Transactional Composite Applications

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ABSTRACT:

Composite applications leveraging the functionalities offered by Web services are today the underpinnings of enterprise computing. However, current Web services composition systems make only use of functional requirements in the selection process of component Web services while transactional consistency is a crucial parameter of most business applications. The transactional challenges raised by the composition of Web services are twofold: integrating relaxed atomicity constraints at both design and composition time and coping with the dynamicity introduced by the service oriented computing paradigm. In this chapter, we present a new procedure towards automating the composition of transactional Web services. This composition procedure does not take into account functional requirements only but also transactional ones based on the Acceptable Termination States model. The resulting composite Web service is compliant with the consistency requirements expressed by business application designers and its execution can easily be coordinated using the coordination rules provided as an outcome of our approach. An implementation of our theoretical results based on OWL-S and BPEL technologies is further detailed as a proof of concept.

KEY WORDS:
Web services, composition, termination states, transactional requirements

INTRODUCTION

Web services composition has been gaining momentum over the last years as it leverages the capabilities of simple operations to offer value-added services. These complex services such as airline booking systems result from interactions between Web services that can span over organizational boundaries. Considering the lack of reliability akin to distributed environments, assuring data and transactional consistency of the outcome of cross-organizational workflow-based applications, such as composite applications, is necessary. The requirements that are relevant to assuring consistency within the execution of Web services composite applications are mainly twofold:

- **Relaxed atomicity**: atomicity of the execution can be relaxed as intermediate results produced by a workflow-based application may be kept despite the failure of a service. The specification process of transactional requirements associated with workflows has to be flexible enough to support coordination scenarios more complex than the coordination rule “all or nothing” specified within the two phase commit protocol (ISO, n.d.).
- **Dynamic assignment of business partners**: composite applications are dynamic in that the workflow partners or component services offering different characteristics can be assigned to tasks depending on the resources available at runtime. Business partners’ characteristics have thus to be combined or composed in a way such that the transactional requirements specified for the workflow are met.

Existing transactional protocols (Elmagarmid, 1992), (Greenfield, Fekete et al. 2003) are not adapted to meet these two requirements as they do not offer sufficient flexibility to cope for instance with the runtime assignment of computational tasks. In addition, existing solutions to combine or compose service providers based on the characteristics they offer appear to be limited when it comes to integrating at the composition phase the consistency requirements defined by workflow designers. These solutions indeed only offer means to validate transactional requirements once the workflow business partners have been selected but no solution to integrate these requirements as part of the composite application building process. The next sections present our approach to overcome these limitations.

Chapter contributions

In this chapter, we present an adaptive transactional protocol to support the execution of composite applications. The execution of this protocol takes place in two phases. First, business partners are assigned to tasks using an algorithm whereby workflow partners are selected based on functional and transactional requirements. Given an abstract representation of a process wherein business partners are not yet assigned to workflow tasks, this algorithm enables the selection of service providers not only according to functional requirements but also based on transactional ones. In our approach, these transactional requirements are defined at the workflow design stage using the Acceptable Termination States (*ATS*) model. The resulting workflow instance is compliant with the defined consistency requirements and its execution can be easily coordinated as our algorithm also provides coordination rules. The workflow execution further proceeds through a coordination protocol that leverages the coordination rules computed as an outcome of the partner assignment procedure.

Chapter outline

The remainder of the chapter is organized as follows. Section 2 discusses related work and technical background. In section 3, we introduce preliminary definitions and the methodology underpinning our approach. A simple example of composite application is presented in section 4 for the purpose of illustrating our results throughout the chapter. Section 5 introduces a detailed description of the transactional model used to represent the characteristics offered by business partners. In section 6, we provide details on the termination states of a workflow then section 7 describes how transactional requirements expressed by means of the *ATS* model are derived from the inherent properties of termination states. Section 8 presents the transaction-aware service assignment procedure and the associated coordination protocol. An implementation of our theoretical results based on Web services technologies including OWL-S (OWL Services Coalition, 2003) and BPEL (Thatte, 2003) is presented in section 9. Finally, section 10 presents concluding remarks.

TECHNICAL BACKGROUND

Transactional consistency of workflows and database systems has been an active research topic over the last 15 years yet it is still an open issue in the area of Web services (Curbera, Khalaf et al. 2003), (Gudgin, 2004), (Little, 2003) and especially composite Web services. Composite Web services indeed introduce new requirements for transactional systems such as dynamicity, semantic description and relaxed atomicity. Existing transactional models for advanced applications (Elmagarmid, 1992) are lacking of flexibility to integrate these requirements (Alonso, Agrawal et al. 1996) as for instance they are not designed to support the execution of dynamically generated collaboration of services. In comparison, the transactional framework presented in this chapter allows the specification of transactional requirements supporting relaxed atomicity for an abstract workflow specification and the selection of semantically described services respecting the defined transactional requirements.

Our work is based on (Bhiri, Perrin et al. 2005) which presents the first approach specifying relaxed atomicity requirements for composite Web services based on the *ATS* tool and a transactional semantic. Despite a solid contribution, this work appears to be limited if we consider the possible integration into automatic Web services composition systems. It indeed only details transactional rules to validate a given composite service with respect to defined transactional requirements. In this approach, transactional requirements do not play any role in the component service selection process which may result in several attempts for designers to determine a valid composition of services. On the contrary, our solution provides a systematic procedure enabling the automatic design of transactional composite Web services. Besides, our contribution also defines the mathematical foundations to specify valid *ATS* for workflows using the concept of coordination strategy that is defined later on.

Within the Web services stack, three specifications feature solutions towards assuring the transactional coordination of services: Web Services Coordination (WS-Coordination, (Langworthy, 2005)), Web Services Atomic Transaction (WS-AtomicTransaction, (Langworthy, 2005)) and Web Services Business Activity Framework (WS-BusinessActivity, (Langworthy, 2005)). They are often referred to as Web Services Transaction Framework (WSTF). The goal of WS-Coordination is to provide a framework that can support various coordination protocols specified in terms of coordination types. When service providers register to transactional coordinators they specify as part of a coordination type, the coordination protocol that should be implemented to support a composite application execution. The WS-AtomicTransaction and WS-BusinessActivity specifications are the two main coordination protocols available. Making use of compensation techniques WS-AtomicTransaction requires all participants to be compensatable and to support certain isolation levels; this is in fact an implementation of the two phase-commit protocol. WS-BusinessActivity on the other hand offers a coordination framework suitable for long-running transactions, called business activities. WS-BusinessActivity does not however specify appropriate tools to describe coordination strategies i.e. how the coordination protocol should react in the face of failures so that a composite application can reach consistent termination states. It is, in

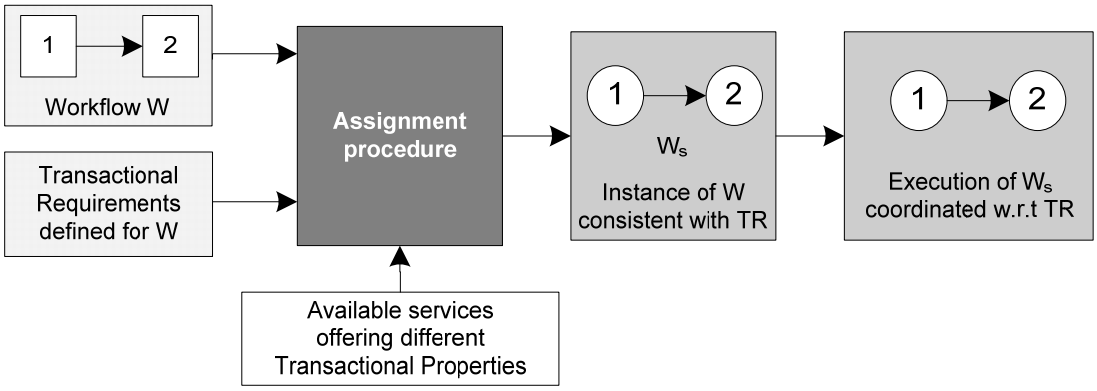


Figure 1: Principles

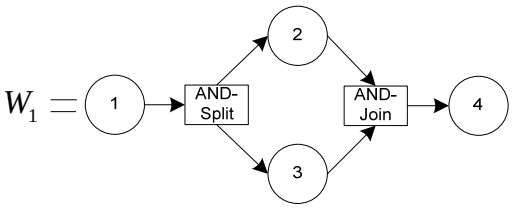
fact, only mentioned that different strategies are possible in addition to the classical "all or nothing" principle. Besides the Web Services Transaction Framework there are several other initiatives towards establishing transaction management within Web service interactions. The Business Process Execution Language for
Web Services (BPEL4WS or BPEL) implements the concept of Long-Running (Business) Transactions (LRT). It supports coordination of transactions in local BPEL processes. A comparison of BPEL Long-running transactions and WS-BusinessActivity and an approach to unify them can be found in (Melzer and Sauter, 2005). The Business Transaction Protocol (BTP, (Abbott, 2005)) specifies roles, interactions, behaviors and messages to coordinate long-running transactions in the fashion of the WS-BusinessActivity specification.

These various coordination protocols do not however offer adequate support for designers to specify flexible coordination scenarios wherein component services feature different transactional properties such as the ability to compensate the execution of a task or to retry the execution of a failed task. The solution presented in this chapter can be used to augment these standardization efforts in order to provide them with adaptive coordination specifications based on the transactional properties of the component services instantiating a given workflow.

PRELIMINARY DEFINITIONS AND METHODOLOGY

Transactional consistency is a crucial aspect of composite services execution. In order to meet consistency requirements at early stages of the service composition process, we need to consider transactional requirements a concrete parameter determining the choice of the component Web services. In this section we present a high level definition of the consistency requirements and a methodology taking into account these requirements during the building process of composite applications and later on during the coordination of their execution.

Consistent composite Web services



$TS(W_1)$	Task 1	Task 2	Task 3	Task 4
ts_1	completed	completed	completed	completed
ts_2	completed	completed	completed	failed
ts_3	completed	compensated	completed	failed
ts_4	completed	compensated	compensated	failed
ts_5	completed	completed	compensated	failed
ts_6	compensated	compensated	compensated	failed
ts_7	compensated	completed	compensated	failed
ts_8	compensated	completed	completed	failed
ts_9	compensated	compensated	completed	failed
ts_{10}	completed	failed	completed	aborted
ts_{11}	completed	failed	compensated	aborted
ts_{12}	completed	failed	canceled	aborted
ts_{13}	compensated	failed	completed	aborted
ts_{14}	compensated	failed	compensated	aborted
ts_{15}	compensated	failed	canceled	aborted
ts_{16}	completed	completed	failed	aborted
ts_{17}	completed	compensated	failed	aborted
ts_{18}	completed	canceled	failed	aborted
ts_{19}	compensated	completed	failed	aborted
ts_{20}	compensated	compensated	failed	aborted
ts_{21}	compensated	canceled	failed	aborted
ts_{22}	failed	aborted	aborted	aborted

Figure 2: Production line process

A composite Web service W_s consists of a set of n Web services $W_s = (s_a)_{a\in[1,n]}$ whose execution is managed according to a workflow W which defines the execution order of a set of n tasks $W = (t_a)_{a\in[1,n]}$ performed by these services (for the sake of simplicity, we consider that one service executes only one task). The assignment of services to tasks is performed by means of composition engines based on functional requirements. Yet, the execution of a composite service may have to meet transactional requirements aiming at the overall assurance of consistency. Our goal is to design a service assignment process that takes into account the transactional requirements associated with W in order to obtain a consistent instance W_s of W as depicted in Figure 1. We consider that each Web service component might fulfill a different set of transactional properties. For instance a service can have the capability to compensate the effects of a given operation or to re-execute the operation after failure whereas some other service does not have any of these capabilities. It is thus necessary to select the appropriate service to execute a task whose execution may be compensated if required. The assignment procedure based on transactional requirements follows the same strategy as the one based on functional requirements. It is a match-making procedure between the transactional properties offered by services and the transactional requirements associated to each task. Once assigned, the services $(s_a)_{a\in[1,n]}$ are coordinated with respect to the transactional requirements during the composite application execution. The coordination protocol is indeed based on rules deduced from the transactional requirements. These rules specify the final states of execution or termination states each service has to reach so that the overall process reaches a consistent termination state. Two phase-commit the famous coordination protocol (ISO, n.d.) uses for instance the simple rule: all tasks performed by different services have to be compensated if one of them fails. The challenges of the transactional approach are therefore twofold.

- Specify a Web service assignment procedure that builds consistent instances of W according to defined transactional requirements,
- Specify the coordination protocol managing the execution of consistent composite services.

Methodology

In our approach, the services involved in W_s are selected according to their transactional properties by means of a match-making procedure. We therefore need first to specify the semantic associated with the transactional properties defined for services. The match-making procedure is indeed based on this semantic. This semantic is also to be used in order to define a tool allowing workflow designers to specify their transactional requirements for a given workflow. Using these transactional requirements, we are able to assign services to workflow tasks based on rules which are detailed later on. Once the composite service is defined, we can define a protocol in order to coordinate these services according to the transactional requirements specified at the workflow designing phase. The proofs of the theorems underpinning the work presented in this chapter can be found in (Montagut and Molva, 2006).

MOTIVATING EXAMPLE

In this section we introduce a simple motivating example that will be used throughout the chapter to illustrate the presented methodology. We consider the simple process W_1 of a manufacturing firm involving four steps as depicted in Figure 2. A first service, order handling service is in charge of receiving orders from clients. These orders are then handled by the production line (step 2) and in the meantime an invoice is forwarded to a payment platform (step 3). Once the ordered item has been manufactured and the payment validated, the item is finally delivered to the client (step 4). Of course in this simple scenario, a transactional approach is required to support the process execution so that it can reach consistent outcomes as for instance the manufacturing firm would like to have the opportunity to stop the production of an item is the payment platform used by a customer is not a reliable one. On the other hand, it may no longer be required to care about canceling the production if the payment platform claims it is reliable and not prone to transaction errors. Likewise, customers may expect that their payment platform offer refunding options in case the delivery of the item they ordered is not successful. Those possible outcomes mostly define the transactional requirements for the execution of this simple process and also specify what actions need to be taken to make sure that the final state of the process execution is deemed consistent by the involved parties. This example although simple perfectly meets our illustration needs within this chapter as it demonstrates the fact that based on the specified transactional requirements a clever selection of the business process participants has to be performed prior to the process instantiation since for instance the selection of both a payment platform that do not offer any refunding options and an unreliable delivery means may result in a disappointed customer. It should be noted that the focus of this example is not the trust relationship between the different entities and we therefore assume the trustworthiness of each of them yet we are rather interested in the transactional characteristics offered by each participant.

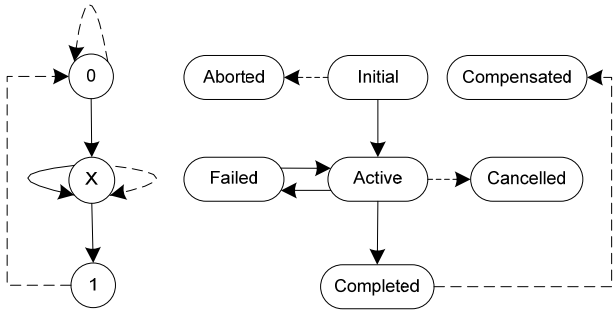


Figure 3: Service state diagram

TRANSACTIONAL MODEL

In this section, we define the semantic specifying the transactional properties offered by services before specifying the consistency evaluation tool associated to this semantic. Our semantic model is based on the "transactional Web service description" defined in (Bhiri, Perrin et al. 2005).

Transactional Properties of Services

In (Bhiri, Perrin et al. 2005) a model specifying semantically the transactional properties of Web services is presented. This model is based on the classification of computational tasks made in (Schuldt, Alonso et al. 1999), (Mehrotra, Rastogi et al. 1992) which considers three different types of transactional properties. An operation and by extension a Web service executing this task can be of type:

- **Compensatable**: the results produced by the task can be rolled back
- **Retriable**: the task is sure to complete successfully after a finite number of tries
- **Pivot**: the task is neither compensatable nor retriable

These transactional properties allow us to define four types of services: Retriable *(r)*, Compensatable *(c)*, Retriable and Compensatable *(rc)* and Pivot *(p)*.

In order to properly detail the model, we can map the transactional properties with the state of data modified by the services during the execution of computational tasks. This mapping is depicted in Figure 3. Basically, data can be in three different states: initial *(0)*, unknown *(x)*, completed *(1)*. In the state *(0)*, either the task execution has not yet started *initial*, the execution has been stopped, *aborted* before starting, or the execution has been properly completed and the modifications have been rolled back, *compensated*. In state *(1)* the task execution has been properly *completed*. In state *(x)* either the task execution is not yet finished *active*, the execution has been stopped, *canceled* before completion, or the execution has *failed*. Particularly, the states *aborted*, *compensated*, *completed*, *canceled*, and *failed* are the possible final states of execution of these tasks. Figure 4 details the transition diagram for the four types of transactional services. We must distinguish within this model the inherent termination states: *failed* and *completed* which

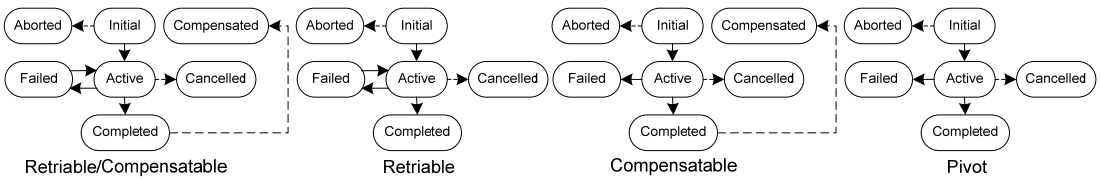


Figure 4: Transactional Properties of services

result from the normal course of a task execution and the one resulting from a coordination message received during a coordination protocol instance: *compensated*, *aborted* and *canceled* which force a task execution to either stop or rollback. The transactional properties of the services are only differentiated by the states *failed*, and *compensated* which indeed respectively specify the retriability and compensatability aspects.

Definition 5.1 We have for a given service *s*:

- *failed* is not a termination state of *s* iff *s* is retriable
- *compensated* is a termination state of *s* iff *s* is compensatable

From the state transition diagram, we can also derive some simple rules. The states *failed*, *completed* and *canceled* can only be reached if the service is in the state *active*. The state *compensated* can only be reached if the service is in the state *completed*. The state *aborted* can only be reached if the service is in the state *initial*.

Termination states

The crucial point of the transactional model specifying the transactional properties of services is the analysis of their possible termination states. The ultimate goal is indeed to be able to define consistent termination states for a workflow i.e. determining for each service executing a workflow task which termination states it is allowed to reach.

Definition 5.2 We define the operator termination state *ts(x)* which specifies the possible termination states of the element *x*. This element *x* can be:

- a service *s* and $ts(s) \in \{aborted, canceled, failed, completed, compensated\}$
- a task *t* and $ts(t) \in \{aborted, canceled, failed, completed, compensated\}$
- a workflow $W = (t_a)_{a \in [1,n]}$ and $ts(W) = (ts(t_1), ts(t_2), ..., ts(t_n))$
- a composite service W_s of W composed of n services $W_s = (s_a)_{a \in [1,n]}$ and $ts(W_s) = (ts(s_1), ts(s_2), ..., ts(s_n))$

The operator *TS(x)* represents the finite set of all possible termination states of the element *x*, $TS(x) = (ts_k(x))_{k \in [1,j]}$. We have especially, $TS(W_s) \subseteq TS(W)$ since the set $TS(W_s)$ represents the actual termination states that can be reached by W_s according to the

$ATS_1(W_1)$		Task 1	Task 2	Task 3	Task 4
ats_1	ts_1	completed	completed	completed	completed
ats_2	ts_6	compensated	compensated	compensated	failed
ats_3	ts_{14}	compensated	failed	compensated	aborted
ats_4	ts_{15}	compensated	failed	canceled	aborted
ats_5	ts_{20}	compensated	compensated	failed	aborted
ats_6	ts_{21}	compensated	canceled	failed	aborted

$ATS_2(W_1)$		Task 1	Task 2	Task 3	Task 4
ats_1	ts_1	completed	completed	completed	completed
ats_2	ts_{17}	completed	compensated	failed	aborted
ats_3	ts_{11}	completed	failed	compensated	aborted
ats_4	ts_5	completed	completed	compensated	failed
ats_5	ts_{18}	completed	canceled	failed	aborted
ats_6	ts_{12}	completed	failed	canceled	aborted

Available Services		Retriable	Compensatable
Task 1	s_{11}	yes	no
	s_{12}	no	yes
	s_{13}	yes	yes
Task 2	s_{21}	yes	no
	s_{22}	no	yes
Task 3	s_{31}	yes	no
	s_{32}	no	yes
Task 4	s_{41}	no	no

Figure 5: Acceptable termination states of W_1 and available services

transactional properties of the services assigned to *W*. We also define for *x* workflow or composite service and $a \in [1,n]$:

- $ts(x,t_a)$: the value of $ts(t_a)$ in *ts(x)*
- *tscomp(x)*: the termination state of *x* such that $\forall a \in [1,n] ts(x,t_a) = completed$

For the remainder of the chapter, $W = (t_a)_{a\in[1,n]}$ represents a workflow of *n* tasks and $W_s = (s_a)_{a\in[1,n]}$ a composite service of *W*.

Transactional consistency tool

We use the Acceptable Termination States *(ATS)* (Rusinkiewicz and Sheth 1995) model as the consistency evaluation tool for our workflow. *ATS* defines the termination states a workflow is allowed to reach so that its execution is judged consistent.

Definition 5.3 An *ATS(W)* is a subset of *TS(W)* whose elements are considered consistent by workflow designers for a specific execution of *W*. A consistent termination state of *W* is called an acceptable termination state $ats_k(W)$ thus $ATS(W) = (ats_k(W))_{k\in[1,i]}$. A set *ATS(W)* specifies the transactional requirements defined by designers associated with a specific execution of *W*.

ATS(W) and *TS(W)* can be represented by a table which defines for each termination state the tuple of termination states reached by the workflow task as depicted in Figure 5. Depending on the application different *ATS* tables can of course be specified by designers for the same workflow, and for the sake of readability we do not introduce in this chapter an index (as in $ATS_i(W)$) in the notation *ATS(W).* As mentioned in the definition, the specification of the set *ATS(W)* is done at the workflow designing phase. *ATS(W)* is mainly used as a decision table for a coordination protocol so that W_s can reach an acceptable termination state knowing the termination state of at least one task. The role of a coordination protocol indeed consists in sending messages to services in order to reach a consistent termination state given the current state of the workflow execution. The coordination decision, i.e. the termination state that has to be reached, made given a state

of the workflow execution has to be unique; this is the main characteristic of a coordination protocol. In order to cope with this requirement, *ATS(W)* which is used as input for the coordination decision-making process has therefore to verify some properties that we detail later on.

ANALYSIS OF *TS(W)*

Since $ATS(W) \subseteq TS(W)$, *ATS(W)* inherits the characteristics of *TS(W)* and we logically need to analyze first *TS(W)*. In this section, we first precise some basic properties of *TS(W)* derived from inherent execution rules of a workflow *W* before examining *TS(W)* from a coordination perspective.

Inherent properties of *TS(W)*

We state here some basic properties relevant to the elements of *TS(W)* and derived from the transactional model presented above. *TS(W)* is the set of all possible termination states of *W* based on the termination states model we chose for services. Yet, within a composite service execution, it is not possible to reach all the combinations represented by a *n*-tuple $(ts(t_1), ts(t_2), ..., ts(t_n))$. The first restriction is introduced by the sequential aspect of a workflow:

- (P_1) A task becomes *activated* iff all the tasks executed beforehand according to the execution plan of *W* have reached the state *completed*

(P_1) simply means that to start the execution of a workflow task, it is required to have properly completed all the workflow tasks required to be executed beforehand.

Second, we consider in our model that only one single task can fail at a time and that the states *aborted, compensated* and *canceled* can only be reached by a task in a given $ts_k(W)$ if one of the services executing a task of *W* has failed. This means that the coordination protocol is allowed to force the abortion, the compensation or the cancellation only in case of failure of a service. We get (P_2):

- (P_2) if $ts_k(W, t_a) \in \{compensated, aborted, canceled\}$ then $\exists! \, l \in [1, n]$ such that $ts_k(W, t_l) = failed$.

Classification within *TS(W)*

As we explained above the unicity of the coordination decision during the execution of a coordination protocol is a major requirement. We try here to identify the elements of *TS(W)* that correspond to different coordination decisions given the same state of a workflow execution. The goal is to use this classification to determine *ATS(W)*. Using the properties (P_1) and (P_2), a simple analysis of the state transition model reveals that there are two situations whereby a coordination protocol has different possibilities of

coordination given the state of a workflow task. Let two tasks t_a and t_b and assume that the task t_b has failed:

- the task t_a is in the state *completed* and either it remains in this state or it is *compensated*
- the task t_a is in the state *active* and either it is *canceled* or the coordinator lets it reach the state *completed*

From these two statements, we define the *incompatibility from a coordination perspective* and the *flexibility.*

Definition 6.1 Two termination states $ts_k(W)$ and $ts_l(W)$ are said incompatible from a coordination perspective iff $\exists$ two tasks t_a and t_b such that $ts_k(W,t_a) = completed$, $ts_k(W,t_b) = ts_l(W,t_b) = failed$ and $ts_l(W,t_a) = compensated$. Otherwise, $ts_l(W)$ and $ts_k(W)$ are said compatible from a coordination perspective.

The value in $\{compensated,completed\}$ reached by a task t_a in a termination state $ts_k(W)$ whereby $ts_k(W,t_b) = failed$ is called recovery strategy of t_a against t_b in $ts_k(W)$. By extension, we can consider the recovery strategy of a set of tasks against a given task.

If two termination states are compatible, they correspond to the same recovery strategy against a given task. In fact, we have two cases for the compatibility of two termination states $ts_k(W)$ and $ts_l(W)$. Given two tasks t_a, t_b such that $ts_k(W,t_b) = ts_l(W,t_b) = failed$:

- $ts_k(W,t_a) = ts_l(W,t_a)$
- $ts_k(W,t_a) \in \{compensated,completed\}, ts_l(W,t_a) \in \{aborted,canceled\}$

The second case is only possible to reach if t_a is executed in parallel with t_b. Intuitively, the failure of the service assigned to t_b occurs at different instants in $ts_k(W)$ and $ts_l(W)$.

Definition 6.2 A task t_a is flexible against t_b iff $\exists ts_k(W)$ such that $ts_k(W,t_b) = failed$ and $ts_k(W,t_a) = canceled$. Such a termination state is said to be flexible to t_a against t_b. The set of termination states of *W* flexible to t_a against t_b is denoted $FTS(t_a,t_b)$.

From these definitions, we now study the termination states of *W* according to the compatibility and flexibility criteria in order to identify the termination states that follow a common strategy of coordination.

Definition 6.3 A termination state of *W*, $ts_k(W)$ is called generator of t_a iff $ts_k(W,t_a) = failed$ and $\forall b \in [1,n]$ such that t_b is executed before or in parallel with t_a, $ts_k(W,t_b) \in \{completed, compensated\}$. The set of termination states of *W* compatible with $ts_k(W)$ generator of t_a is denoted $CTS(ts_k(W),t_a)$.

The set $CTS(ts_k(W),t_a)$ specifies all the termination states of *W* that follow the same recovery strategy as $ts_k(W)$ against t_a.

Definition 6.4 Let $ts_k(W) \in TS(W)$ be a generator of t_a. Coordinating an instance W_s of *W* in case of the failure of t_a consists in choosing the recovery strategy of each task of *W* against t_a and the $z_a < n$ tasks $(t_{a_i})_{i \in [1,z_a]}$ flexible to t_a whose execution is not *canceled* when t_a fails. We call coordination strategy of W_s against t_a the set:

$$CS(W_s, ts_k(W), (t_{a_i})_{i\in[1,z_a]}, t_a) = CTS(ts_k(W), t_a) - \bigcup_{i=1}^{z_a} FTS(t_{a_i}, t_a)$$

If the service s_a assigned to t_a is retriable then $CS(W_s, ts_k(W), (t_{a_i})_{i\in[1,z_a]}, t_a) = \varnothing$

W_s is said to be coordinated according to $CS(W_s, ts_k(W), (t_{a_i})_{i\in[1,z_a]}, t_a)$ if in case of the failure of t_a, W_s reaches a termination state in $CS(W_s, ts_k(W), (t_{a_i})_{i\in[1,z_a]}, t_a)$. Of course, it assumes that the transactional properties of W_s are sufficient to reach $ts_k(W)$.

From these definitions, we can deduce a set of properties:

Theorem 6.5 W_s can only be coordinated according to a unique coordination strategy at a time.

Theorem 6.6 Let $ts_k(W)$ such that $ts_k(W,t_a) = failed$ but not generator of t_a. If $ts_k(W) \in TS(W_s)$ then $\exists\, l \in [1,j]$ such that $ts_l(W) \in TS(W_s)$ is a generator of t_a compatible with $ts_k(W)$. This theorem states that if a composite service is able to reach a given termination state wherein a task t_a fails, it is also able to reach a termination state generator compatible with the latter.

Given a task t_a the idea is to classify the elements of *TS(W)* using the sets of termination states compatible with the generators of t_a. Using this approach, we can identify the different recovery strategies and the coordination strategies associated with the failure of t_a as we decide which tasks can be *canceled*.

FORMING *ATS(W)*

Defining *ATS(W)* is deciding at design time the termination states of *W* that are consistent. *ATS(W)* is to be inputted to a coordination protocol in order to provide it with a set of rules which leads to a unique coordination decision in any cases. According to the definitions and properties we introduce above, we can now explicit some rules on *ATS(W)* so that the unicity requirement of coordination decisions is respected.

Definition 7.1 Let $ts_k(W) \in ATS(W)$ such that $ts_k(W, t_a) = failed$. *ATS(W)* is valid iff $\exists\ !\ l \in [1, j]$ such that $ts_l(W)$ generator of t_a compatible with $ts_k(W)$ and $CTS(ts_l(W), t_a) - \bigcup_{i=1}^{z_a} FTS(t_{a_i}, t_a) \subset ATS(W)$ for a set of tasks $(t_{a_i})_{i \in [1, z_a]}$ flexible to t_a.

The unicity of the termination state generator of a given task comes from the incompatibility definition and the unicity of the coordination strategy. A valid *ATS(W)* therefore contains for all $ts_k(W)$ in which a task fails a unique coordination strategy associated to this failure and the termination states contained in this coordination strategy are compatible with $ts_k(W)$. In Figure 5, an example of possible *ATS* is presented for the simple workflow W_1. It just consists in selecting the termination states of the table $TS(W_1)$ that we consider consistent and respect the validity rule for the created $ATS(W_1)$.

DERIVING COMPOSITE SERVICES FROM *ATS*

In this section, we introduce a new type of service assignment procedure: the transaction-aware service assignment procedure which aims at assigning *n* services to the *n* tasks t_a in order to create an instance of *W acceptable* with respect to a valid *ATS(W)*. The goal of this procedure is to integrate within the instantiation process of workflows a systematic method ensuring the transactional consistency of the obtained composite service. We first define a validity criteria for the instance W_s of *W* with respect to *ATS(W)*, the service assignment algorithm is then detailed. Finally, we specify the coordination strategy associated to the instance created from our assignment scheme.

Acceptability of W_s with respect to *ATS(W)*

Definition 8.1 W_s is an acceptable instance of *W* with respect to *ATS(W)* iff $TS(W_s) \subseteq ATS(W)$.

Now we express the condition $TS(W_s) \subseteq ATS(W)$ in terms of coordination strategies. The termination state generator of t_a present in *ATS(W)* is noted $ts_{k_a}(W)$. The set of tasks whose execution is not *canceled* when t_a fails is denoted $(t_{a_i})_{i \in [1, z_a]}$.

Theorem 8.2 $TS(W_s) \subseteq ATS(W)$ iff $\forall a \in [1,n] CS(W_s, ts_{k_a}(W), (t_{a_i})_{i\in[1,z_a]}, t_a) \subset ATS(W)$

An instance W_s of W is therefore an acceptable one iff it is coordinated according to a set of n coordination strategies contained in *ATS(W)*. It should be noted that if $failed \notin ATS(W, t_a)$ where $ATS(W, t_a)$ represents the acceptable termination states of the task t_a in *ATS(W)* then $CS(W_s, ts_{k_a}(W), (t_{a_i})_{i\in[1,z_a]}, t_a) = \varnothing$.

Transaction-aware assignment procedure

In this section, we present the procedure that is used to assign services to tasks based on transactional requirements. This algorithm uses *ATS(W)* as a set of requirements during the service assignment procedure and thus identifies from a pool of available services those whose transactional properties match the transactional requirements associated to workflow tasks defined in *ATS(W)* in terms of acceptable termination states. The assignment procedure is an iterative process, services are assigned to tasks one after the other. The assignment procedure therefore creates at each step *i* a partial instance of *W* noted W_s^i. We can define as well the set $TS(W_s^i)$ which represents the termination states of *W* that the transactional properties of the *i* services already assigned allow to reach. Intuitively the acceptable termination states refer to the degree of flexibility offered when choosing the services with respect to the different coordination strategies verified in *ATS(W)*. This degree of flexibility is influenced by two parameters:

- The list of acceptable termination states for each workflow task. This list can be determined using *ATS(W)*. This is a direct requirement which specifies the termination states allowed for each task and therefore introduces requirements on the service's transactional properties to be assigned to a given task: this service can only reach the states defined in *ATS(W)* for the considered task.
- The assignment process is iterative and therefore, as we assign new services to tasks, $TS(W_s^i)$ changes and the transactional properties required to the assignment of further services too. For instance, we are sure to no longer reach the termination states $CTS(ts_k(W), t_a)$ allowing the failure of the task t_a in *ATS(W)* when we assign a service of type (*r*) to t_a. In this specific case, we no longer care about the states reached by other tasks in $CTS(ts_k(W), t_a)$ and therefore there is no transactional requirements introduced for the tasks to which services have not already been assigned.

We therefore need to define first the transactional requirements for the assignment of a service after *i* steps in the assignment procedure.

Extraction of transactional requirements

From the two requirements above, we define for a task t_a :

- $ATS(W,t_a)$: Set of acceptable termination states of t_a which is derived from *ATS(W)*
- $DIS(t_a,W_s^i)$: This is the set of transactional requirements that the service assigned to t_a must meet based on the previous assignments. This set is determined based on the following reasoning:

(DIS$_1$): the service must be compensatable iff $compensate\ d \in DIS(t_a,W_s^i)$

(DIS$_2$): the service must be retriable iff $failed \notin DIS(t_a,W_s^i)$

Using these two sets, we are able to compute $MIN_{TP}(s_a,t_a,W_s^i) = ATS(W,t_a) \bigcap DIS(t_a,W_s^i)$ which defines the transactional properties a service s_a has at least to comply with in order to be assigned to the task t_a at the *i+1* assignment step. We simply check the retriability and compensatability properties for the set $MIN_{TP}(s_a,t_a,W_s^i)$:

- $failed \notin MIN_{TP}(s_a,t_a,W_s^i)$ iff s_a has to verify the retriability property
- $compensate\ d \in MIN_{TP}(s_a,t_a,W_s^i)$ iff s_a has to verify the compensatability property

The set $ATS(W,t_a)$ is easily derived from *ATS(W)*. We need now to compute $DIS(t_a,W_s^i)$. We assume that we are at the *i+1* step of an assignment procedure, i.e. the current partial instance of *W* is W_s^i. Computing $DIS(t_a,W_s^i)$ means determining whether *(DIS$_1$)* and *(DIS$_2$)* are true. From these two statements we can derive three properties:

1. *(DIS$_1$)* implies that state *compensated* can definitely be reached by t_a
2. *(DIS$_2$)* implies that t_a can not *fail*
3. *(DIS$_2$)* implies that t_a can not be *canceled*

The two first properties can be directly derived from *(DIS$_1$)* and *(DIS$_2$)*. The third one is derived from the fact that if a task can not be *canceled* when a task fails, then it has to finish its execution and reach at least the state *completed*. In this case, if a service can not be *canceled* then it can not fail, which is the third property. To verify whether 1., 2. and 3. are true, we introduce the theorems Theorem 8.3, Theorem 8.4and Theorem 8.5.

Theorem 8.3 The state *compensated* can definitely be reached by t_a iff $\exists b \in [1,n] - \{a\}$ verifying (***8.3b***): s_b not retriable is assigned to t_b and $\exists\ ts_k(W) \in ATS(W)$ generator of t_b such that $ts_k(W,t_a) = compensated$.

Theorem 8.4 t_a can not fail iff $\exists b \in [1,n] - \{a\}$ verifying (***8.4b***): (s_b not compensatable is assigned to t_b and $\exists\ ts_k(W) \in ATS(W)$ generator of t_a such that $ts_k(W,t_b) = compensated$) or ($t_b$ is flexible to t_a and s_b not retriable is assigned to t_b and $\forall\ ts_k(W) \in ATS(W)$ such that $ts_k(W,t_a) = failed$, $ts_k(W,t_b) \neq canceled$).

Theorem 8.5 Let t_a and t_b such that t_a is flexible to t_b. t_a is not *canceled* when t_b fails iff (***8.5b***): s_b not retriable is assigned to t_b and $\forall\ ts_k(W) \in ATS(W)$ such that $ts_k(W,t_b) = failed$, $ts_k(W,t_a) \neq canceled$.

Based on the theorems 8.3, 8.4 and 8.5, in order to compute $DIS(t_a, W_s^i)$, we have to compare t_a with each of the *i* tasks $t_b \in W - \{t_a\}$ to which a service s_b has been already assigned. This is an iterative procedure and at the initialization phase, since no task has been yet compared to t_a, s_a can be of type (*p*): $DIS(t_a, W_s^i) = \{failed\}$.

1. if t_b verifies (***8.3b***) then $compensated \in DIS(t_a, W_s^i)$
2. if t_b verifies (***8.4b***) then $failed \notin DIS(t_a, W_s^i)$
3. if t_b is flexible to t_a and verifies (***8.5b***) then $failed \notin DIS(t_a, W_s^i)$

The verification stops if $failed \notin DIS(t_a, W_s^i)$ and $compensated \in DIS(t_a, W_s^i)$. With $MIN_{TP}(s_a, t_a, W_s^i)$, we are able to select the appropriate service to be assigned to a given task according to transactional requirements.

Service assignment process

Services are assigned to each workflow task based on an iterative process. Depending on the transactional requirements and the transactional properties of the services available for each task, different scenarios can occur:

(i) Services of type *(rc)* are available for the task. It is not necessary to compute transactional requirements as such services match all transactional requirements.

(ii) Only one service is available for the task. We need to compute the transactional requirements associated to the task and either the only available service is sufficient or there is no solution.

(iii) Services of types *(r)* and *(c)* but none of type *(rc)* are available for the task. We need to compute the transactional requirements associated to the task and we have three cases. First, (retriability and compensatability) is required in which case there is no solution. Second, retriability (resp. compensatability) is required and we assign a service of type *(r)* (resp. *(c)*) to the task. Third, there is no requirement.

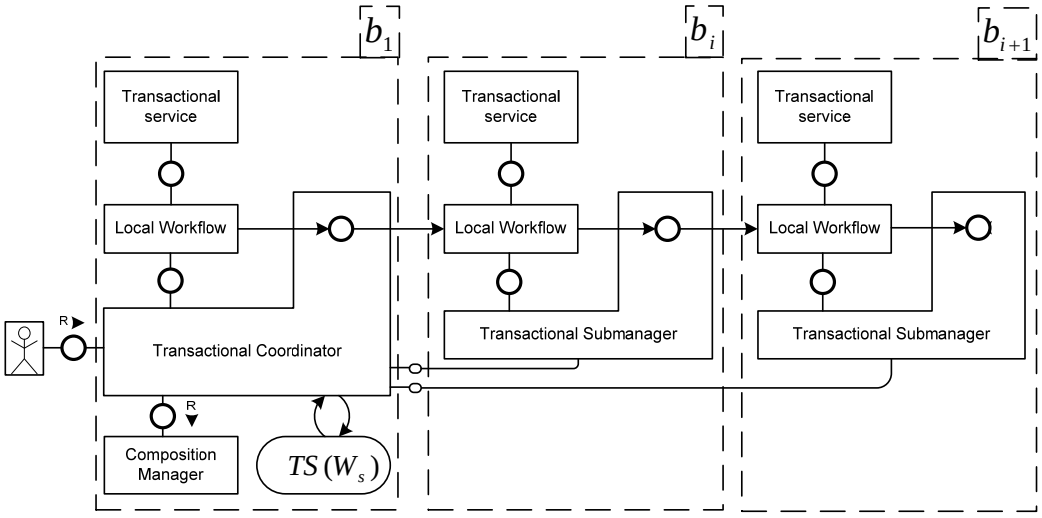


Figure 6: Transactional Architecture

The idea is therefore to assign first services to the tasks verifying *(i)* and *(ii)* since there is no flexibility in the choice of the service. Tasks verifying *(iii)* are finally analyzed. Based on the transactional requirements raised by the remaining tasks, we first assign services to tasks with a non-empty transactional requirement. We then handle the assignment for tasks with an empty transactional requirement. Note that the transactional requirements of all the tasks to which services are not yet assigned are also affected (updated) as a result of the current service assignment. If no task has transactional requirements then we assign the services of type *(r)* to assure the completion of the remaining tasks' execution.

Coordination of W_s

Using the notations introduced so far, we are able to specify the coordination strategy of W_s against each workflow task. We get indeed the following theorem.

Theorem 8.6 Let W_s be an acceptable instance of W with respect to *ATS(W)*. We note $(t_{a_i})_{i\in[1,n_r]}$ the set of tasks to which no retriable services have been assigned.

$$TS(W_s) = \{tscomp(W_s)\} \cup \bigcup_{i=1}^{n_r} \left(CTS(ts_{k_{a_i}}(W), t_{a_i}) - \bigcup_{j=1}^{z_a} FTS(t_{a_{i_j}}, t_{a_i}) \right)$$

Having computed $TS(W_s)$, we can deduce the coordination rules associated to the execution of W_s.

Example

Back to our motivating example, we consider the workflow W_1 of Figure 2. Designers have defined $ATS_2(W_1)$ as the transactional requirements for the considered business application and the set of available services for each task of W_1 is specified in Figure 5. The goal is to assign services to workflow tasks so that the instance of W_1 is valid with respect to $ATS_2(W_1)$ and we apply the assignment procedure presented in section 6.2. We first start to assign the services of type *(rc)* for which it is not necessary to compute any

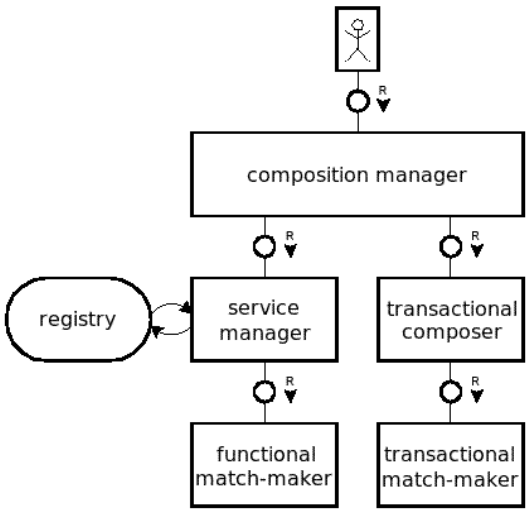


Figure 7: Transactional Web services composition system

transactional requirements. s_{13} which is available for task 1 is therefore assigned without any computation. We then consider the tasks for which only one service is available. This is the case for task 4 for which only one service of type *(p)* is available. We therefore verify whether s_{41} can be assigned to task 4. We compute $MIN_{TP}(s_a, t_4, W_{1s}^1) = ATS_2(W_1, t_4) \cap DIS(t_4, W_{1s}^1)$.

$ATS_2(W_1, t_4) = \{completed, failed\}$ and $DIS(t_4, W_{1s}^1) = \{failed\}$ as s_{13} the only service already assigned is of type *(rc)* and the theorems 8.3, 8.4 and 8.5 are not verified, none the conditions required within these theorems are indeed verified by the service s_{13}. Thus $MIN_{TP}(s_a, t_4, W_{1s}^1) = \{failed\}$ and s_{41} can be assigned to task 4 as it matches the transactional requirements. Now we compute the transactional requirements of task 2 for which services of type *(r)* and *(c)* are available and we get $MIN_{TP}(s_a, t_2, W_{1s}^2) = \{failed\}$. As described in the assignment procedure we do not assign any service to this task as it does not introduce at this step of the procedure any transactional requirements to make a decision on the candidate service to choose. We therefore compute the transactional requirements of task 3 and we get $MIN_{TP}(s_a, t_3, W_{1s}^2) = \{failed, compensated\}$ as theorem 8.3 is verified with the service s_{41} that is indeed not retriable. The service s_{32} which is of type *(c)* can thus be assigned to task 3 as it matches the computed transactional requirements. We come back now to task 2 and compute the transactional requirements once again and we get $MIN_{TP}(s_a, t_2, W_{1s}^3) = \{failed, compensated\}$ as theorem 8.3 is now verified with the service s_{32} which is indeed not retriable. It should be noted that at this step, the transactional requirements associated
to task 2 have been modified because of the assignment of the service s_{32} to task 3. As the service s_{22} matches the transactional requirements it can be assigned to the task.

COORDINATION OF COMPOSITE APPLICATIONS

In this section an implementation of the work presented in this chapter based on Web services technologies is described. The implementation features the transactional coordination of a cross-organizational composite application that is built based on our transaction-aware assignment procedure. To that respect, the business partners involved in the composite application share their services and communicate through local workflow engines that help them manage the overall collaboration in a distributed manner. These workflow engines are based on the BPEL workflow description language. Of course, the services they share may offer various transactional properties as the ones we detailed so far in the chapter. It is thus required to adapt local workflow engines to integrate into the composite application business logic the transactional model we presented in section 8. The system architecture is depicted in Figure 6. In order to support the execution of cross-organizational composite applications, we implemented in the fashion of the WS-Coordination initiative (Langworthy, 2005) a transactional stack composed of the following components:

- **Transactional coordinator**: this component is supported by the composite application initiator. On the one hand it implements the transaction-aware business partner assignment procedure as part of the composition manager module and on the other hand it is in charge of assuring the coordinator role of the transactional protocol relying on the set $TS(W_s)$ outcome of the assignment procedure.
- **Transactional submanager**: this component is deployed on the other partners and is in charge of forwarding coordination messages from the local workflow to the coordinator and conversely.

In the remainder of this section, our implementation is described in terms of the implementation of the transaction-aware partner assignment procedure, the internal communications that take place between the elements deployed on a business partner and the structure that the BPEL processes deployed on each business partner's workflow engine should be compliant with in order to support the coordination protocol execution.

OWL-S transactional and functional matchmaker

To implement the assignment procedure presented in this chapter we augmented an existing functional OWL-S matchmaker (Tang, Liebetruth et al. 2003) with transactional matchmaking capabilities. In order to achieve our goal, the matchmaking procedure has been split into two phases. First, the functional matchmaking based on OWL-S semantic matching is performed in order to identify subsets of the available partners that meet the functional requirements for each workflow vertex. Second, the implementation of the transaction-aware partner assignment procedure is run against the selected sets of partners in order to build an acceptable instance fulfilling defined transactional requirements.

The structure of the matchmaker consists of several components whose dependencies are displayed in Figure 7. The composition manager implements the matchmaking process

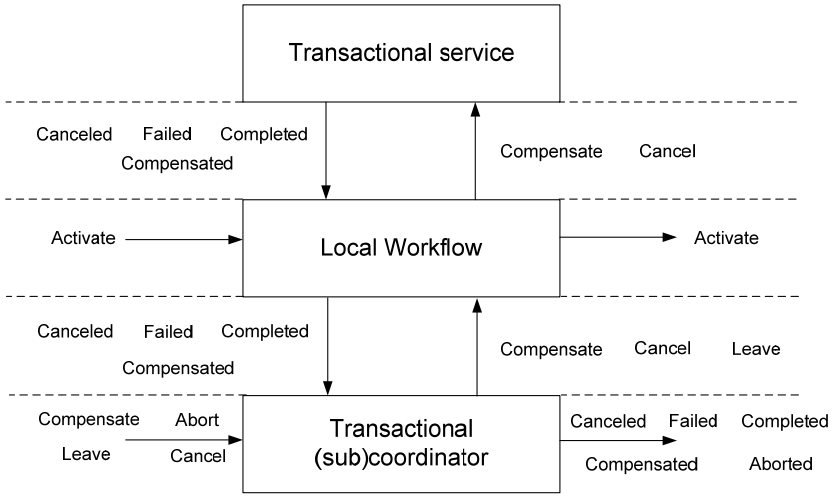


Figure 8: Infrastructure internal communications

and provides a Java API that can be invoked to start the selection process. It gets as input an abstract process description specifying the functional requirements for the candidate partners and a table of acceptable termination states. The registry stores OWL-S profiles of partners that are available. Those OWL-S profiles have been augmented with the transactional properties offered by business partners. This has been done by adding to the non-functional information of the OWL-S profiles a new element called *transactionalproperties* that specifies two Boolean attributes that are retriable and compensatable as follows.

```
<tp:transactionalproperties retriable="true" compensatable="true"/>
```

In the first phase of the selection procedure, the business partner manager is invoked with a set of OWL-S profiles that specify the functional requirements for each workflow vertex. The business partner manager gets access to the registry, where all published profiles are available and to the functional matchmaker which is used to match the available profiles against the functional requirements specified in the workflow. For each workflow vertex, the business partner manager returns a set of functionally matching profiles along with their transactional properties. The composition manager then initiates the second phase, passing these sets along with the process description, and the table of acceptable termination states to the transactional composer. The transactional composer starts the transaction-aware business partner assignment procedure using the transactional matchmaker by classifying first those sets into five groups:

- sets including only services of type *(p)*
- sets including only services of type *(r)*
- sets including only services of type *(c)*
- sets including services of types *(r)* and *(c)*
- sets including services of type *(rc)*

Once those sets are formed the iterative transactional composition process takes place as specified above based on the table of acceptable termination states. Depending on the set of available services and the specified acceptable termination states, the algorithm may terminate without finding a solution.

Internal communications within a business partner infrastructure

In the infrastructure that is deployed on each business partner to implement the transactional protocol presented in this chapter, the transactional coordinator plays the role of interface between the business process and the other business partners when it comes to managing the notification messages exchanged during the execution of the transactional protocol. Some of these messages received by the transactional coordinator should be forwarded to the local business process to take appropriate actions while some others are only relevant to the local transactional (sub)coordinator. The business process may also require to issue a notification to its local transactional (sub)coordinator when a failure occurs. The messages exchanged between these three layers are derived from the state model depicted in Figure 3. The infrastructure deployed on a given business partner basically consists of three layers:

- **The transactional service layer** representing the business partner's available operations,
- **The local workflow layer** corresponding to the local workflow engine,
- **The coordination layer** implementing the local (sub)coordinator module.

The message exchanges that can take place on a given business partner between these three layer are depicted in Figure 8. The set of notification messages that is exchanges between the different components of the infrastructure is basically derived from the transactional model depicted in Figure 4.

- **Activate**: The activate message is basically issued by the local workflow engine to the local workflow engine of the next business partner involved in the workflow. In fact this message instantiates the process execution on the business partner side.
- **Compensate, Cancel**: The compensate and cancel messages are received at the coordination layer and forwarded to the local workflow layer that forwards them in a second time to the transactional service layer to perform to corresponding functions i.e. compensation or cancellation of an operation.
- **Compensated, Canceled, Completed**: These messages simply notify that the corresponding events have occurred: compensation, cancellation, or completion of an operation. Issued at the transactional service layer, they are forwarded to the coordination layer in order to be dispatched to the composite application coordinator.
- **Failed**: Issued at the transactional service layer, the failed message is forwarded to the coordination layer in order to be dispatched to the composite application coordinator. If the operation performed at the transactional service layer is retriable, no failed message is forwarded to the local workflow layer as we consider that the retry primitive is inherent to any retriable operation.

- **Abort, Aborted**: The abortion message is received at the coordination layer and acknowledged with an aborted message. Upon receipt of this message, the business simply leaves the composite application execution; no message is forwarded to the other layers since the local workflow has not yet been instantiated.
- **Leave**: The leave message is received at the coordination layer and the business partner can leave the execution of the composite application execution. The leave message is forwarded to the local workflow layer if the business partner implements an operation that is compensatable. In this case, the business process deployed on the local workflow engine indeed has two possible outcomes, either the results produced by its task are compensated or it can leave the process execution.

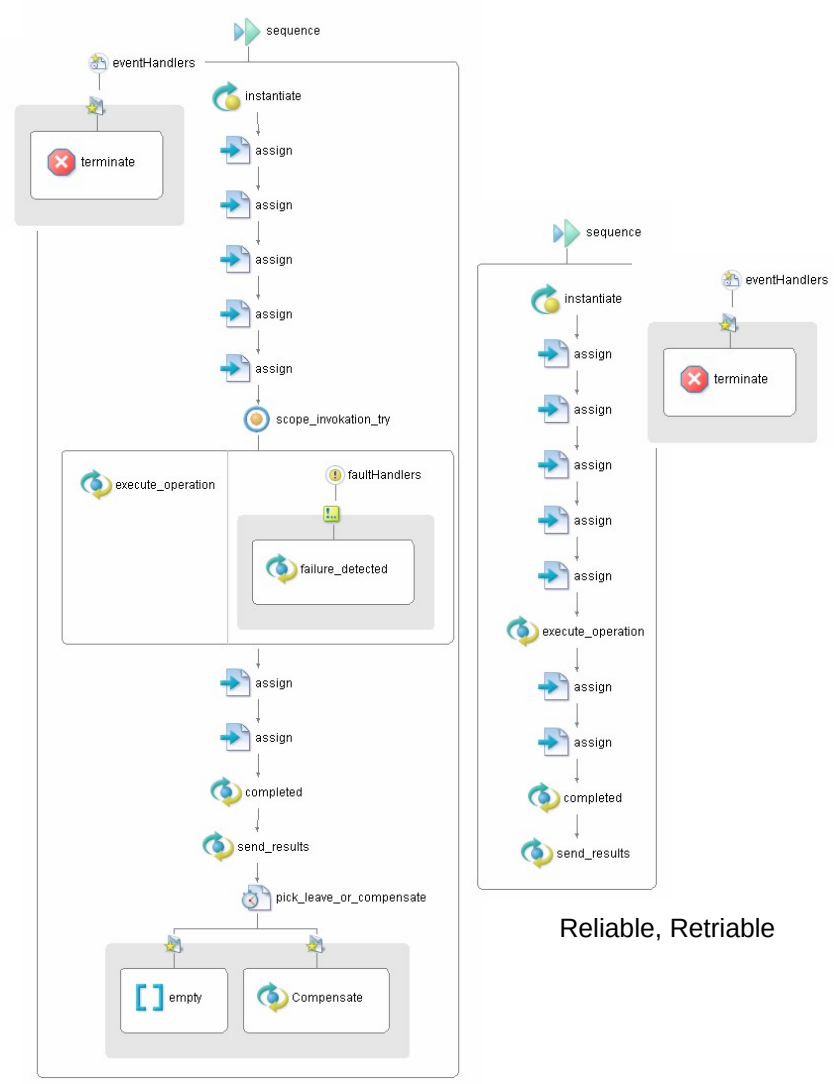


Figure 9: Transactional BPEL processes (Process graphs from ActiveBPEL engine)

Specification of Transactional BPEL processes

In our implementation, the local workflow engine is implemented using BPEL as the workflow specification language. In order to support the message exchanges identified in section 9.2 the structure of BPEL business processes has to match some templates that we describe in this section. Using the constructs available in the BPEL language, the specification of these transactional BPEL processes is straightforward.

The business process activation is performed using the usual BPEL process instantiation construct `<receive>` described as follows.

```
<receive createInstance="yes" operation="launch" partnerLink="PLT"
         portType="PT" variable="Data">
    <correlations>
      <correlation initiate="yes" pattern="in" set="CS1"/>
    </correlations>
</receive>
```

The cancel message can be received at any moment during the execution of the process and is thus handled using the `<eventHandlers>` construct as follows. Of course the BPEL process has to expose a dedicated operation to receive the cancel message.

```
<eventHandlers>
  <onMessage partnerLink="PLT" portType="PT"
             operation="Cancel" variable="workflowid">
      <correlations>
        <correlation set="CS1"/>
      </correlations>
    <terminate/>
  </onMessage>
</eventHandlers>
```

In order to detect the failure of an operation that is not retriable, the `<scope>` and the `<faultHandlers>` constructs are used as follows. The failure of the operation is forwarded to the transactional coordination layer inside the `<faultHandlers>`.

```
<scope name="invokation_try">
  <faultHandlers>
    <catchAll>
       <invoke inputVariable="failedid" name="1"
               operation="transacFailed" partnerLink="PLT"
               portType="LocalAdminImpl"/>
    </catchAll>
  </faultHandlers>
  <invoke inputVariable="DataInc" outputVariable="DataOut"
          name="invoke1" operation="Addition"
          partnerLink="PLT" portType="Add">
  </invoke>
</scope>
```

Finally, if the business process implements an operation that is compensatable, the process execution can lead to two possible outcomes depending on whether a compensate

or a leave message is received. We use the <pick> construct to express this choice as follows.

```
<pick>
  <onMessage partnerLink="PLT" portType="publicPT"
             operation="Leave" variable="workflowid">
    <correlations>
      <correlation set="CS1"/>
    </correlations>
    <empty/>
  </onMessage>
  <onMessage partnerLink="PLT" portType="PT"
             operation="Compensate" variable="workflowid">
    <correlations>
       <correlation set="CS1"/>
    </correlations>
    <invoke inputVariable="serviceid" name="invoke1"
            operation="Compensate"
            partnerLink="PLT" portType="Add"/>
  </onMessage>
</pick>
```

It should be noted that in the listings depicted in this section, we use BPEL correlation sets because the coordination messages are received asynchronously during the process execution and need to be mapped to the appropriate instance of the workflow to be processed by the engine. These BPEL listings can be combined in the design of transactional BPEL processes depending of course on the transactional properties offered by business partners. Two examples of transactional BPEL processes are depicted in Figure 9. For instance, if the task executed by a business partner is not compensatable, the associated BPEL process only ends with the completed notification since it is not required to wait for a leave message. Similarly, a task which is retriable is not surrounded by <scope> constructs as there is no fault to catch.

CONCLUSION

We presented an adaptive transactional protocol to support the execution of cross-organizational composite applications. This approach actually meets the requirements that are relevant to assuring consistency of the execution of cross-organizational processes which are mainly twofold:

- **Relaxed atomicity**: atomicity of the workflow execution can be relaxed as intermediate results produced by the workflow may be kept intact despite the failure of one partner.
- **Dynamic selection of business partners**: the execution of cross-organizational workflows may require the execution of a composition procedure wherein candidate business partners offering different characteristics are assigned to tasks depending on functional and non-functional requirements associated with the workflow specification.

The execution of the protocol we proposed takes place in two phases. First, business partners are assigned to workflow tasks using an algorithm whereby partners are selected based on functional and transactional requirements. Given an abstract representation of a process wherein business partners are not yet assigned to workflow tasks, this algorithm enables the selection of partners not only according to functional requirements but also to transactional ones. The resulting workflow instance is compliant with the defined consistency requirements and its execution can be easily coordinated as our algorithm also provides coordination rules. The workflow execution further proceeds through a hierarchical coordination protocol managed by the workflow initiator and controlled using the coordination rules computed as an outcome of the partner assignment procedure. This transactional protocol thus offers a full support of relaxed atomicity constraints for workflow-based applications and is also self-adaptable to business partners' characteristics.

Besides, a complete transactional framework based on the Web services technologies has been implemented as a proof of concept of our theoretical results. On the one hand the business partner assignment procedure we designed can be used to augment existing composition systems (Agarwal, Dasgupta, et al. 2005) as it can be fully integrated in existing functional match-making procedures. On the other hand, our approach defines adaptive coordination rules that can be deployed on recent coordination specifications (Langworthy, 2005) in order to increase their flexibility.

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