimeout(vEPR, v_1), s) \xrightarrow{throw} (empty, s)}$$
where $vEPR, v_1 \in VAR$ and $s' = (\sigma[val(\rho, vEPR)/v_1], \rho)$.

(SetProperty) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(setProp(vEPR, expr), s) \xrightarrow{setProp(\sigma(vEPR),expr)} (empty, s')}$$

(SetProperty2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(setProp(vEPR, expr), s) \xrightarrow{throw} (empty, s)}$$
where $vEPR \in VAR$ and $s' = (\sigma, \rho[expr/vEPR]_1)$.

(SetTimeout) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \in \rho}{(setTimeout(vEPR, t), s) \xrightarrow{setTimeout(\sigma(vEPR),t)} (empty, s')}$$

(SetTimeout2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(setTimeout(vEPR, t), s) \xrightarrow{throw} (empty, s)}$$
where $s' = (\sigma, Add\_subs(\rho, vEPR, O, cond', A))$

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

(Subscribe2) $$\frac{s = (\sigma, \rho), \sigma(vEPR) \notin \rho}{(subscribe(O, vEPR, cond', A), s) \xrightarrow{throw} (empty, s')}$$
where $t \geq 1$, $s' = (\sigma, \rho[t/vEPR]_2)$.

(Discover1) $$\frac{s = (\sigma, \rho), tag \in \rho}{(discover(tag, vEPR), s) \xrightarrow{discover(tag,sel(\rho,tag))} (empty, s')}$$
where $vEPR \in VAR, s' = (\sigma[sel(\rho, tag)/vEPR], \rho))$

(Discover2) $$\frac{s = (\sigma, \rho), tag \notin \rho}{(discover(tag, vEPR), s) \xrightarrow{discover(tag,-1)} (empty, s')}$$
where $vEPR \in VAR, s' = (\sigma[-1/vEPR], \rho))$

Table 4.4: Action transition rules.

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 man-

$$\textbf{(Wait1D)}\ \frac{t > 1}{(wait(t), s) \rightarrow_1 (wait(t-1), s^+)} \qquad \textbf{(Wait2D)}\ (wait(1), s) \rightarrow_1 (empty, s^+)$$

$$\textbf{(SeqD)}\ \frac{(A_1, s) \rightarrow_1 (A_1', s^+)}{(A_1; A_2, s) \rightarrow_1 (A_1'; A_2, s^+)} \qquad \textbf{(EmptyD)}\ (empty, s) \rightarrow_1 (empty, s^+)$$

$$\textbf{(ParD)}\ \frac{(A_1, s) \rightarrow_1 (A_1', s^+) \wedge (A_2, s) \rightarrow_1 (A_2', s^+)}{(A_1 || A_2, s) \rightarrow_1 (A_1' || A_2', s^+)} \qquad \textbf{(InvD)}\ (invoke(pl, op, v_1), s) \rightarrow_1 (invoke(pl, op, v_1), s^+)$$

$$\textbf{(RecD)}\ (receive(pl, op, v), s) \rightarrow_1 (receive(pl, op, v), s^+) \qquad \textbf{(PickD)}\ (pick(\{(pl_i, op_i, v_i, A_i)\}_{i=1}^n, A, 1), s) \rightarrow_1 (A, s^+)$$

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

Table 4.5: Delay transition rules without notifications.

agement, 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 the variable vEPR. This results 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 4.5, notice that the activities for which the passage of time is allowed are *wait, empty, receive, invoke* and *pick*.

At the orchestrator level (Table 4.6), 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 4.6 captures.

Definition 19 Orchestration Operational semantics
The transitions in this level have the following form:

1. $(O : (A, s)^m) \xrightarrow{a} (O : (A', s')^{m'})$, a $\in$ 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 4.7, we define the corresponding transition rules for the choreography semantics. Observe that Table 4.7 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.

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

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

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

Table 4.6: Action and delay transition rules for orchestrators.

Definition 20 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. □

As commented when we defined the types of transitions, our operational semantics evolves at three levels, the internal one corresponds to the evolution of one activity without notifications. In the second one, we state the transitions which yield the evolution of the system in the case that some notifications are triggered, whereas the third level corresponds to the composition of different orchestrators and resources. The former two parts have been covered with the operational semantics described above. Hereby, we are going to explain in the following lines how the system evolves as a whole. In the following we will denote choreography as a composition of orchestrations and their associated web services resources. The rule *Cor1* allows the passage of time on the orchestration activity in execution and in the event handling activity, whereas *Cor2-3* allow the evolution of the activity in execution, except in the case of failure. In that case, rule *Cor4* are used to activate the fault handling activity.

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

(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* $k \neq i, A'_k = A_k$.

(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* $m'_k = m_k$.

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

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

(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* $k \neq i, k \neq j, A'_k = A_k, m'_k = m_k$.

(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* $k \neq i, k \neq j, A'_k = A_k, m'_k = m_k$.

(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 4.7: Choreography transition rules.

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, $Var_{sys} = \{v_w, v_{EPR}, end\_bid\}$, $Var_1 = \{v_1, v_{w_1}\}$, $Var_2 = \{v_2, v_{w_2}\}$, $A_{f_1} = exit$, 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, end_bid is used to terminate the auction. 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:

$A_{sys} = assign(1, end\_bid); createResource(EPR, 25, 48, O_{sys}, A_{not});$
$\quad while(end\_bid > 0, A_{bid})$
$A_1 = subscribe(O_1, EPR, EPR >= 0, A_{cond_1}); while(v_{w_1} == 0, A_{pick_1})$
$A_2 = subscribe(O_2, EPR, EPR >= 0, A_{cond_2}); while(v_{w_2} == 0, A_{pick_2})$, being:
$A_{not} = assign(0, end\_bid); getProp(EPR, v_w);$
$\quad ((invoke(pl_3, bid\_finish_1, v_w)||invoke(pl_4, bid\_finish_2, v_w))$
$A_{bid} = getProp(EPR, v_{EPR});$
$\quad pick((pl_1, cmp, v_1, while(v_1 > v_{EPR}, assign(v1, v_{EPR}); setProp(EPR, v_{EPR}))),$
$\quad (pl_2, cmp, v_2, while(v_2 > v_{EPR}, assign(v2, v_{EPR}), setProp(EPR, v_{EPR}))), empty, 48)$
$A_{cond_1} = getProp(EPR, v_{EPR}); invoke(pl_1, bid\_up_1, v_{EPR})$
$A_{cond_2} = getProp(EPR, v_{EPR}); invoke(pl_2, bid\_up_2, v_{EPR})$
$A_{pick_1} = pick((pl_1, bid\_up_1, v_1, assign(v_1, v_1 + random()); invoke(pl_1, cmp, v_1);$
$\quad subscribe(O_1, EPR, EPR >= v_1, A_{cond_1})), (pl_3, bid\_finish_1, v_{w_1}, empty), empty, 48)$
$A_{pick_2} = pick((pl_2, bid\_up_2, v_2, assign(v_2, v_2 + random()); invoke(pl_2, cmp, v_2);$
$\quad subscribe(O_2, EPR, EPR >= v_2, A_{cond_2})), (pl_4, bid\_finish_2, v_{w_2}, empty), empty, 48)$

Let us note that the operations bid_up_1 and bid_up_2 are used to increase the current bid by means of a random function, the operations bid_finish_1, bid_finish_2 update the value of v_w to finish both buyers. Finally, cmp is an auction system operation that receives the bids, v_i, and if the variable value is greater than the current value of v_{EPR}, then v_{EPR} is updated. As well, by means of the activity $setProp(EPR, v_{EPR})$, we update the resource property.

In Fig. 4.1 shows a part of the labelled transition system of C. This figure shows a trace sample where after creating the resource EPR both bidders O_1 and O_2 subscribe to this resource. Afterwards, both bidders are able to increase theirs bids by means of bid_up_i operations and therefore the auction starts. The auction process is depicted here by the states $Chor_5^{+n}$, $Chor_6^{+n}$, $Chor_7^{+n}$, $Chor_8$, $Chor_9$ and $Chor_{10}$. In these states, there are several actions running in parallel: A_{bid}, A_{pick1} and A_{pick2} representing the communication over the partnerlinks, A_{cond1} and A_{cond2} representing the bidding and A_{not} to finalize the auction. The states indexed by $+n$ have a self-loop to symbolize the passage of time, whereas the transitions labelled with condition expressions control whether the timeout has expired finishing the auction with A_{not}.

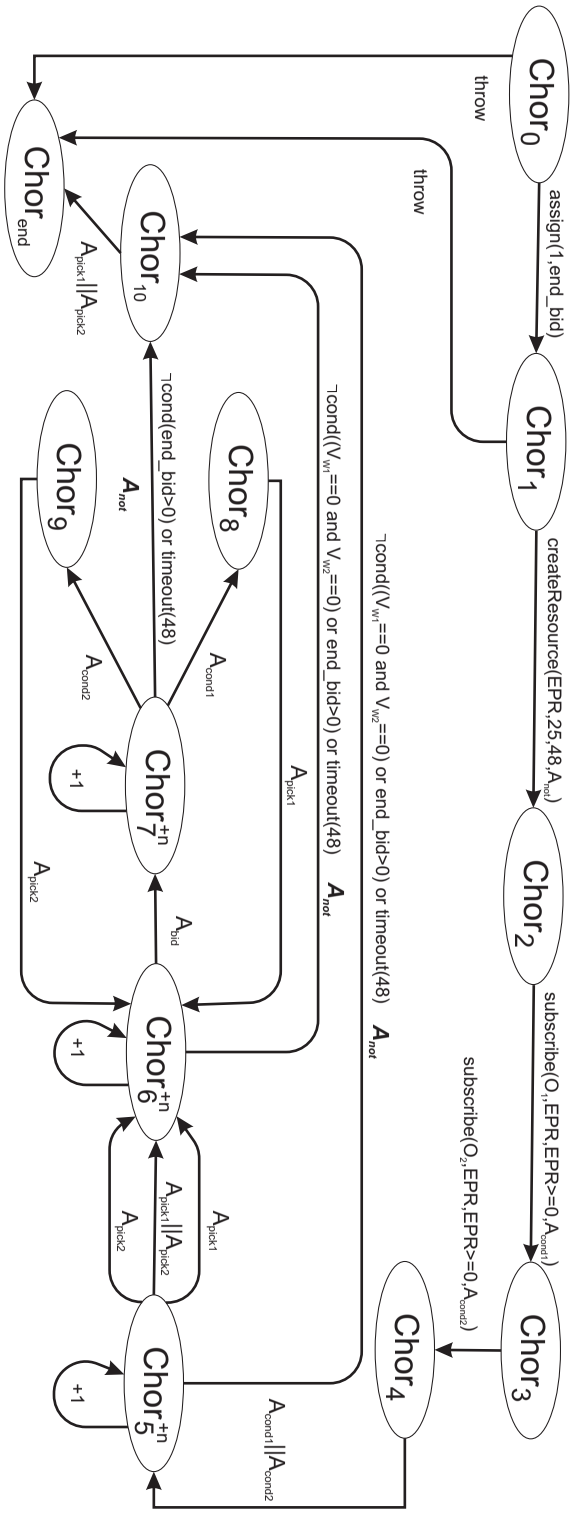


Figure 4.1: A piece of $lts(C)$ for the online auction service.

4.2 Prioritised-Timed Coloured Petri Nets Semantics for BPELRF

bla bla bla

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.

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.

As commented in Chapter 3, we use prioritised-timed coloured Petri nets, a prioritised-timed extension of coloured Petri nets [32], supported by the well-known toolbox CPNTools[4].

Definition 21
(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[1]:

- 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

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

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

activity. We will use timed and untimed coloured tokens, so timed tokens will have associated a time stamp, according to the CPNTools interpretation [32].

- 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.
- 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*.

- $D : T \longrightarrow \mathbb{N}_0 \times \mathbb{N}_0$*(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.

- $\pi : T \longrightarrow \mathbb{N}_0$ 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 [32].

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. We will reuse the same syntax as in the operational semantics presented previously.

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. 4.2. 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.

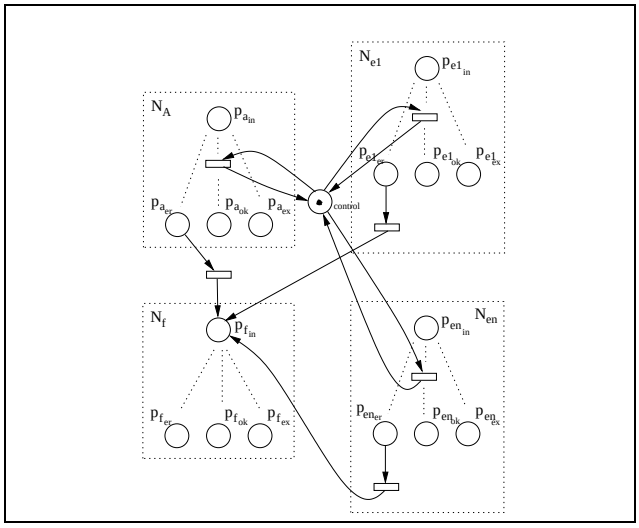


Figure 4.2: Orchestration Translation

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.

Basic activities

- *Throw, Empty, Assign, Exit* and *Wait* activities:
  These are translated as indicated in Fig. 4.3, 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*,

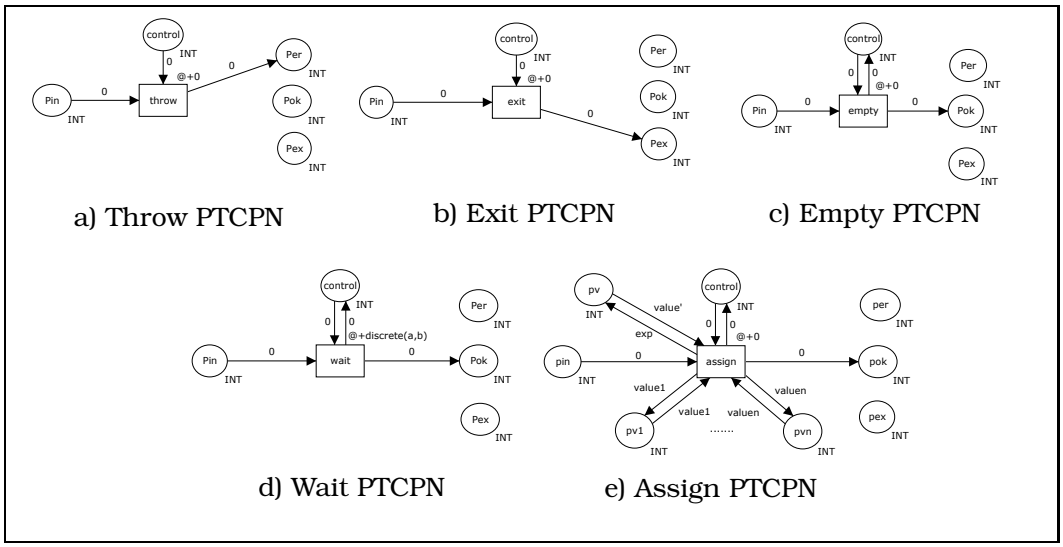


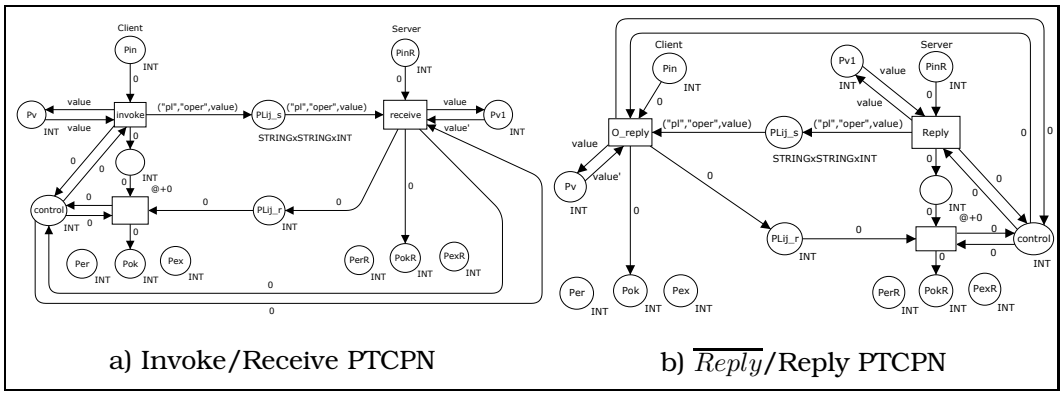
Figure 4.3: Basic Activities Translation

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 4.1.

  Fig. 4.4 shows the translation for both the invoke/receive and the reply/$\overline{reply}$ pairs of activities. Part a) of the figure corresponds to the invoke/receive translation, in which the net of the invoke activity is depicted on the left-



a) Invoke/Receive PTCPN b) $\overline{Reply}$/Reply PTCPN

Figure 4.4: Invoke/Receive Activities Translation

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 Part b) Fig. 4.4 is analogous.

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 [5], 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. 4.5), 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.

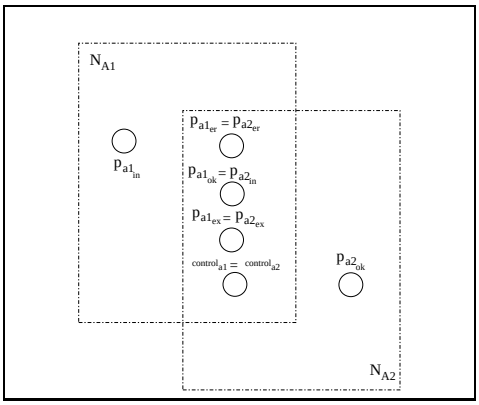


Figure 4.5: Sequence Translation

- *Parallel*: The translation for a parallel activity is depicted in Fig. 4.6, 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. A similar reasoning is done with the *exit* places. It is a must to remark we do not treat some BPEL flow construction attributes such as join conditions, dead path elimination, etc., since there are out of the scope of the language BPELRF.

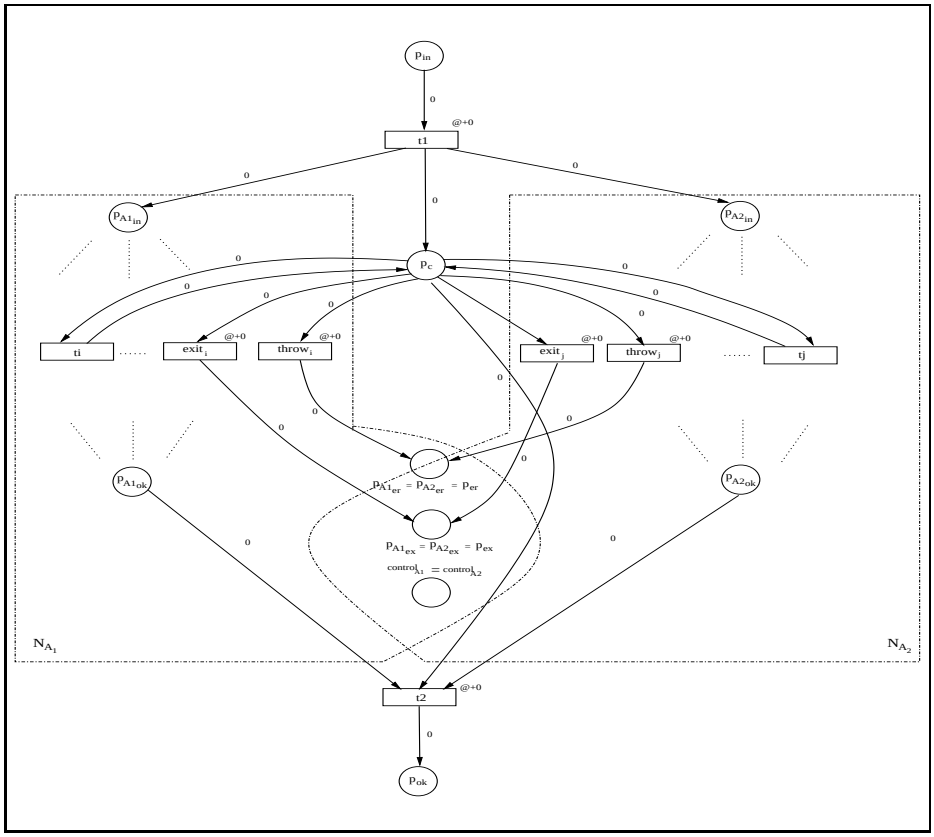


Figure 4.6: Parallel Activity Translation.

- *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. 4.7 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*. The <pick> activity completes when the selected activity finishes, 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>. The <pick> activity is comprised of a set of branches, each containing an event-activity pair. The activities contained in this construction can come in two forms:

- *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. 4.8 shows this translation.

The <while> activity provides for repeated execution of a contained activity. The contained activity is executed as long as the boolean condition evaluates to true at the beginning of each iteration. The meaning of the places and transitions of the net represented in Fig. 4.8 is fairly straightforward, so, due to space limitations, we are going to omit any explanation of its elements. The meaning of the places and transitions are fairly straightforward, so, due to space limitations, we are going to omit any explanation of the elements contained in this net

WSRF/WSN-compliant

In this section, we state the WSRF activities we have integrated with the BPEL activities in order to create a framework for modelling stateful workflows. It is worth noting that in recent years have appeared a new redefinition of workflow nets which deals with resources called Resource-Constrained Workflow Nets **??**. As commented in the Related Work section, this approach extends the well-known formalism, Workflow nets, with finite resources such as money, memory and so on, but the authors do not provide the machinery to create and destroy such resources, so this extension of Workflow nets matches with the idea of WSRF standard, i.e., the creation and destruction of resources is out of the scope of the specification. Nevertheless, our approach was devised to manage the whole lifetime of the resource from its creation until its destruction.

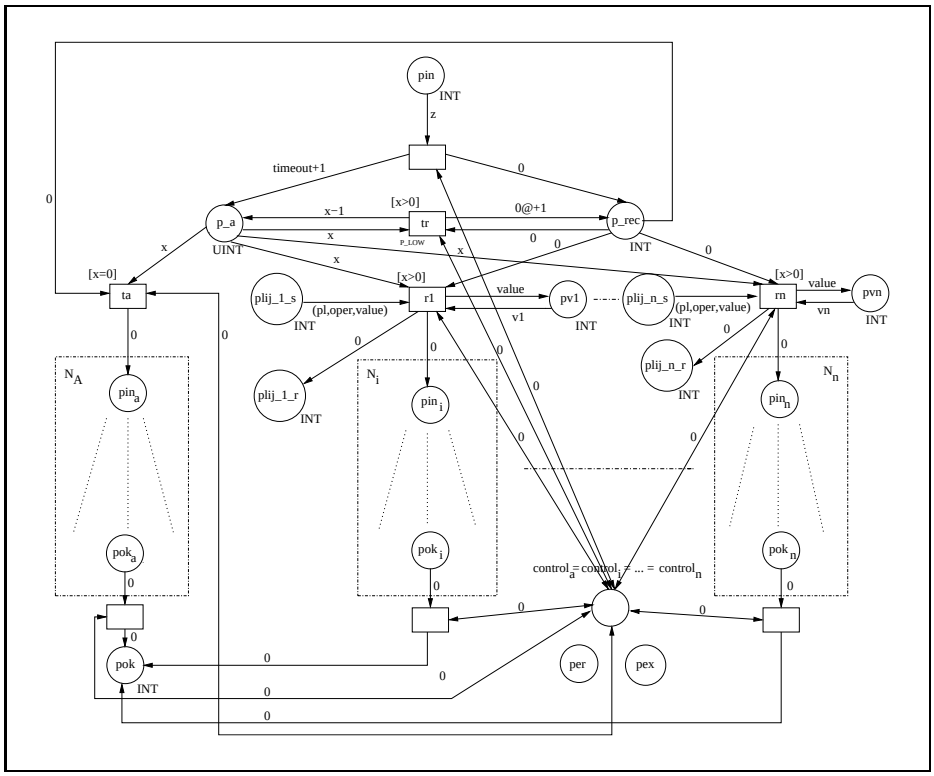


Figure 4.7: Pick Activity Translation.

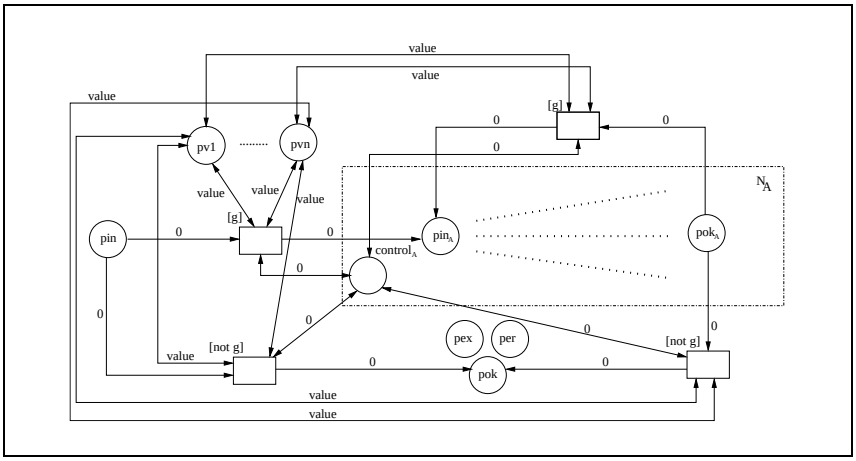


Figure 4.8: While Activity Translation.

To date, we have presented the activities corresponding to the “BPEL” activities part of our model. Next, we will state the counterpart of our approach, i.e., the activities, which permit the creation and modification of the resources as well as the management of the subscriptions to them following the indications of the

standard WSRF. Notice that a novelty in our model is the creation of resources since WSRF does not specify how this creation is done.

To begin with, we depict the creation of resources in Fig. 4.9. In order to guarantee our PTCPNs are 1-safe, we opted as commented above to model each resource with two dedicated places, p_{r_i}, and p_{r_a}, which represent the possible state of the resources, instantiated or not instantiated, respectively. Thus, when an orchestrator wants to create a resource, the firing of the transition *createResource* moves the token from the "inactive" (p_{r_i}) to the "active" place (p_{r_a}) making available this resource to the subscribers. Once the place p_{r_a} is marked and an orchestrator executes the activity *subscribe*, our translation can automatically build the subscriptions nets. Here, a subscription net is formed by a transition, whose guard is the subscription condition, and the subnet which corresponds to the translation of the activity that the subscriber wants to be executed just in case the subscription condition gc_i holds. Notice that WSRF allows the creation of multiple subscriptions to the same resources by the same orchestrator, so we will allow this restriction. Despite the *subscribe* construction will be presented later, just comment here we have endowed each resource with a list that represents its subscribers with their *id* and an integer, 0 or 1, to denote whether the orchestrator with identifier *id* is subscribed or not. Finally, in the leftmost part of Fig. 4.9, we depict the net that will be fired in the event of the resource lifetime expires. In this situation, we return the token from the active place to the inactive place and immediately execute the activity $Activity_timeisup$, which will be passed as an argument of the *createResource* activity. This argument is not included in the WSRF specification, but we have incorporated it to show the benefits of the integration of both standards.

- *CreateResource (EPR,val,timeout,A)*: *EPR* is the resource identifier, for which we have two complementary places in Fig. 4.9, 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. 4.9 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 lifetime (max), and its value (val).

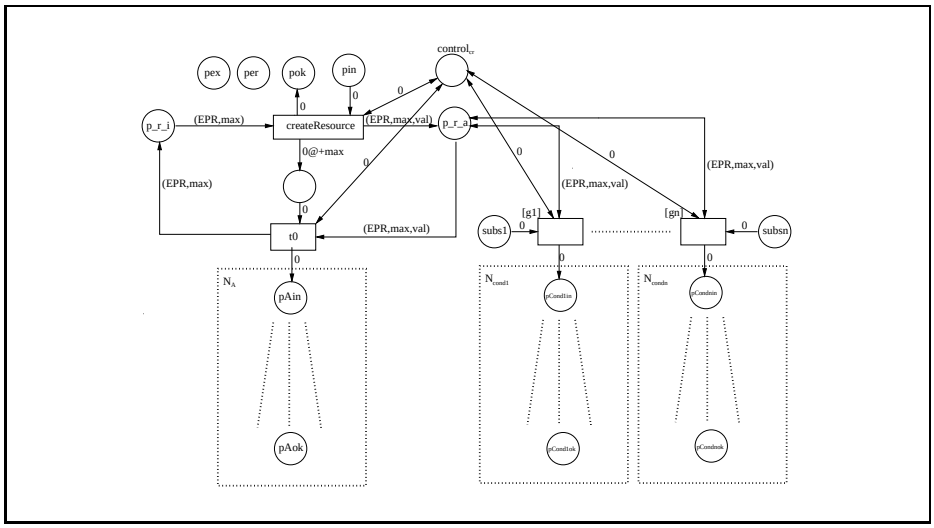


Figure 4.9: CreateResource Activity Translation.

Transition $t0$ is executed when the lifetime 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 corresponding 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. 4.10 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.

- GetProp (EPR,v) and SetProp (EPR,expr): These are easily translated, as shown in Figs. 4.11 and 4.12, where the resource value is obtained and assigned to variable v (GetProp), or a new value is assigned to the resource (SetProp).

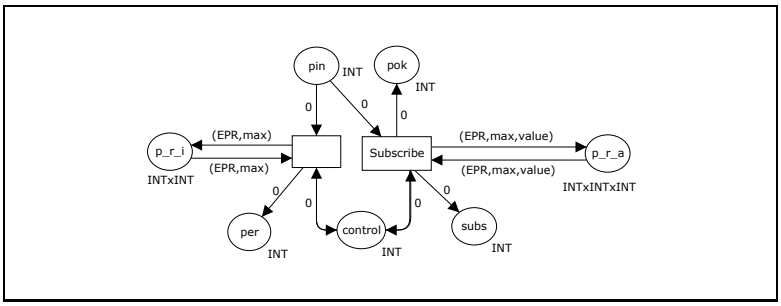


Figure 4.10: Subscribe Activity Translation.

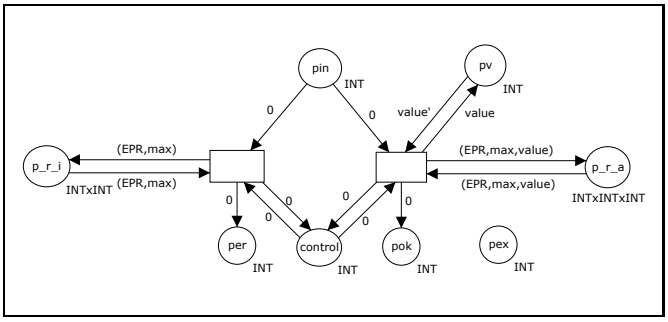


Figure 4.11: GetProperty Activity Translation.

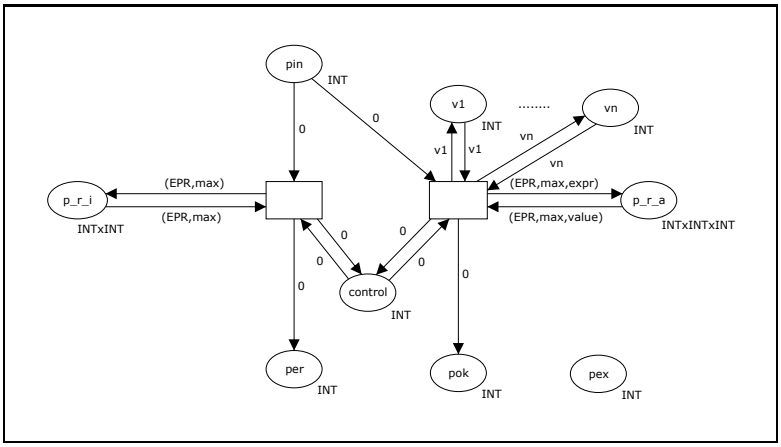


Figure 4.12: SetProperty Activity Translation.

- SetTimeout (EPR,timeout): This activity is analogous to *SetProp* activity. In this case, the resource lifetime is updated with a new value. Fig. 4.12 shows this translation.

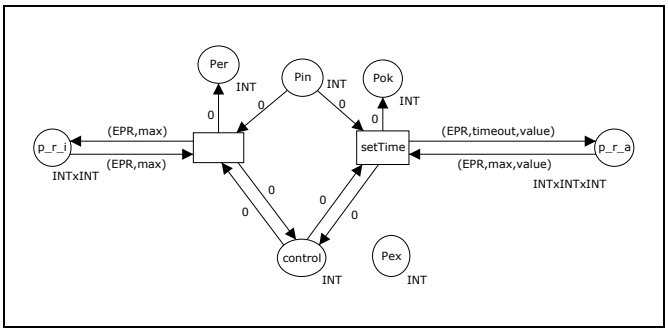


Figure 4.13: SetTimeout Activity Translation.

4.3 Tool Support

Sacar del WODES

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:

$$
\begin{aligned}
A_{sys} &= assign(10, at); createResource(EPR, 25, 11, A_{not});\\
&\quad while(actualTime() <= at, A_{bid})\\
A_1 &= wait(1,1); subscribe(O_1, EPR, EPR >= 0, A_{cond_1});\\
&\quad invoke(pl1, auction\_time_1, at1); \overline{reply}(pl1, auction\_time_1, at1);\\
&\quad while(actualTime() <= at1, A_{bid_1}); receive(pl3, bid\_finish_1, vw_1, empty)\\
A_2 &= wait(1,1); subscribe(O_2, EPR, EPR >= 0, A_{cond_2});\\
&\quad invoke(pl2, auction\_time_2, at2); \overline{reply}(pl2, auction\_time_2, at2);\\
&\quad while(actualTime() <= at2, A_{bid_2}); receive(pl4, bid\_finish_2, vw_2, empty)\\
A_{not} &= ((invoke(pl_3, bid\_finish_1, v_w)||invoke(pl_4, bid\_finish_2, v_w))\\
A_{bid} &= getprop(EPR, v_{EPR}); pick(\\
&\quad (pl1, auction\_time1, t, reply(pl1, auction\_time1, at)),\\
&\quad (pl2, auction\_time2, t, reply(pl2, auction\_time2, at)),\\
&\quad (pl_1, cmp, v_1, while(v_1 > v_{EPR}, assign(v1, v_{EPR});\\
&\qquad setProp(EPR, v_{EPR}); assign(1, vw))),\\
&\quad (pl_2, cmp, v_2, while(v_2 > v_{EPR}, assign(v2, v_{EPR});\\
&\qquad setProp(EPR, v_{EPR}); assign(2, vw))), empty, 1)\\
A_{cond_1} &= getProp(EPR, v_{EPR}); invoke(pl_1, bid\_up_1, v_{EPR})\\
A_{cond_2} &= getProp(EPR, v_{EPR}); invoke(pl_2, bid\_up_2, v_{EPR})\\
A_{bid_1} &= receive(pl_1, bid\_up_1, v_1); assign(v_1 + random(), v_1);\\
&\quad invoke(pl_1, cmp, v_1); subscribe(O_1, EPR, EPR > v_1, A_{cond_1}); wait(1,1)\\
A_{bid_2} &= receive(pl_2, bid\_up_2, v_2); assign(v_2 + random(), v_2);\\
&\quad invoke(pl_2, cmp, v_2); subscribe(O_2, EPR, EPR > v_2, A_{cond_2}); wait(1,1)
\end{aligned}
$$

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. 4.14, 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 [32]. 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.

4.4 Summary

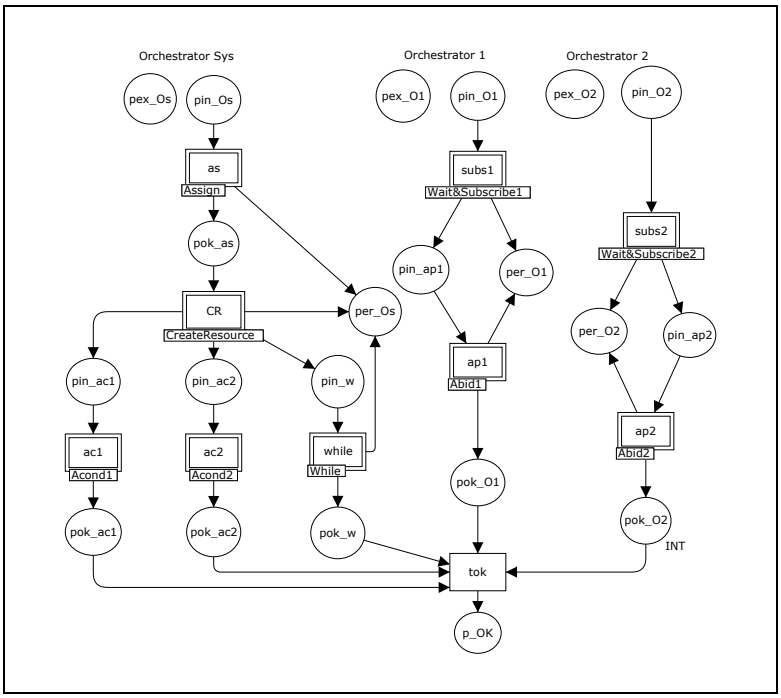


Figure 4.14: A simplified PTCPN for the online auction system.

Chapter 5

Timed-arc workflow nets

Recordar incluir los challenges of workflow modelling (resaltar el tiempo y la tool).

Chapter 6

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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