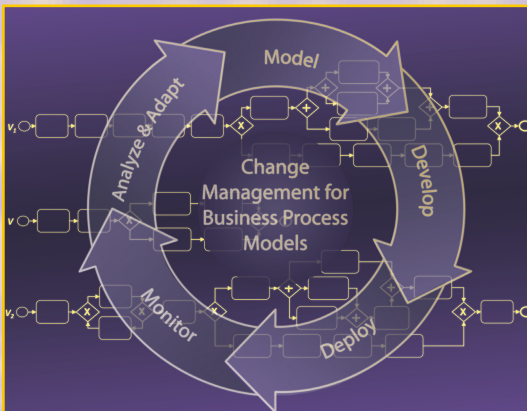


Christian Gerth

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Change Management



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Christian Gerth

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The image on the front cover was created by Inga Gerth in 2013. It shows the main activities in Business-Driven Development (BDD) [Mitra, 2005, Koehler et al., 2008], which is a software engineering methodology with a strong focus on a close alignment of business and IT requirements.

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*To my wife, Inga,
my children, Frieda, Laurens & Martha,
and my parents, Gudrun & Peter.*

Foreword

Procedures and processes determine our daily lives. Every day, we come across regularly repeating sequences in which we, e.g., organize our household, do our job, or are active in sports in our spare time. Depending on the process and goal, we prepare breakfast, handle customer requests, produce products, or attend the gym's personal training. These activities are always guided by a number of rules that are either pre-defined or have evolved over time. When cooking, we call these rules "recipes," at work they are called "instructions," and in the gym they are called "training programs." On the level of enterprises, we are talking about business process models.

Also in software engineering, business process models are leveraged for the development of software systems. For instance, the tasks that should be performed by a software system are specified in terms of process models, in order to understand them more precisely and to ensure that they are implemented correctly. Models of business processes are created when the processes of a company are determined in discussion with a client and are mapped onto a process model. These business process models constitute key business and process knowledge and provide a significant added value for the company. As a consequence, from a business perspective it is important to specify process models precisely and to maintain as well as improve them continuously, to ensure their sustainable usability in the company. In the business world, we speak in this context of change management for business process models.

In our modern working world with its global engagement and complex software systems, this task is typically performed by teams of people in distributed work environments. Thereby, several different versions of a process model may be created owing to individual modifications applied by different people. During an improvement step of a process model, these different versions may temporarily exist in parallel. However, after the completion of the step, the different versions must be merged into a unique and improved reference process model version. For this purpose, differences, dependencies, and conflicts between the different process models must be detected and resolved in the merged process model. This well-known problem in the field of software configuration management is largely solved for textual documents and appropriate tools support the development of software systems in daily

business. In the case of (graphical) models and in particular for process models, previously no adequate solution existed.

Christian Gerth uniquely addresses this problem of change management for business process models in his dissertation. In order to support the merging of process models that can be modeled in different languages, he first developed a normalized representation for process models. This language-independent intermediate representation specifies process models at a higher level of abstraction. On the intermediate representation, Mr. Gerth defined change operations for process models and described differences between process models using these operations.

For the detection of change operations, he developed a method that is also capable of detecting composite changes, i.e., sequences of operations, which can be traced back to atomic change operations. The set of change operations detected between two process model versions describe the differences between these versions, and can directly be used to merge them. In the next step, Christian Gerth evaluated whether dependencies in the set of change operations between process model versions are present and developed a method for their automated detection. For that purpose, he used techniques from the theory of parallel graph transformations and transferred them to his task. Subsequently, he examined what types of conflicts can arise in a team-oriented, i.e., parallel development of process models and how these conflicts can be discovered and resolved during the merging of different process model versions. To this extent, he compared process models semantically and used the obtained results to identify syntactically different but semantically equivalent process models. Also here, Mr. Gerth developed a novel solution by transferring existing theoretical results, in this case from the area of term rewriting systems, to his problem at hand and applied them with a new focus.

The results achieved by Mr. Gerth are not only of a high scientific value, but also of great practical, industry-relevant value. This fact is demonstrated impressively by the very successful collaboration with IBM Research - Zurich (CH), which led, among other things, to four patent applications, and the contribution of major parts of the work to the Compare & Merge framework for the “IBM WebSphere Business Modeler” (Version 7.0), which was released as an IBM product. The main findings of the dissertation have been published in conference proceedings of high-ranking scientific conferences and for their high quality received a “Best Paper Award” twice.

Overall, Christian Gerth has shown with his dissertation and its contained scientific results an above average excellence. He has worked on the largely unsolved problem of change management for business process models comprehensively as well as completely and has developed a sophisticated, practically usable solution. He described his solution in a very clear and easy to understand structure, which consists of a series of partial solutions that build on each other. He has shown that he has a broad knowledge in the practical and formal modeling world and is able to use existing (theoretical) results for his work. Mr. Gerth has proven with his dissertation that he can advance the scientific field of software engineering originally.

Gregor Engels

Acknowledgments

My dissertation and this resulting book were developed and written at the University of Paderborn in the Database and Information Systems research group of Prof. Dr. Gregor Engels in cooperation with the IBM Research - Zurich laboratory.

Although only my name is on the front cover of this dissertation, a great many people supported me in this venture. I would like to thank the following people for sharing their experience, time, and patience.

I owe my deepest gratitude to my advisor, Prof. Dr. Gregor Engels, who is a great source of inspiration. Gregor, I really appreciate the prosperous environment you offered me by giving me the freedom to explore on my own and at the same time providing guidance when I was lost. I would like to express my gratitude to Prof. Dr. Gerti Kappel and Prof. Dr. Wilhelm Schäfer for examining my dissertation as reviewers. Further, I thank Prof. Dr. Leena Suhl, Dr. Jochen Küster, and Dr. Theodor Lettmann for being members of my doctoral committee.

I am heartily thankful to my industrial supervisor Dr. Jochen Küster from IBM Research - Zurich. Jochen, I thank you for your encouragement in teaching me how to work scientifically. I am really grateful for your endless practical advice and our chats on and off the topic. I am also thankful to all members of the Business Integration Technologies group for making my time with IBM Research in Zurich so pleasant and successful. I thank my manager Dr. Jana Koehler for her continual support and her valuable feedback.

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Apart from my scientific and professional environment, it would have been next to impossible to write this book without the support of my family. I thank my parents for their unconditional love, for giving me the opportunity to study, and for making me believe that I can achieve anything I want.

The greatest thanks go to my wife and my three kids. Frieda, Laurens, and Martha, thank you for showing me that there are “even” more important things than a dissertation. Most important, I would like to thank my wife, Inga, for standing all my moods during the course of this work and for putting things into perspective — you let the sun shine in me!

Finally, I appreciate the financial support from the International Graduate School of Dynamic Intelligent Systems at the University of Paderborn that funded parts of the research discussed in this book.

Abstract

In recent years, the role of process models in the development of enterprise software systems has increased continuously. Today, process models are used at different levels in the development process. For instance, in service-oriented architectures (SOA), high-level business process models become input for the development of IT systems, and in running IT systems executable process models describe choreographies of Web services. A key driver behind this development is the necessity for a closer alignment of business and IT requirements, to reduce the reaction times in software development to frequent changes in competitive markets.

Typically in these scenarios, process models are developed, maintained, and transformed in a team environment by several stakeholders that are often from different business units, resulting in different versions. To obtain integrated process models comprising the changes applied to different versions, the versions need to be consolidated by means of model change management. Change management for process models can be compared to widely used concurrent versioning systems (CVS) and consists of the following major activities: matching of process models, detection of differences, computation of dependencies and conflicts between differences, and merging of process models.

Although in general model-driven development (MDD) is accepted as a well-established development approach, there are still some shortcomings that let developers decide against MDD and opt for more traditional development paradigms. These shortcomings comprise a lack of fully integrated and fully featured development environments for MDD, such as a comprehensive support for model change management.

In this book, we present a framework for process model change management. The framework is based on an intermediate representation for process models that serves as an abstraction of specific process modeling languages and focuses on common syntactic and semantic core concepts for the modeling of workflow in process models. On the basis of the intermediate representation, we match process models in versioning scenarios and compute differences between process models generically. Further, we consider the analysis of dependencies between differences and

show how conflicts between differences can be computed by taking into account the semantics of the modeling language.

As proof-of-concept, we have implemented major parts of this framework in terms of a prototype. The detection of differences and dependencies contributed also to the Compare & Merge framework for the IBM WebSphere Business Modeler V 7.0¹ (WBM), which was released as a product in fall 2009.

¹ <http://www.ibm.com/software/integration/wbimodeler/entry/>

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Introduction

In this chapter, we give a detailed motivation for the work presented in this book and point out our research goals and contributions. At the end of the chapter, we give a structural overview of the book.

1.1 Motivation and Problem Statement

Business Process Management (BPM) is a management approach that comprises the creation, development, maintenance, and optimization of business processes in enterprises and institutions. A business process is a collection of ordered tasks that need to be carried out to achieve a certain business goal, such as the production of a product or a service delivery. Tasks within a business process may represent activities that are performed manually by a human or automatically by an IT system. The focus of BPM is the automation and optimization of business processes as well as the support of human interaction with the use of information technologies.

BPM consists of different phases, such as analysis, design, implementation, deployment, monitoring, and evaluation [Dumas et al., 2005]. In the analysis and design phases, a business case is analyzed and a desired solution is modeled. Then, the solution is implemented and executed in an existing environment (implementation and deployment phase). The running solution is controlled in the monitor phase and the solution is adapted for continuous improvement during the evaluation phase.

In BPM, business processes of an enterprise are represented in terms of process models capturing the business logic that shall be automated. A process model comprises a set of activities connected by edges that determine the order in which the activities are performed. Process models can be specified visually or textually. Figure 1.1 shows a visual process model from the banking domain in the Business Process Model and Notation (BPMN) [OMG, 2011a]. The process model describes the necessary steps to open an account for a customer in a bank. *Record Customer Data*, *Compute Customer Scoring*, and *Prepare Bank Card* are examples for activities, where *Record Customer Data* may be an example for an activity that is performed manually by a bank clerk and the latter activities may be examples for

automatically performed activities. The activities in the process model are connected by edges that indicate their execution order.

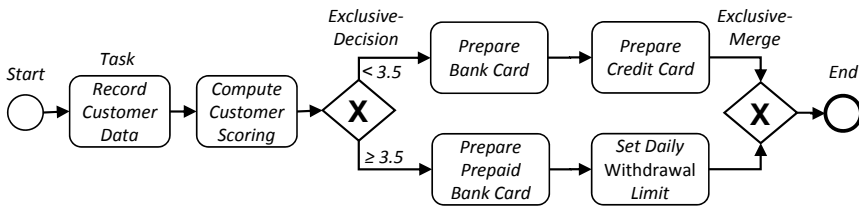


Fig. 1.1 Process Model describing the Opening of a Banking Account

For the development of IT solutions that support the automation of business processes, typically model-driven software development approaches are applied. In these approaches, business process models are used at different levels in the development process. For instance in Service-Oriented Architectures (SOA), high-level business process models become input for the development of IT systems and in running IT systems executable process models describe choreographies of Web Services [Zimmermann et al., 2003]. Business-Driven Development (BDD) [Mitra, 2005] is a paradigm towards the development of SOAs that starts with high-level business processes, which are stepwise refined until they are executable. A key driver behind this development is the necessity for a closer alignment of business and IT requirements, in order to reduce the reaction times in software development to frequent changes in competitive markets.

Similar to other artifacts in development, business process models underlie constant change. That means, process models are created and refined by different business modelers and software architects in distributed environments. This results in different versions reflecting the different views of the involved stakeholders. At some point in time, different versions of a process model have to be compared and merged with each other to obtain an integrated version by means of *process model change management*. The aim of process model change management is to provide a systematic approach for the consistent development of process models. To that extent, process model change management comprises different activities, such as model matching, difference detection, and model merging by resolving differences between process model versions.

In scenarios, where running process models shall be merged that are already executed by a business process execution engine, additionally the state of the process execution must be considered [Rinderle et al., 2004, Rinderle et al., 2006, Reichert and Dadam, 2009]. For instance, to ensure that currently executed activities are not modified by a difference resolution.

In the remainder, we focus on process model change management that is used during design time to merge process models that are not executed yet, similar to widely used software version and configuration management (SCM), e.g. concurrent versions systems [CVS, 2011] (CVS) or Subversion [Subversion, 2011]

for textual documents. Analogously to the merging of textual documents, process model change management is a prerequisite to enable *optimistic version control* [Mens, 2002], i.e. business modelers can work independently on their own version. However, in contrast to textual documents that are compared syntactically line by line, the comparison and merging of business process models must consider the graph-like structure of process models.

Change management of process models may also be beneficial in case of process mining approaches, where reference process models are discovered based on an analysis of versioning logs [Kindler et al., 2006, Kindler et al., 2005] of SCM systems or by analyzing changes applied to different process versions [Li et al., 2009]. In order to improve existing process models, the discovered reference process models are merged with existing process models by means of change management.

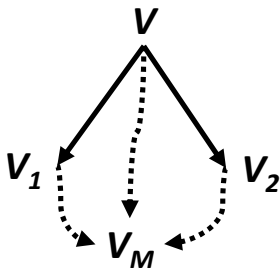


Fig. 1.2 Scenario Overview

An overview of a process model change management scenario is given in Figure 1.2. The merging of different versions of a process model into an integrated version is a classical 3-way merge scenario. The integrated version V_M incorporates the changes, which were applied to the different versions V_1 and V_2 . For that purpose, we have to consider the changes between the source process model V and the two versions V_1 and V_2 . V_M is then created by applying a subset of the changes that were applied to achieve V_1 and V_2 . Figure 1.3 gives a concrete example. In the middle of the figure, the process

model V from Figure 1.1 is shown again together with two versions V_1 and V_2 . We consider V as the source process model that was created first and afterwards V was individually refined by different users into the versions V_1 and V_2 .

Before the process model versions can be merged into an integrated version V_M , the versions need to be matched. Model matching is concerned with the identification of corresponding elements between two models. The result of a matching is a mapping that links related elements between models. In the trivial case, matching can be based on equal model element identifiers. If equal identifiers are not available, matching is based on the similarity of other characteristics of model elements such as their name, their path, and/or their environment.

Based on a mapping, differences between models can be identified. If a change log exists that records applied model modifications, differences between model versions are already given and do not need to be identified. However, in typical business process modeling scenarios, no change log is available that records changes applied to different model versions. Reasons for this are the use of different modeling tools by different stakeholders and the distributed environment of large software development projects. As a consequence, different versions of a process model need to be compared to identify differences between the versions before they can be merged. To ease the understandability, for each detected difference, appropriate change

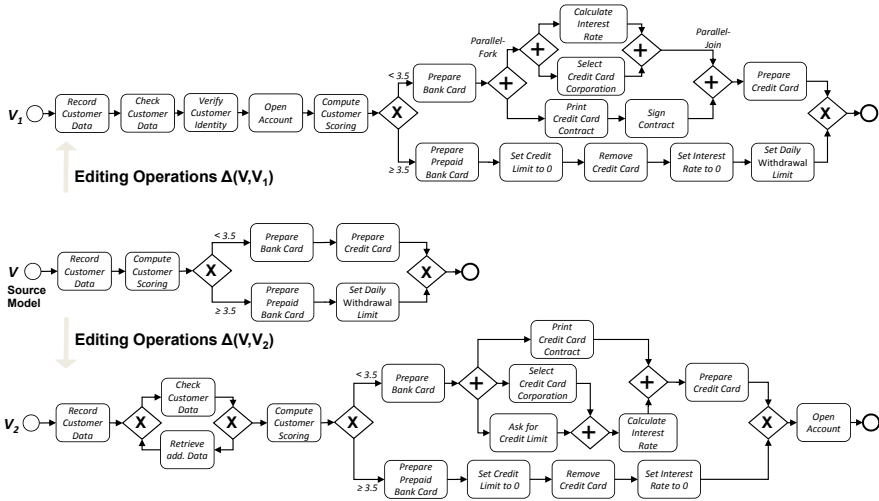


Fig. 1.3 Different Versions of a Business Process Model

operations have to be derived that shall be close to the intended meaning of the change that caused the difference.

To enable a high degree of automation within merging of different process model versions, it is important to understand dependencies and conflicts of changes. Informally if two changes are dependent, then the second one requires the application of the first one. If two changes are in conflict, then only one of the two can be applied. As a consequence, an approach for computing dependent and conflicting differences is required.

A further challenge arises from the fact that change management is a modeling language-dependent problem, i.e. a solution for a particular process modeling language cannot be reused easily for another language, due to different syntax and semantics of the languages. This is in particular important, since a multitude of well-established modeling languages for process models exist: The de-facto standard for process modeling is the Business Process Model and Notation (BPMN) [OMG, 2011a]. Very popular in the industrial context is the Business Process Execution Language (BPEL) [OASIS, 2007]. Using the Unified Modeling Language (UML) [OMG, 2010a], process models are supported by UML Activity Diagrams (UML-AD) [OMG, 2010b]. These examples just present three languages to model business processes and are not meant to be exhaustive. Further examples include Event-driven Process Chains (EPC) [Keller et al., 1992], Yet Another Workflow Language (YAWL) [van der Aalst et al., 2005], or XML Process Definition Language (XPDL) [WFMC, 2005].

At present, existing approaches do not effectively support change management of process models. Typical solutions provide support for model change management for a broad range of models, e.g. for MOF-based models [Alanen and Porres, 2003], for UML models [Ohst et al., 2003, Kelter et al., 2005], or for Ecore-based models

[Eclipse Foundation, 2011c, Westfechtel, 2010, Kögel et al., 2010]. These solutions do not distinguish between specific model types, such as structural or behavioral models. The flexibility by being applicable to different model types on the one hand, comes with disadvantages when model-specific features are important, which is the case in process model change management. First of all, model-independent approaches are based on the syntax of models and do not consider the semantics of specific modeling languages. Thereby, differences can only be considered on an elementary level, since composite differences require knowledge about the semantics of the underlying modeling language. Elementary differences are not intuitively understandable and harden the dependency and conflict analysis.

In summary, to leverage the advantages of business process models in model-based development approaches, the entire life cycle of business process models needs to be addressed effectively and efficiently. To that extent, a suitable solution for process model change management is required that supports the development and evolution of process models in distributed environments. Such a solution needs to address the following problems:

- Differences between different process models must be identified in a suitable granularity that is intuitively understandable to different stakeholders in software development projects.
- To enable a high degree of automation within merging of different process model versions, it is important to identify dependencies and conflicts of differences.
- Due to the variety of different process modeling languages, a change management solution shall be generally applicable to process models in commonly used modeling languages, such as BPMN [OMG, 2011a], UML Activity Diagrams [OMG, 2010b], and BPEL [OASIS, 2007].

In this book, we introduce a comprehensive approach to change management of process models that tackles these problems. Parts of the presented works were developed during my time at IBM Research - Zurich (Switzerland), where I worked in the Business Integration Technologies (BIT) group led by Dr. Jana Koehler.

An overview of our proposed solution together with our research contributions is presented next.

1.2 Solution Overview and Research Contribution

An overview of our solution for process model change management, addressing the described problems, is sketched in Figure 1.4. The framework consists of seven main components, which are described in Chapters 3-10 of this book.

First, process models modeled in a specific process modeling language, such as the BPMN or BPEL, are abstracted to an intermediate representation (IR) to enable a language-independent comparison. In the matching component, corresponding model elements between process models in the IR are identified, resulting in a mapping of the process models. Then, different options for difference representations are evaluated and a suitable solution for difference representation based on

compound change operations is selected. Based on the IR, differences, dependencies, and conflicts are computed in Components 3-6. In Component 7, IR differences are translated into differences for the concrete modeling language of the original process models, which can then be resolved in order to merge the process models.

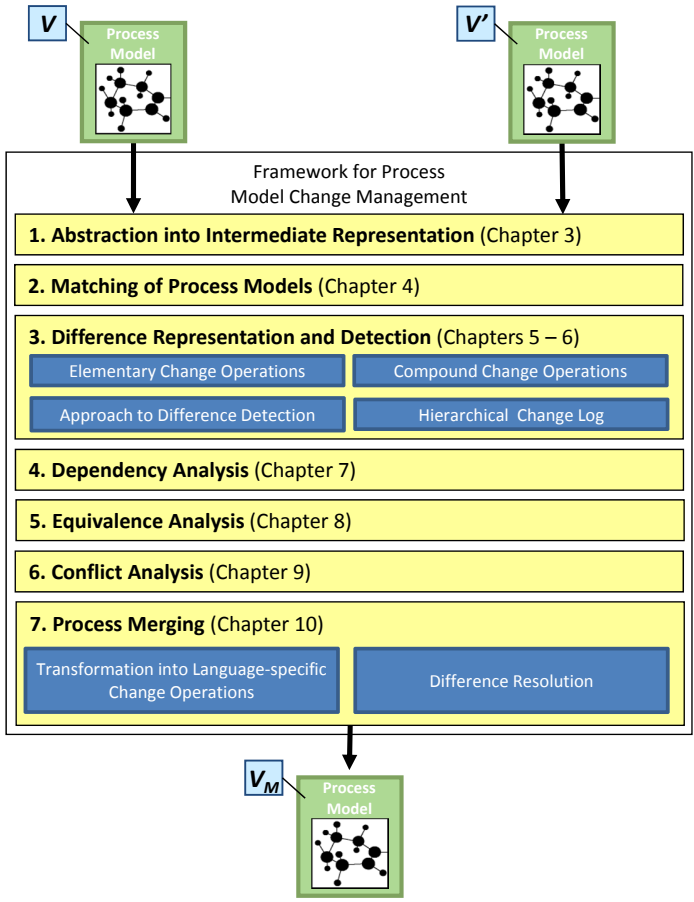


Fig. 1.4 Framework for Process Model Change Management

Tool support is implemented in terms of prototypes for most of the components in the framework. To prove the applicability of our approach, we have instantiated the framework for models in the Business Process Model and Notation (BPMN) [OMG, 2011a] and models in the Business Process Execution Language (BPEL) [OASIS, 2007]. Parts of this work contributed also to the Compare & Merge framework for WebSphere Business Modeler V 7.0, which was released as an IBM product in fall 2009.

In the following, we briefly describe the individual components of the framework and point out our research contributions.

1. *Process Model Abstraction into Intermediate Representation (Chapter 3)*

In general, process model merging is a modeling language-dependent problem. That means, a solution for a particular process modeling language cannot be reused easily for another language, due to different syntax and semantics of the languages. However, to make our approach applicable to models in different modeling languages, we propose a so-called intermediate representation (IR) that serves as an abstraction of process models in concrete modeling languages. Based on the IR, we compute differences between process models and identify dependencies as well as conflicts between the differences on a language-independent level. The IR is defined by a meta-model that contains key concepts of process modeling languages and ignores syntactic redundancies of semantically equivalent concepts. We specify the semantics of the IR in a formal way using Dynamic Meta Modeling (DMM) [Engels et al., 2000]. DMM is based on graph transformations [Ehrig et al., 1999] that are used to describe how instances of a meta model change over the time.

Further, to align graph-oriented and block-oriented process modeling languages [Mendling et al., 2006], the IR decomposes process models into fragments. Therefore, we adapted the decomposition approach for process models [Vanhatalo et al., 2007] and refined the set of canonical fragments for the purpose of process merging. Finally, we present a mapping from Business Process Model and Notation (BPMN) [OMG, 2011a] to the IR. The main contributions are as follows:

- An *intermediate language definition* in terms of a meta-model that serves as an abstraction of existing process modeling languages;
- A *formal semantic specification* of the intermediate representation based on Dynamic Meta Modeling (DMM) [Engels et al., 2000];
- A *decomposition of process models* into suitable fragments for process merging;
- A *mapping* of a subset of the Business Process Model and Notation (BPMN) elements to the intermediate language definition.

2. *Process Model Matching (Chapter 4)*

For the comparison of process models the knowledge about corresponding model elements is required. For that purpose, we provide individual matching strategies for models in the intermediate representation. In our stepwise approach, we combine textual, structural as well as semantic matching approaches to identify corresponding model elements as well as corresponding fragments between models in the intermediate representation. For process model matching, the main contributions are as follows:

- *Matching strategies* to identify corresponding model elements based on syntax and semantics of process models;
- An approach to *match process model fragments* based on their position in the process model and their type (sequential, parallel, alternative, ...).

3. *Difference Representation and Detection (Chapter 5 and Chapter 6)*

Typically in distributed scenarios, modifications applied to process models are not logged, requiring that differences must be identified in order to merge different process model versions to obtain integrated process models. For the representation of differences, we introduce two different approaches based on change operations. We evaluate the suitability of both difference representations for change management of process models with respect to a set of requirements and show that a difference representation based on compound change operations is advantageously. Compound change operations cover the insertion, deletion, and movement of single model elements as well as fragments. Thereby, they comprise several elementary changes, such as the insertion or deletion of edges, and take care that the process model stays connected. We show that the granularity of compound change operations is suitable for effective process model merging.

Further, we propose an approach to difference detection between process models that results in a reconstructed change log consisting of compound change operations. The main contributions are as follows:

- A *difference model* comprising a set of *compound change operations* that is required and sufficient to merge process models;
- An approach for the *detection of differences* between process models based on the intermediate representation and their representation in terms of compound change operations.

4. *Dependency Analysis of Compound Change Operations (Chapter 7)*

When a process model is modified by applying change operations, dependencies between applied change operations may arise. Informally, two change operations depend on each other if the application of the second operation requires the application of the first one. Before versions of a process model can be merged, these dependencies between change operations need to be detected. To that extent, we first capture each of our compound change operations as a model transformation and then compute critical pairs [Bottoni et al., 2000, Hausmann et al., 2002, Heckel et al., 2002], which can be used for detecting dependent transformations. Dependencies obtained by a critical pair analysis heavily depend on the order in which change operations were applied during the development of the underlying process model. To improve the dependency computation for process merging, we introduce the concept of dynamically specified change operations that reduces the number of dependencies and enables an arbitrary application order of change operations during the merging of process models.

Further, we show how dependencies between change operations can be efficiently computed by leveraging information about the hierarchical structure of the underlying process models. The main contributions are as follows:

- A definition of *dependency* for compound change operations and an approach to compute dependencies between compound change operations;

- A *formalization* of change operation for process models in terms of *model transformations*;
- An approach for the *dynamic specification of change operations* that enables an arbitrary application order when change operations are applied to merge process models.

5. *Equivalence Analysis of Process Models (Chapter 8)*

When compound change operations are applied on different process model versions, it may happen that individually applied changes result in syntactically different process model versions, which are semantically equivalent. Change operations that result in semantically equivalent process models (or substructures of process models) must be identified before different versions of a process model can be merged. For that purpose, we propose an approach for deciding equivalence of business process models and individual parts of them. Our approach is based on a term representation of process models and a term rewriting system, which can be used to reduce syntactically different but semantically equivalent process models to the same syntactical representation. The main contributions for conflict analysis are as follows:

- A *term representation of business process models* together with a *term rewriting system* that enables the efficient identification of semantically equivalent process models and fragments;
- A *normalization of process models* and their contained fragments into their normal form, which is free of syntactic redundancies.

6. *Conflict Analysis of Compound Change Operations (Chapter 9)*

In scenarios, where process models are developed independently by different users, different versions of a single process model are obtained. Change operations that were applied to these versions might be conflicting. Informally, two change operations are in conflict if only one of the two operations can be applied in the merged process model. Conflicts between change operations must be detected before multiple versions of a process model can be merged, since they require user intervention and cannot be applied automatically.

The identification of conflicts can be performed syntactically by analyzing the structure of the models and/or by comparing change operations, e.g. using a conflict matrix [Mens, 2002]. However, conflict detection that is solely based on syntactic features of process models potentially results in false-positive conflicts. That is, two changes are detected as being conflicting, although the application of the changes results in semantically equivalent structures. To address these issues, we propose a method that combines syntactic and semantic detection techniques for conflicting change operations and results in a precise set of conflicts. The main contributions for conflict analysis are as follows:

- A definition of *syntactic* and *semantic conflict* between compound change operations;
- A method for the detection of *precise conflicts* between change operations by taking the semantics of the change operations into account.

7. *Merging of different Process Model Versions and Tool Support (Chapter 10 and Chapter 11)*

Compound change operations together with dependencies and conflicts between them constitute a change log. Such a change log determines the differences between two process models in the IR precisely. However, to merge the underlying process models in their concrete process modeling language, the general compound change operations need to be translated back into concrete change operations of the original modeling language. To that extent, we propose an iterative approach that translates IR change operations to their corresponding concrete change operations.

Based on the concrete compound change operations, we then merge process models by applying change operations contained in the hierarchical change logs, which we have reconstructed in the previous components. For that purpose, we present an approach to apply non-conflicting change operations and additionally provide different strategies for the resolution of conflicts between compound change operations.

As an initial evaluation of our solution for process model change management, we have implemented a prototype of our framework for models in the Business Process Model and Notation (BPMN) and models in the Business Process Execution Language (BPEL). Both solutions share approximately 85 % of their code.

The main contributions are as follows:

- An approach for the *translation of IR compound change operations* into language-specific change operations for a concrete modeling language;
- An approach for the *application of non-conflicting change operations* and the *resolution of conflicting compound change operations*;
- A prototypic *implementation of our solution for process model change management*.

1.3 Publication Overview

Most of the presented contributions in this book have been published as peer-reviewed papers at various international conferences. An overview of these papers is given in Figure 1.5. There, our publications are categorized according to the components of our framework (cf. Figure 1.4) to clarify how they are connected to our solution. In the following, we briefly summarize our publications in chronological order.

In 2008, we demonstrated our tool support for business process merging at the 20th International Conference on Advanced Information Systems Engineering (CAiSE'08) [Küster et al., 2008a] and we presented an approach to difference detection between process models in the absence of a change log at the 6th International Conference on Business Process Management (BPM'08) [Küster et al., 2008b].

In [Küster et al., 2009], we published a first approach for the computation of dependencies and conflicts based on syntactical features of change operations and the underlying process models, which was presented at the 5th European Conference on Model-Driven Architecture Foundations and Applications (ECMDA-FA'09).

Peer-reviewed papers	
Dependency and Conflict Analysis of Change Operations	Softw. and Systems Modeling - [Gerth et al., 2011a] <i>Detection and Resolution of Conflicting Change Operations in Version Management of Process Models</i>
	MODELS'10 - [Gerth et al., 2010a] ☆ ☆ <i>Precise Detection of Conflicting Change Operations using Process Model Terms</i>
	ECMFA'10 - [Küster et al., 2010] <i>Dynamic Computation of Change Operations in Version Management of Business Process Models</i>
	ECMDA-FA'09 - [Küster et al., 2009] <i>Dependent and Conflicting Change Operations of Process Models</i>
Equivalence Analysis	SCC'10 – [Gerth et al., 2010b] ☆ <i>Detection of Semantically Equivalent Fragments for Business Process Model Change Management</i>
Framework and Intermediate Representation	MODELS'09 - [Gerth et al., 2009] <i>Language-Independent Change Management of Process Models</i>
Difference Detection and Mapping	SCC'11 - [Gerth et al., 2011b] <i>Precise Mappings between Business Process Models in Versioning Scenarios</i>
	BPM'08 - [Küster et al., 2008b] <i>Detecting and Resolving Process Model Differences in the Absence of a Change Log</i>
Tool Support	CAiSE'08 - [Küster et al., 2008a] <i>A Tool for Process Merging in Business-Driven Development</i>
☆ ☆ ACM Distinguished Paper Award ☆ IEEE Best Student Paper Award	

Fig. 1.5 Publication Overview

We generalized our results in terms of a framework for language-independent change management for process models, which was published in the proceedings of the ACM/IEEE 12th International Conference on Model Driven Engineering Languages and Systems (MODELS'09) [Gerth et al., 2009]. Our technique for dynamic computation of change operations was published at the 6th European Conference on Modeling Foundations and Applications (ECMFA'10) [Küster et al., 2010].

Techniques for the identification of equivalent process models and fragments were published in the proceedings of the IEEE 7th International Conference on Services Computing (SCC'10) [Gerth et al., 2010b]. This paper received the *IEEE Best Student Paper Award* of the IEEE 7th International Conference on Services Computing (SCC'10). Based on this work, we improved the conflict detection

between change operations by considering the semantics of process modeling languages in a follow-up publication, published in the proceedings of MODELS'10 [Gerth et al., 2010a]. Also this paper was awarded at the conference with the *ACM/Sigsoft Distinguished Paper Award*.

In 2011, we proposed an approach that results in precise matchings between process models in versioning scenarios, which was published in the proceedings of the IEEE 8th International Conference on Services Computing (SCC'11) [Gerth et al., 2011b]. Further, we extended our earlier work [Gerth et al., 2010a] on conflict detection between change operations by a classification of syntactic and semantic conflicts and proposed several resolution strategies for conflicting change operations. This work was published in the Journal on Software and Systems Modeling (SoSym) [Gerth et al., 2011a].

In the remainder, we describe the parts of our framework and our method for process merging in detail. Next, we give an overview of the book's structure.

1.4 Structure of the Book

The remainder of this book is organized as follows: In Chapter 2, we introduce the background for process model change management and present a general overview of related work in important areas of model versioning. References to related work concerning detailed aspects of process merging are considered more detailed in later chapters.

Chapter 3 is concerned with the Intermediate Representation that we propose as an abstraction and normalization for process models in different modeling languages. Based on models in the IR, difference, dependency and conflict detection can be performed on an abstract level. Chapter 4 addresses the matching of process models in the intermediate representation in order to identify corresponding model elements. In Chapter 5, we consider different options for the representation of differences based on change operations.

Consequently in Chapter 6, we present our approach to detect differences between different process model versions that results in a reconstructed change log consisting of compound change operations. Chapter 7 considers the identification of dependencies between change operations that restrict the order in which change operations can be applied. We propose an approach to analyze process models and contained fragments to identify semantic equivalences in Chapter 8. Using this approach, we propose a method for the detection of syntactic and semantic conflicts that avoids false-positive conflicts by taking into account semantic equivalences of business process models in Chapter 9.

Chapter 10 comprises the merging of different process model versions into an integrated business process model. Chapter 11 is concerned with tool support for our solution for change management of business process models. Finally, we summarize the contributions of our work and give an outlook on possible future work in Chapter 12.

Background

In this chapter, we lay out the basic foundation for the work presented in this book. We begin with a general introduction of models in software engineering, followed by a description of business process modeling in specific. Then, we consider the role of business process models in model-based development approaches by introducing business-driven development as a paradigm for the development of service-oriented architectures. We give an overview of the state of the art in model versioning. Finally, we conclude this chapter with a summary and a discussion.

2.1 Models in Software Engineering

In the context of software engineering (SE), models are leveraged in nearly all stages of the development process. During analysis, models provide an abstract representation of the desired solution, e.g. in terms of use case diagrams. In the design phase, the structure of the software is determined, e.g. by component diagrams and class diagrams. In addition, the communication between components is modeled with sequence diagrams. From structural and behavioral models, code can partially be generated in the implementation phase. For the purpose of testing, models are used to generate test cases.

In general, the benefits of using models in SE are manifold: Building models is usually easier than building the actual IT system. Modeling helps to capture, structure, and understand an IT system and to reveal possible problems. Models can be tested or validated using, e.g. model checking techniques. The use of models in SE has a long standing tradition. In 1976 the Entity-Relationship Model (ERM) [Chen, 1976] was developed as an abstract representation of data used in database design. An ERM represents entities, their attributes, and relations between the entities in a graphical form. In the end of the 1980s and the early 1990s object-oriented design and analysis arised [Booch, 1994, Coad and Yourdon, 1991, Jacobson et al., 1992, Rumbaugh et al., 1991], which adopted concepts of ER models and resulted in various graphical modeling languages. These different languages were finally unified by the standardization of the Unified Modeling Language (UML) [OMG, 2010a] that is today developed by the Object Management Group

(OMG). The UML is a collection of graphical modeling languages that are defined over a common meta-model.

To support the development of IT systems in specific domains, e.g. in the banking domain or in the insurance domain, Domain-Specific Languages (DSL) are utilized. A DSL shall simplify the modeling in its dedicated domain by capturing domain knowledge and domain terms directly in the modeling language. Thereby, DSLs enable an intuitive modeling and facilitate the understanding of the created models by different stakeholders.

As a systematic approach for the model-driven development of IT systems the OMG proposes Model Driven Architecture (MDA) [OMG, 2009]. MDA distinguishes between different modeling abstraction levels: Starting point is typically the creation of a computational independent model (CIM) that serves as a domain model by describing the system from a computational independent viewpoint using the vocabulary that is familiar in the domain. Based on the CIM a platform independent model (PIM) is created that focuses on the functionality of the system. Finally, a platform specific model (PSM) is derived that combines the PIM with implementation details for a specific platform. Transitions between these models used on the different abstraction levels can partially be automated by model transformations that convert a source model into a target model. For the description of model transformations different languages such as Query View Transformation (MOF QVT) [OMG, 2011b] exist.

The syntax of modeling languages is typically described by meta-models. A meta-model describes elements and their relations in terms of a graphical model. In contrast to textual language specifications, such as grammars, meta-models are more suitable to represent complex relations and dependencies within a language. For the definition of meta-models standardized meta-meta-models, such as the Meta Object Facility (MOF) [OMG, 2010c] or Ecore [Eclipse Foundation, 2011b] exist.

The semantics of modeling languages is usually specified textually in natural language, see e.g. the behavior of the UML [OMG, 2010a] or the behavior of the Business Process Model and Notation [OMG, 2011a]. Semantic specifications in natural language have the disadvantage that they are ambiguous and cannot be verified automatically. In [Engels et al., 2000, Hausmann, 2005], an approach for the visual and precise semantics specification for modeling languages is presented that overcomes the disadvantages of specifications in natural language.

In the following two sections, we describe business process models and their role in software development in detail.

2.2 Business Process Modeling

The activity of constructing models to represent business processes is commonly known as business process modeling (BPM). BPM is an integral part of business process management, which addresses the design, maintenance, analysis, and improvement of business processes in enterprises. The core of BPM are business

process models. A business process model arranges a set of activities to a workflow, which fulfills a certain business goal. The early origins of business process modeling go back to the work management theories of Taylor [Taylor, 1911] and to Gantts [Gantt, 1919] works in the area of project management in the beginning of the twentieth century. By the rise of Workflow Management Systems, the focus shifted from organizing work into small tasks that are performed by humans to the automation of these tasks by the use of software. Today, a multitude of modeling languages exists for the modeling of business processes. In the next section, we give a brief overview of some popular modeling languages.

2.2.1 Overview of Business Process Modeling Languages

The most used languages to specify business processes are UML Activity Diagrams (UML-AD) [OMG, 2010b], Business Process Execution Language (BPEL) [OASIS, 2007], Business Process Model and Notation (BPMN) [OMG, 2011a], and Event-driven Process Chains (EPC) [Keller et al., 1992]. We briefly introduce these languages and give examples for their graphical representation.

The Unified Modeling Language (UML) [OMG, 2010a] is nowadays the industrial standard for multi-purpose modeling and comprises 14 different diagrams. Among these, the modeling of business processes is supported by UML **Activity Diagrams** (UML-AD) [OMG, 2010b] that belong to the behavior diagrams of the UML. Activity diagrams describe the sequence of elementary *Actions* within a business process. The control-flow is determined by edges that connect the nodes of a UML-AD. Control-flow splits and joins are modeled using dedicated *ControlNodes* that support AND, XOR, and OR logic. As a part of the UML, the syntax of UML-ADs is also defined by the UML meta-model. The semantics of UML-ADs is described in natural language in the UML specification. Figure 2.1 shows the source process model *V* (from Figure 1.3) modeled as a UML-AD.

The **Business Process Execution Language** for Web Services (BPEL4WS or BPEL for short) [OASIS, 2007] is the standard for the description of processes that orchestrate web services, e.g. in Service Oriented Architectures (SOA) [Erl, 2005]. BPEL is a mainly block-oriented language that defines the execution order of activities (e.g. *Invoke*, *Assign*,...) by nesting basic control elements, such as *Sequence*, *Switch*, and *Flow*. BPEL is organized by the Organization for the Advancement of Structured Information Standards (OASIS) and currently available in Version 2. The

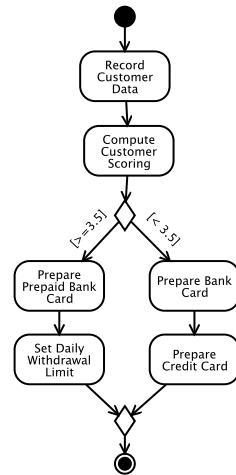


Fig. 2.1 Source Process Model *V* (from Figure 1.3) modeled as a UML Activity Diagram

BPEL specification defines the abstract syntax and its semantics and is therefore executable. Figure 2.2 shows the source process model V (from Figure 1.3) modeled in the BPEL.

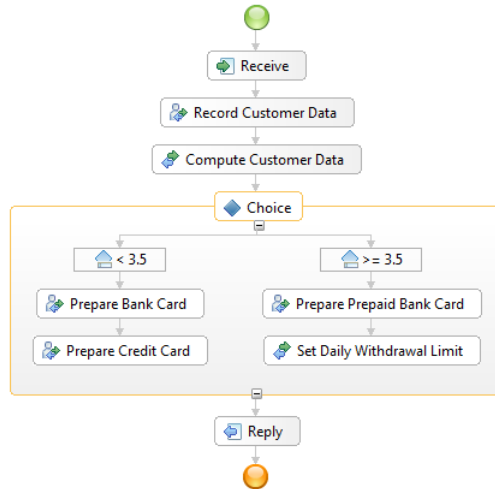


Fig. 2.2 Source Process Model V (from Figure 1.3) modeled in the BPEL

The de-facto standard for the modeling of business process models is the **Business Process Model and Notation (BPMN)**. BPMN Business Process Diagrams are composed of *Flow Nodes* such as *Activities*, *Gateways*, and *Events* that are connected by *Connecting Objects*. The BPMN was developed with a strong focus on understandability for domain experts as well as IT experts. Since 2005, the BPMN is developed by the OMG. In its previous Version 1.*, the BPMN only specified a notation for process models, a meta-model or a behavior specification was missing. Instead, a partial mapping of BPMN models to BPEL, which is semantically defined, was provided in the BPMN specification. In the current version 2.0, major improvements are added, e.g. a meta-model and behavior description in natural language. Concrete examples for BPMN models are presented in the next section.

The **Event-driven Process Chain (EPC)** [Keller et al., 1992] is a graphical modeling language for business process models. Modeling processes in terms of EPCs is quite popular, especially in Germany, since the language is leveraged by several tool vendors such as SAP AG and IDS Scheer AG. The language was developed in 1992 at the Saarland University in Germany in cooperation with SAP AG. EPC models are composed of *functions* and *events* in an alternating manner. Concurrent and exclusive behavior can be modeled by *logical relationships* that support AND, XOR, and OR logic. In EPCs, nodes are connected by edges, which represent control flow. Figure 2.3 shows the source process model V (from Figure 1.3) modeled as an EPC.

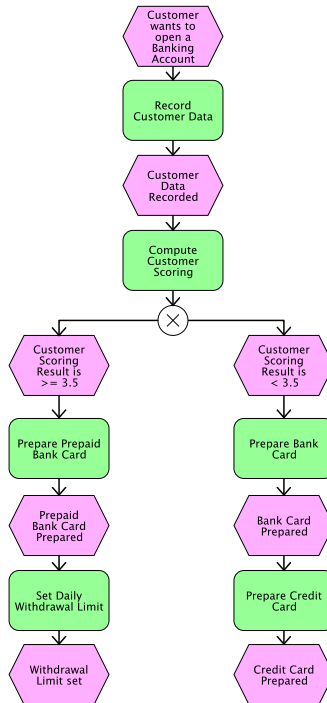


Fig. 2.3 Source Process Model *V* (from Figure 1.3) modeled as an EPC

Beside these four popular languages, further process modeling languages exist including, e.g. Yet Another Workflow Language (YAWL) [van der Aalst et al., 2005] and XML Process Definition Language (XPDL) [WFMC, 2005]. YAWL is a language based on Petri nets with a strong focus on the support of workflow patterns. XPDL is mainly used as an exchange format between different tools.

2.2.2 BPMN in Detail

As introduced in the previous section, BPMN is the de-facto standard for process modeling. For this reason, we adopt the BPMN for the examples presented in this book. In the following, we give a detailed overview of the BPMN Version 2.0 [OMG, 2011a], which is the current version announced in March 2011. BPMN 2.0 is far more mature and specific than the previous Version 1.2, since it is now defined in terms of a meta-model and the language's semantic is textually specified.

The BPMN provides three different diagram types: Business Process Diagrams (BPD), Choreography Diagrams, and Conversation Diagrams. The former two already existed in the previous BPMN Version 1.2. In the following, we introduce the different diagrams together with their main model elements.

Business Process Diagrams

The main diagram type of the BPMN is the *Business Process Diagram* (BPD) that is used to represent business processes in enterprises. Figure 2.4 shows the source process of our example from Figure 1.3 modeled with the BPMN. The process model describes the necessary steps to open an account for a customer in a bank. The individual steps are represented by BPMN *Tasks* labeled with *Record Customer Data*, *Compute Customer Scoring*, or *Prepare Bank Card*.

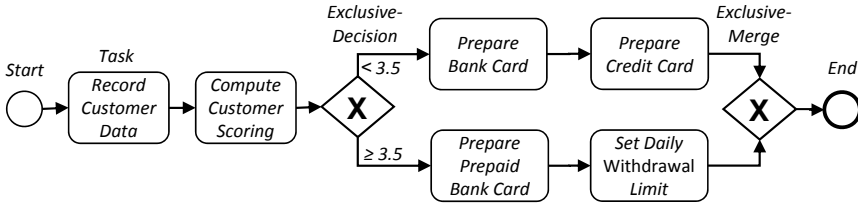


Fig. 2.4 Source Process Model V (from Figure 1.3) modeled as a BPD of the BPMN

Figure 2.5 shows an excerpt of the BPMN 2.0 meta-model for Business Process Diagrams. In general a BPD (*Process*) contains different types of *FlowNodes*, such as *Activities*, *Events*, and *Gateways*. These *FlowNodes* are connected by *SequenceFlows*, which describe the control flow of a process by determining the execution order of the contained nodes. A *SequenceFlow* connects a source node with a target node and specifies that the source node is executed before the target node. For that purpose, we can imagine the concept of a token, which flows from a source node to the target node through the *SequenceFlow* that connects the two nodes.

Activities represent the actual work that is carried out in process. Activities are further divided into simple activities such as *Tasks* and structured activities such as *Subprocesses*. Structured activities are connected to other nodes in a process model and may contain other *Activities* and *Edges*. Subprocesses can be used to structure processes hierarchically. A BPMN subprocess helps to separate logically connected parts in processes models. *Activities* may contain a *LoopCharacteristic* that indicates that the activity behaves like a *Loop*, i.e. the activity is repeated sequentially. Figure 2.6 shows the concrete notation of selected BPMN activities.

An *Event* is used to indicate that something occurs in a process. Three different categories of events can be distinguished: *Start Events* specify where a process starts. Analogously, *End Events* specify the end of a process (or the end of a path through the process) and *Intermediate Events* specify things that can happen in between the start and the end of a process, e.g. the arrival of a message or the modification of a data object. Figure 2.7 shows the concrete notation of the BPMN *Start* and *End Event*.

Gateways are used to split and join the control flow within a process model by controlling the *SequenceFlows* that are connected to them. To that extent, the

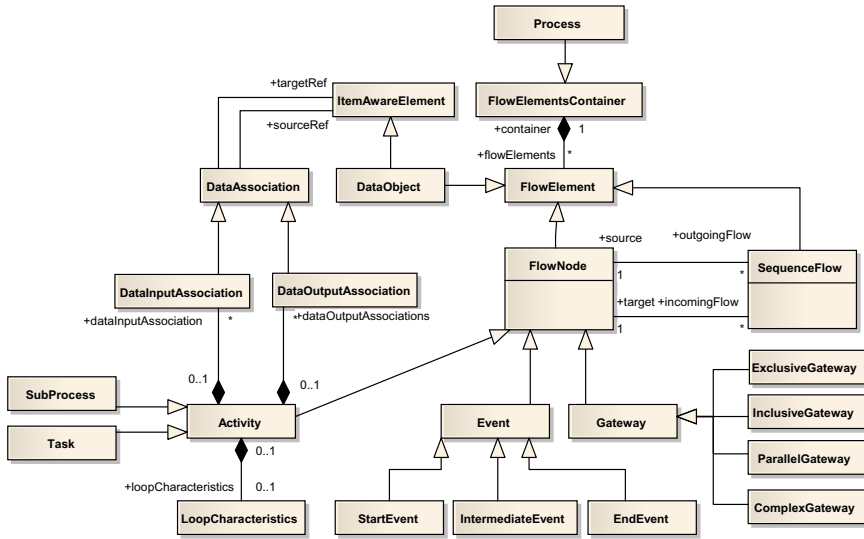


Fig. 2.5 An Excerpt of the BPMN Meta-model

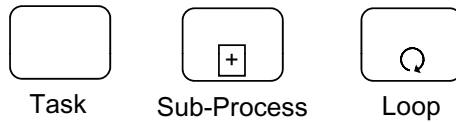


Fig. 2.6 Selected BPMN Activities

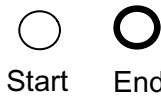


Fig. 2.7 BPMN Start and End Event

number of tokens arriving at the incoming *SequenceFlows* of a gateway may be increased or decreased and are then distributed on the outgoing *SequenceFlows* of the gateways. Whether tokens are produced or consumed and how they are distributed on the outgoing *SequenceFlows* depends on the type of the gateway. BPMN supports the following gateway types: *ExclusiveGateway* (XOR), *InclusiveGateway* (OR), *ComplexGateway*, and *ParallelGateway* (AND). Figure 2.8 shows notations for the main types of BPMN gateways.

As already introduced, *SequenceFlows* belong to the set of *Connections* that can connect nodes in a BPD. Other *Connections* that are provided by the BPMN are *DataAssociations* and *MessageFlows*. The former describe the *data-flow* in a

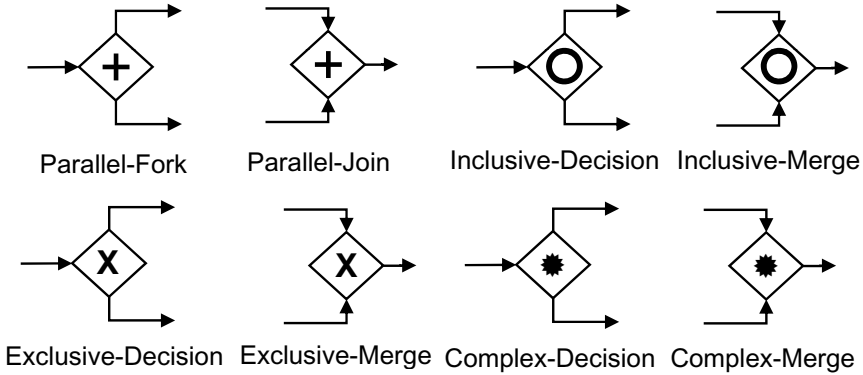


Fig. 2.8 BPMN Gateways

process, i.e. they specify how *DataObjects* are passed between the nodes of a process. *MessageFlows*¹ describe how participants of a process communicate via *Mes-*
sages. Figure 2.9 shows the concrete syntax of the BPMN connections.

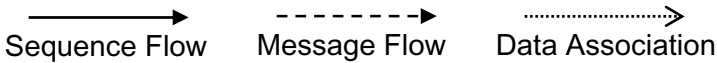


Fig. 2.9 BPMN Connections

Collaboration Diagrams

To provide a more complete overview of the BPMN, we briefly present the BPMN *Collaboration* package and its contained diagram types in this section. However, in the remainder of this book, we focus on business process diagrams of the BPMN and we do not consider the diagrams of this package in our solution for business process change management.

In general, the collaboration package provides different means to model participants that work together. A collaboration consists of at least two participants, which represent either a specific *PartnerEntity*, such as specific stakeholder or a general *PartnerRole*, such as a buyer or a seller. In general, two different diagram types exist to model a collaboration, which are briefly introduced in the following.

¹ For readability reasons, *MessageFlows* are not shown in the excerpt of the BPMN meta-model. For further information, we refer to [OMG, 2011a].

Conversation Diagram

A *Conversation Diagram* describes the message flow between participants in a collaboration on a high level. Participants are modeled in terms of *Conversation Nodes* that are connected by *Conversation Links*. A conversation link composes several related and individual message exchanges into a logical group. A conversation node is visualized by a labeled rectangle called *Pool* and can contain a Business Process Diagram. Figure 2.10 shows a conversation diagram from our example. It describes the conversation between two participants, namely a *Bank Clerk* and a *Rating Agency* that provides the rating of a customer.

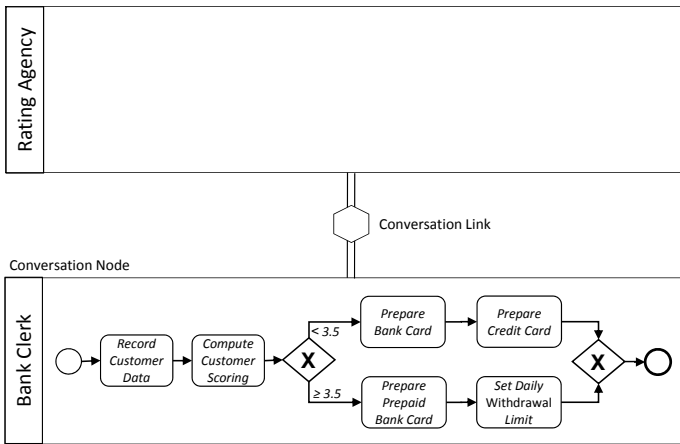


Fig. 2.10 A BPMN Conversation Diagram of our Example

Choreography Diagram

To specify an order in which the message exchanges in a conversation diagram shall take place, a *Choreography Diagram* can be used. This diagram type arranges the message flow between participants using *Choreography Activities*, which represent related message flows between several participants. A sender of a message is depicted by a transparent bar of the activity and the receiver of a message is visualized by a shaded bar. Choreography activities contained in a choreography diagram are arranged by sequence flows and other flow nodes that are also used in business process diagrams.

Figure 2.11 provides an example of a choreography diagram. The diagram arranges the message flows of our two participants (*Bank Clerk* and *Rating Agency*) by the two choreography activities “*Request Customer Rating*” and “*Provide Customer Rating*”, which are executed sequentially.

In the next section, we consider the semantics of process models.

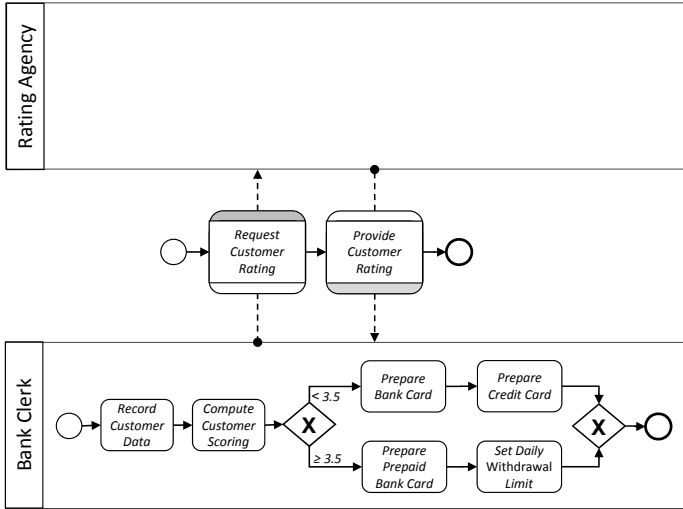


Fig. 2.11 A BPMN Choreography Diagram of our Example

2.2.3 Semantics of Process Models

In this section, we give an overview of the semantics of process models in general and describe two ways for semantics specification.

When we talk about the semantics of process models, we talk about the behavior of a process model when it is executed. The behavior of process models is typically defined based on the semantics of Petri nets [Murata, 1989] in terms of *token-flow*, which utilizes the theoretical concept of a *token* flowing from an input place to an output place of a transition. The nodes of a process model represent the transitions of a Petri net, and the edges are the places of the Petri net. A state of a process model can then be described as the number of tokens carried by the nodes and edges of a process model.

Usually, the execution semantics of process models is described informally in terms of natural language. Prominent examples are the semantics specification of BPD in [OMG, 2011a] or the semantics specification of UML Activity Diagrams [OMG, 2010b]. To give an example, in the BPMN Specification (Version 2.0) exclusive gateways are semantically specified as follows:

“A diverging Exclusive Gateway (Decision) is used to create alternative paths within a Process flow. This is basically the diversion point in the road for a Process. For a given instance of the Process, only one of the paths can be taken. [...] A converging Exclusive Gateway is used to merge alternative paths. Each incoming Sequence Flow token is routed to the outgoing Sequence Flow without synchronization.” [OMG, 2011a]

Semantic specifications in natural language have the disadvantage that they are usually ambiguous; e.g. in the case of the BPMN's exclusive gateway specifications from above, the concept of a token is used only for the description of a converging exclusive gateway, but not for the diverging gateway. Further, textual semantic specifications break the visual design concept, i.e. the syntax is specified visually by a meta-model whereas the semantics is described textually in natural language. Thereby, textual semantic specifications are often interpreted differently resulting in undesired behaviors. In addition, semantics specifications in natural language cannot be verified automatically, e.g. by applying model checking techniques.

An approach to overcome these issues is Dynamic Meta Modeling (DMM) [Engels et al., 2000, Hausmann, 2005], which was developed to enable a precise and formal way to specify the semantics of a modeling language and being understandable at the same time. The DMM approach is based on graph transformations [Ehrig et al., 1999] and can be universally applied to any kind of modeling language, whose syntax is specified in terms of a meta-model. DMM extends the meta-models of languages with concepts for the description of dynamic semantics. For process modeling languages this means that the concept of token flow needs to be added. In [Engels et al., 2007], the concept of token-flow is added to the meta-model of UML Activity Diagrams. In Chapter 3, we extend the meta-model of our intermediate representation for process models and introduce the concept of token-flow.

To describe the behavior of an instance of such an extended meta-model, instances are mapped to *typed graphs* [Corradini et al., 1994]. A *typed graph* consists of nodes and edges, which are *typed* over the extended meta-model of the language², whose semantic shall be specified. A DMM rule is defined as a *typed graph transformation rule*, which modifies these typed graphs and describes valid changes of the graphs. Figure 2.12 visualizes the DMM rule that specifies the behavior of a diverging exclusive BPMN gateway.

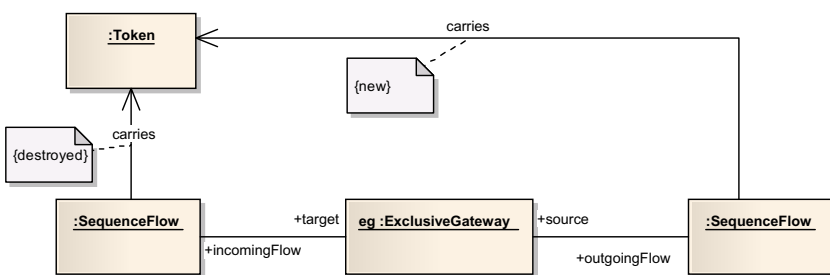


Fig. 2.12 DMM rule that specifies the behavior of a diverging exclusive gateway of the BPMN

The typed graph transformation rule shown in Figure 2.12 consists of two instance graphs: one describing the situation before the rule is applied (L) and another

² We will provide an example of such an extended meta-model in the course of this book.

one describing the situation after the application of the rule (R). L consists of all unmarked elements and the elements marked {destroyed}. R consists of all unmarked elements and the elements marked {new}.

The rule op_r is applied and transforms a graph G into a graph H if a graph homomorphism exists such that L is embedded in G . In this case, G is transformed into H by deleting all elements that are marked {destroyed} and creating all elements marked {new}.

Using the DMM approach, the semantics of a modeling language can be defined precisely being at the same time highly understandable. Additionally, visual and model-based semantic specification integrates well in the MDA approach proposed by the OMG. In this book, we will specify the semantics of the intermediate representation (Chapter 3) by applying the DMM approach.

2.3 Business Processes in Model-Based Development

The importance of business processes and business process modeling in the development of IT systems is continuously growing. Key driver for this development is the need to react more flexibly to steadily changing markets. That means, business processes undergo a constant change and accordingly the underlying IT solutions and architectures have to keep pace.

New software engineering approaches focus on a closer alignment of the IT level of an enterprise with its business needs and requirements expressed by business processes. A promising methodology is Business-Driven Development (BDD) [Mitra, 2005, Koehler et al., 2008].

BDD adopts the model-driven approach and allows to derive IT solutions directly from a business process model. In addition, BDD promises an increased flexibility and shorter turnaround times when changing the business and adapting the IT systems. The approach starts with the development of business process models that represent the business strategy and requirements for an IT solution. During several phases the business processes are then transformed into an executable IT solution. The transformation is typically achieved by applying model transformations. The main phases of business-driven development are depicted in Figure 2.13.

In the *Model* phase the process models of the underlying business processes are created. Thereby, also the business goals and requirements are included. In the *Develop* phase the process models are refined through several model transformation steps until an implementation is reached. Afterwards, the implementation can be

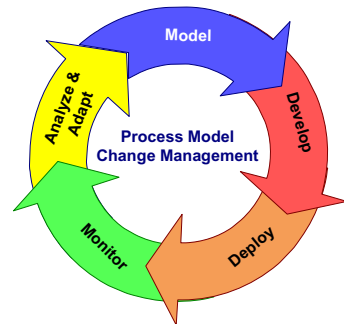


Fig. 2.13 Main Phases of Business Driven Development (BDD) [Koehler et al., 2008]

inserted into an existing IT environment in the *Deploy* phase. In the following *Monitor* phase the integrated implementation is examined and it is checked whether the business goals and requirements are fulfilled. Finally, in the *Analyze & Adapt* phase possible improvements and adaptations are detected and are transferred to the original process models. BDD tries to establish a linkage between the business and the IT requirements created by the process models in order to ensure that business requirements are considered on the IT level and vice versa.

Since BDD is a cyclic development process and its phases can be applied in multiple iterations, several versions of an input process model with different degrees of refinement are created. As a consequence, it will frequently be necessary to merge different versions of a business process model within and between phases of BDD. Key concepts for the merging of process models are introduced in the following section.

2.4 State of the Art in Model Versioning

In the previous section, we have considered the use of business processes in model-driven development approaches of IT-systems. In such approaches, process models are developed independently by different people and different versions are created. These versions need to be integrated at some point in time to obtain a merged version. For that purpose, a solution for change management of process models including model versioning is required.

In this section, we present the state of the art in model versioning. In general, model versioning comprises (at least) the following activities: *Model Matching and Similarity Analysis*, *Difference Representation and Detection*, *Dependency and Conflict Analysis*, and *Model Merging*. *Model Matching* considers the identification of corresponding model elements between different models and utilizes different similarity measures to obtain a mapping between corresponding process model elements. This mapping is the input for *Difference Representation and Detection*, where differences between the models are identified and captured in a suitable kind of difference representation. Finally, during *Dependency and Conflict Analysis*, detected differences between models are analyzed to identify differences that must be resolved together (dependencies) and differences, whose resolutions mutually exclude each other (conflicts). Finally, based on the identified differences, in *Model Merging* different models are merged to obtain an integrated version. To that extent, the different models are harmonized in an integrated version by resolving the differences between them.

In the remainder, we first present criteria for the classification of model versioning approaches. Then, we summarize existing approaches, which are finally evaluated according to the classification criteria.

2.4.1 Classification of Model Versioning

In general, approaches to model versioning can be classified according to different criteria. In the following, we briefly introduce a set of distinguishing criteria, which we later use to classify existing approaches to model versioning.

Generic vs. Language-Specific Approaches

Firstly, approaches to model versioning can be classified according to the kinds of models they support. Here, we distinguish between generic approaches that are independent of the modeling language and approaches that are language-specific.

The former group of approaches can be generically applied to merge models in different modeling languages. Typically, the only restriction is the underlying meta-meta-model of the modeling language, which is usually the MOF [OMG, 2010c] or EMF/Ecore [Eclipse Foundation, 2011b, Steinberg et al., 2009]. However, the generic applicability comes with the price that language-specific details such as the semantics of a concrete modeling language that is specified on the meta-model level is not considered. As a consequence, some activities of model versioning, such as difference detection and conflict analysis can only be applied on a syntactical level.

In contrast to generic approaches, language-specific approaches to model versioning focus on models in a particular language like UML state diagrams [OMG, 2010a] or a group of similar languages such as process modeling languages. Which language-specific aspects are considered depends on the approach and typically ranges from support for the detection of composite differences, such as refactorings, to the identification of syntactic redundancies that model semantically equivalent concepts.

Two-Way vs. Three-Way Merging

A further classification criteria is the number of models, which are considered for merging. In a two-way merge scenario, two models are involved. These may be two successive versions or two distinct models in a reference model customization scenario, e.g. an as-is model and a related to-be model that shall improve the as-is model. In the following, we refer to these two models as source and target model. The goal of a two-way merge is to bring the source model closer to the target model. For that purpose, it is necessary to identify differences between the source and the target model. The source and the target model are then merged by resolving a subset of differences between them. Figure 2.14 illustrates a two-way merge. The two models V and V_1 are merged by resolving differences between them. Thereby, the integrated model V_M is obtained that is somewhere between the source model V and the target model V_1 .

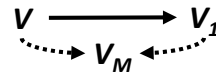


Fig. 2.14 Two-Way Merge Scenario

In three-way merge scenarios, three models are involved: two independently changed versions V_1 and V_2 as well as a common source version V of them. Figure 2.15 visualizes a three-way merge scenario. The

goal of a three-way merge is to integrate the two individual versions into an integrated version V_M , which is somewhere in between V_1 , V_2 , and V . The integrated version V_M is constructed based on the common source version V by resolving differences between the source version V and V_1 as well as differences between V and V_2 . In contrast to a two-way merge, the resolution of differences may result in conflicts, i.e. the resolution of some differences between V , V_1 and V , V_2 may mutually exclude each other. For instance, a corresponding model element is located at different positions in the Versions V_1 and V_2 . However, in the integrated version V_M , this model element can only be located at one of these positions. Conflicts must be identified before models can be merged and require manual user intervention during the merging process.

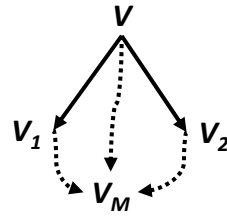


Fig. 2.15 Three-Way Merge Scenario

State-Based vs. Change-Based Merging

In state-based merging approaches, only the source model and the target model(s) are considered for comparison. Information about the changes that were applied to obtain the target model(s) or the order in which the changes were applied are not given. Typically, in state-based merging no change log exists and differences and similarities between different model versions must be identified by comparing the models.

In addition to the information given in the different model versions, change-based merging approaches utilize also change logs that provide a history of applied changes. In these change logs, changes are typically logged chronologically when they are applied to modify a model. In change-based merging approaches, differences between models do not need to be reconstructed by comparing the models. However, existing change logs need to be purged in order to get rid of redundant and overwritten changes [Rinderle et al., 2006].

Matching Based on Unique Identifiers vs. Matching Based on Heuristics

Matching of models to gather knowledge about corresponding model elements between them is a prerequisite for model merging. As a consequence, existing approaches to model versioning propose a solution for model matching or at least assume that corresponding model elements have been identified.

Generally, model matching approaches can be distinguished into approaches that rely on unique identifiers of model elements or approaches that use heuristics for matching. The former approaches require that each model element has a unique identifier, e.g. an ID, and trivially consider two model elements with the same ID as corresponding. However, these approaches can only be utilized in a scenario where unique identifiers exist, which is not always the case, e.g. if models are modified across tool boundaries. The latter heuristics-based approaches are more elaborate

and use different similarity measures to obtain a mapping between corresponding process model elements. For instance, heuristic-based approaches identify corresponding model elements by measuring the distance between the names of the elements or consider the structure of the models.

Granularity of Differences: Elementary vs. Composite

Approaches to model versioning can be distinguished according to their supported granularity of difference representation. We distinguish between approaches that support elementary differences and approaches that support composite differences.

The former approaches represent differences between models on an elementary level based on corresponding single model elements. Relationships between elementary differences, such as dependencies, are often numerous and are not directly understandable. The latter approaches also support composite differences, such as refactorings [Fowler et al., 1999], and are far more intuitive and user friendly. For instance, they potentially result in a more precise set of conflicts between differences. However, the detection of composite differences is more difficult and often requires predefined difference patterns.

Syntactic and Semantic Conflict Analysis

Finally, the conflict analysis of versioning approaches can be distinguished according to the types of conflicts that can be detected. We distinguish here between approaches that solely consider the modeling language's syntax for conflict analysis and approaches that additionally consider the language's semantics for conflict analysis.

The former approaches result in false-positive conflicts if models contain syntactic redundant elements (also known as *syntactic sugar*) or entire substructures which are equivalent from a semantic point of view like the partial equivalences between the parallel structures in process models V_1 and V_2 from our example introduced in Figure 1.3. This problem is in particular important in the case of process modeling, since well-established modeling languages, such as the Business Process Model and Notation (BPMN) [OMG, 2011a] or UML Activity Diagrams (UML-AD) [OMG, 2010a], generally allow a user to connect elements such as Activities or Gateways in an arbitrary way. This favors the construction of syntactically very different process models, which are at the same time semantically equivalent regarding their execution logic and execution order.

Semantics-based approaches to conflict detection additionally consider the semantics of a modeling language during model comparison and are hence able to identify such equivalences. We distinguish the semantic conflict detection approaches into approaches that are able to identify semantic equivalences between syntactically different elements and approaches that are able to identify equivalences between syntactically different substructures.

In the next section, we introduce existing works to model versioning.

2.4.2 Overview of Existing Approaches

Existing related works for model versioning exist on a broad range. In the following, we give a brief overview of these works. References to related work concerning more detailed aspects of model versioning, such as model matching or conflict analysis, are considered later in the respective chapters.

Lippe and Oosterom first introduced operation-based merging of models in [Lippe and van Oosterom, 1992]. Their approach compares recorded elementary change operations syntactically to identify conflicts.

Alanen and Porres [Alanen and Porres, 2003] describe an approach to versioning of MOF-based models. The approach comprises the detection of differences between models in terms of elementary change operations. Further, they describe how syntactic conflicts between detected operations can be identified and address the resolution of conflicts.

In [Ohst et al., 2003], an approach to the versioning of UML diagrams is presented. The approach identifies elementary differences between model versions in terms of a mapping that is obtained by comparing the model versions syntax. Differences are represented by overlapping the model versions in such a way that common model elements and model elements that are specific to a version can be distinguished. The approach does not consider the detection of dependencies or conflicts between model differences. Merging of models is not addressed.

In [Pottinger and Bernstein, 2003], a generic merge operator is presented that merges two input models based on a given mapping between them. The merged model contains all common elements and all non-duplicated model elements. Such a merged model may contain conflicts, which need to be identified and resolved afterwards either by applying a resolution pattern or by manual user intervention. Conflicts are distinguished into three categories: conflicts that occur on the model level, meta-model level, and meta-meta-model level. For some conflicts of the latter category, they introduce resolution patterns.

Chawathe et al. present a generic approach for the detection and representation of differences in tree-structured data [Chawathe et al., 1996]. The approach is state-based and uses similarity heuristics to match nodes in trees. Identified differences between two trees are represented in terms of change operations that are visualized directly in the two trees that have been overlapped. Dependencies between differences or conflicts between them are not considered.

In [Schneider et al., 2004, Schneider and Zündorf, 2007], the CoObRA framework is presented, which is the build-in versioning support of the Fujaba tool suite³ [Nickel et al., 2000]. The versioning approach is change-based and it is assumed that corresponding model elements in different model versions have the same identifier. Differences are identified on an elementary level but can be manually grouped into composite differences. Dependencies between individual differences are not considered. Two models are merged by applying the changes contained in the change log of one model iteratively also on the other model. If a change cannot be applied, a conflict is detected. However, the concrete changes that are in conflict are not identified.

³ <http://www.fujaba.de/>

[Kelter et al., 2005] present a generic approach for matching and difference detection of UML models. Differences are obtained in terms of elementary change operations and are visually presented to the user by overlapping the different model versions. Dependencies or conflicts between differences are not addressed.

EMF Compare [Eclipse Foundation, 2011c, Brun and Pierantonio, 2008] is an Eclipse [Eclipse Foundation, 2011a] project that enables the matching, difference detection, and merging of Ecore-based models. Support for language-specific aspects such as composite operations is not considered. Models are merged in an iterative approach by applying elementary change operations. EMF compare is used in several other approaches, e.g. [Altmanninger et al., 2008], or in commercial tools like the IBM Rational Software Architect [Letkeman, 2005]. A very similar approach to matching and difference detection of UML models is described in [Xing and Stroulia, 2005].

Odyssey-VCS [Murta et al., 2007, Murta et al., 2008] provides versioning support for UML models. The approach requires model elements with unique identifiers and considers differences on an elementary level. The conflict detection is syntax-based and does not consider the semantics of individual UML diagrams, such as UML activity diagrams.

[Kögel, 2008] present UniCASE as a tool to integrate the heterogeneous tool-landscape in software engineering projects based on a unified model that contains and relates typical models used in software engineering such as Use Cases or UML class diagrams. UniCase also supports the versioning of these models in a change-based approach. For that purpose, the approach relies on a recorded change log consisting of elementary and composite change operations. Conflicts between change operations are detected in a purely syntax-based approach. The approach is in particular suitable for structured models, like class diagrams. In contrast to our versioning approach for process models, the execution semantics of the underlying modeling languages is not considered.

[Kögel et al., 2010] introduce a repository for EMF models called EMFStore, which originates from the UniCASE tool introduced above and also supports model versioning. In contrast to UniCASE, EMFStore seems to be usable generically for EMF-based models. Additionally, the syntactic conflict detection has been improved by proposing levels of conflict severity, i.e. hard and soft conflicts.

Westfechtel [Westfechtel, 2010] proposes a generic approach to three-way merging of EMF or Ecore-based models. The approach is based on the syntax of the modeling language and considers applied changes on an elementary level. Based on a syntactic comparison of the input models and mappings between them, a merged version is produced that incorporates all non-conflicting changes and resolved conflicts that are shown as alternatives to a user.

These generic approaches have in common that they can be applied on models in different modeling languages and the detection of conflicts is based on the syntax of the modeling language. However, the generic applicability comes with the price, that the semantics of a concrete modeling language cannot be considered. As a consequence, semantic equivalences between syntactic different models cannot be identified, resulting in potential false-positive conflicts. Two changes are conflicting

if their applications mutually exclude each other. A detected conflict between two change operations is false-positive if the applications of the change operations result in semantically equivalent models that may be syntactically different.

Moreover, generic approaches compute differences based on elementary changes, e.g. [Alanen and Porres, 2003, Kögel et al., 2010, Westfechtel, 2010]. In the case of process modeling, these elementary change operations are often numerous, since even minor changes like the insertion of an activity and the subsequent reconnection of control-flow result in several elementary change operations. As a consequence, multiple conflicts may occur that need manual user interventions when models are merged. To address this issue, composite change operations have been proposed for process modeling [Weber et al., 2007, Küster et al., 2008b].

Following this line, Altmanninger et al. propose a semantically enhanced model version control system (SMoVer) [Altmanninger, 2007] for EMF-based models. This generic approach can be extended by specifications of semantic aspects for specific modeling languages. Thereby, semantic conflicts can be identified and some false-positive conflicts can be avoided. For instance, false-positive conflicts due to syntactic redundancies of single model elements that are semantically equivalent are avoided. However, SMoVer cannot identify semantic equivalences between more complex model structures.

Further, Altmanninger et al. introduced an adaptable model versioning system (AMOR) [Altmanninger et al., 2008, Brosch et al., 2009] that aims to combine the advantages of generic and language-specific approaches. Their approach incorporates language-specific composite operations that are predefined by a user in the conflict detection in order to obtain precise conflicts that cannot be computed based on elementary operations. The approach does not support the execution semantics of behavioral models, such as process models. Accordingly, AMOR does not identify semantic equivalences between syntactically different elements or entire model structures. The work is extended in [Brosch et al., 2010], where an approach for the resolution of conflicts based on predefined patterns is presented. The definition of conflict resolution patterns may also be beneficial in our approach.

The conflict detection approach used in AMOR is improved in [Taentzer et al., 2010]. There, notions of operation-based and state-based conflicts are introduced and dedicated detection approaches based on graph modifications are described for both notions. The approach is syntax-based and can be applied generically on graph-structured models. For the detection of operation-based conflicts, model versions must not differ too much, otherwise potential operations may be difficult to identify based on minimal rules. However, in business process modeling, individually developed model versions may differ to a large degree.

In [Nejati et al., 2007], a language-specific approach to match and merge state charts is presented. In this work, a match operator identifies correspondences between model elements of state charts by considering their syntax and execution semantics. Based on these correspondences a merge operator then automatically merges different state charts by creating an integrated state chart that represents the union of the shared behavior of the different state charts. Individual behavior is

integrated in terms of variabilities with guards. Conflicts between different state charts are not addressed.

Similarly, in [Rosa et al., 2010] different process models are merged, by creating a configurable process model that is the union of the common behavior of the different process models. Differences are included using configurable connectors. Conflicts between the input process models, e.g. due to mutually excluding behavior, are not considered.

Cicchetti et al. [Cicchetti et al., 2008] have recently proposed a domain-specific language for the specification of conflicts that can be applied in versioning scenarios. Conflicts are specified in terms of models representing conflicting concurrent changes. Thereby, elementary as well as composite changes can be specified, e.g. changes that introduce a singleton patterns together with changes that violate this pattern. The conflict models are then interpreted syntactically on difference models. The approach does not consider syntactically different elements or structures that are semantically equivalent.

ADEPT/ADEPT2 [Reichert et al., 2003, Reichert et al., 2005] is a process management system that manages process model types and running instances, which underlie constant change. For the migration of running process models to a modified process type definition, techniques are used that can also be used to establish versioning support for process models. In [Rinderle et al., 2004], conflict detection between applied changes is addressed on a syntactical level by comparing process models and applied change operations. However, the approach does not consider model matching and difference detection, since the approach is integrated in a single modeling environment and all applied changes are recorded in a change log.

[Ekanayake et al., 2011] propose a repository system for the storage of large collections of process models that also provides versioning support. The core idea of the approach is to store subgraphs of process models instead of entire process models. The subgraphs (fragments) may be shared by different process models. The approach is state-based and does not consider matching of process models. Conflicts between concurrent changes are prevented by locking subgraphs that are currently under modification.

Next, we evaluate the existing approaches to model versioning.

2.4.3 Evaluation

In this section, we evaluate the existing approaches according to our classification for model versioning. In the evaluation, we considered all presented approaches from above, except the two merge operators proposed in [Nejati et al., 2007, Rosa et al., 2010], since these approaches basically compute a “duplicate-free” union containing the complete behavior of the underlying models and do not consider conflicts between model changes. Accordingly, their merge result cannot be used in versioning systems. Similarly, we exclude the proposed repository for process model [Ekanayake et al., 2011] from our evaluation, since the presented approach relies on pessimistic version control and hence does not consider conflicts between concurrent changes. Matching of process models is also not addressed.

Table 2.1 shows the result of our evaluation. Most of the approaches in our evaluation are generically applicable to merge models in different modeling languages, typically models with the same meta-meta-model are supported, e.g. MOF [OMG, 2010c] or Ecore [Eclipse Foundation, 2011b]. Nearly all approaches support three-way merging.

Table 2.1 Evaluation of existing Approaches to Model Versioning

	Approach		Matching		Difference Detection		Conflict Analysis				
	generic (G) / language-specific (L)	state-based (SB) / change-based (CB)	2-way merging (2) / 3-way merging (3)	unique identifier	heuristics	elementary differences	composite differences	dependencies	syntactic	sem. equivalent elements	sem. equivalent structures
[Lippe and van Oosterom, 1992]	G	CB	3	□	□	+	-	(+)	+	-	-
[Alanen and Porres, 2003]	G	SB	3	+	-	+	-	+	+	-	-
[Ohst et al., 2003]	G	SB	3	+	-	+	-	-	+	-	-
[Pottinger and Bernstein, 2003]	G	SB	3	□	□	+	-	-	+	-	-
[Kelter et al., 2005]	G	SB	3	-	+	+	-	-	□	□	□
EMF Compare [Eclipse Foundation, 2011c]	G	SB	3	+	+	+	-	+	+	-	-
[Chawathe et al., 1996]	L	SB	2	+	+	+	-	□	□	□	□
Odyssey-VCS [Murta et al., 2007, Murta et al., 2008]	G	SB	3	+	-	+	-	-	+	-	-
[Cicchetti et al., 2008]	G	CB	3	□	□	+	+	-	+	-	-
UniCASE [Kögel, 2008]	L	CB	3	+	-	+	+	+	+	-	-
EMFStore [Kögel et al., 2010]	G	CB	3	+	-	+	+	+	+	-	-
[Westfechtel, 2010]	G	SB	3	+	+	+	-	-	+	-	-
SMoVer [Altmanninger, 2007]	G	SB	3	+	-	+	+	-	+	+	-
AMOR [Altmanninger et al., 2008]	G	SB	3	+	-	+	+	-	+	-	-
CoObRA [Schneider et al., 2004, Schneider and Zündorf, 2007]	G	CB	3	+	-	+	-	-	+	-	-
ADEPT [Reichert et al., 2003, Reichert et al., 2005]	L	CB	3	□	□	+	+	+	+	-	-

+ supported (+) partially supported - not supported □ not considered

The matching of models to identify corresponding model elements is not considered in all approaches, some of the approaches simply assume that a matching is given, e.g. [Pottinger and Bernstein, 2003] or suggest the use of EMF Compare [Eclipse Foundation, 2011c] like [Westfechtel, 2010]. However, for the matching of individually modified process models, an approach that matches models based on similarity heuristics is required, since it is not always the case that unique identifiers are given. In particular in scenarios, where models are developed using different tools unique identifier are typically not given.

In the case of difference detection, the majority of existing model versioning approaches only considers differences between models on an elementary level. Some of the change-based approaches support composite differences [Kögel et al., 2010, Reichert et al., 2003], that have been recorded directly when models are manipulated. Only AMOR [Altmanninger et al., 2008] and SMoVer [Altmanninger, 2007] support the detection of composite differences based on predefined differences in terms of graph transformations.

Nearly all versioning approaches support conflict analysis between independently applied modifications based on the syntax of the models. SMoVer [Altmanninger, 2007] additionally supports the identification of syntactically different but semantically equivalent model elements. None of the evaluated versioning approaches is able to identify semantic equivalences between partial model structures, like the equivalences between the parallel structures in process models V_1 and V_2 from our example introduced in Figure 1.3.

In our language-specific approach to process model versioning, we will address all these issues.

2.5 Summary and Discussion

In this chapter, we provided the necessary background for the remainder of the book, comprising process modeling, the role of process models in model-based development, as well as an evaluation of the state of the art in model versioning.

Based on this foundation, we now present the individual components of our framework for process model change management. As discussed in Chapter 1, these components comprise:

- An **Intermediate Representation** for business process models as a base for language-independent change management;
- **Matching** strategies for the identification of corresponding elements between different process models;
- A suitable **Representation of Differences** and an approach to **Difference detection** between different process model versions;
- **Dependency Analysis**, concerned with the identification of relationships between individual differences;
- an approach to **Equivalence Analysis** of different process model versions and parts of it to identify equivalent modifications;
- **Conflict Analysis**, comprising detection strategies for syntactic and semantic conflicts between independently applied changes;
- and finally, a method for **Process Model Merging** that respects dependencies and conflicts of differences to obtain an integrated version of a process model.

The above-listed components are described in detail in the following eight chapters.

Intermediate Representation

In this chapter, we introduce the intermediate representation (IR) that serves as an abstraction for concrete process modeling languages to enable change management of process models independent of language-specific details. In Section 3.1, we discuss general options for an IR. We describe challenges that need to be addressed by such an IR and derive requirements for it in Section 3.2. Based on the requirements, we then present the syntax and semantics of the intermediate representation in Section 3.3. In Section 3.4, we focus on the decomposition into fragments as an integral part of the IR. In Section 3.5, we map exemplary a core subset of the BPMN to the IR. Finally, we conclude the chapter with a summary and discussion. The following sections of this chapter are partially based on our earlier publication [Gerth et al., 2009].

3.1 Options for an Intermediate Representation

Generally, the merging of process models in different languages requires individual solutions for change management. That means, change management techniques implemented for process models in a concrete modeling language, such as BPMN [OMG, 2011a] cannot be easily reused for process models in another process modeling language, e.g. BPEL [OASIS, 2007].

However, to enable a language-independent approach that reuses implemented techniques, the core activities of change management including model matching, difference detection, as well as dependency, equivalence, and conflict analysis, have to be performed on a common representation of process models, as described in Chapter 1. In this book, we address this issue by introducing a common representation for process models in different modeling languages, which we call *intermediate representation* (IR).

In general, such an IR can be realized in (at least) two ways: Either the IR covers all model elements and semantic concepts of concrete modeling languages, i.e. the IR is complete, comparable to the complete MOF [OMG, 2010c], or the IR is an

abstraction of concrete modeling languages in the sense of an *essential IR*, analogously to the essential MOF.

In the case of a *complete IR*, each model element and semantic concept of a concrete modeling language must be represented in the IR. To support a new concrete language, the IR potentially must be extended to cover also the syntactic and semantic concepts, which are yet not covered. For instance, to cover the BPMN, the IR also has to provide corresponding model elements for specialized BPMN tasks, such as *Human Task* or *Service Task*.

In contrast to that, an *essential IR* covers a core subset of process model elements and the dynamic semantics of process models in terms of token-flow as described in Section 2.2.3 in Chapter 2. Concrete modeling languages are abstracted to the IR by reducing their model elements and semantic concepts to the core model elements provided by the IR. To give an example, the specialized BPMN tasks from above (*Human Task* and *Service Task*) are reduced to a single element in the IR, since they have the same dynamic behavior, i.e. they pass a token that has been arrived on an incoming edge to an outgoing edge in the same way. When new process modeling languages shall be abstracted to the essential IR it is usually not necessary to extend the IR.

In our solution for process model change management, we prefer the use of an essential IR as an abstraction of concrete modeling languages for the following reasons: First, an essential IR is less complex than a complete IR and thereby eases the comparison of process models. Second, an approach to change management of process models based on an essential IR can be extended to support further process modeling languages without the need to extend the essential IR.

In the next sections, we establish requirements such an essential IR for process models in concrete modeling languages has to fulfill.

3.2 Requirements for an Essential Intermediate Representation

As discussed in the previous section, we intend to build the intermediate representation (IR) as an abstraction of concrete process modeling languages covering a core subset of essential process model elements. For convenience, we refer to this essential intermediate representation with the term intermediate representation or IR for short in the remainder of this book. In this section, we describe potential challenges that need to be addressed by such an IR and derive requirements an IR for process models must fulfill, to be suitable for change management of process models.

To enable language-independent change management, it must be possible to transform process models in concrete modeling languages into process models in the IR. To that extent, the IR must provide a common core syntax and semantics to which commonly used process modeling languages, such as BPMN [OMG, 2011a], UML Activity Diagrams [OMG, 2010b], and BPEL [OASIS, 2007] can be mapped. An example for such a mapping of model elements in concrete languages to elements in the IR is, e.g. a *Switch* in BPEL and an *Exclusive Decision* in combination

with an *Exclusive Merge* gateway in the BPMN that are mapped to an alternative branching (i.e. *XOR-Split* and *XOR-Join*) in the IR. The different syntactic and semantic concepts of commonly used process modeling languages have to be investigated and mapped to a common representation in terms of the IR.

Moreover, even within a single process modeling language different syntactic elements or compositions of them can be used to model one and the same semantic concept. On the one hand, these syntactic redundancies, simplify modeling, however on the other hand, they potentially harden the comparison of different process models. An example for a syntactic redundancy is the modeling of loops in the BPMN, which either can be modeled by a dedicated model element called *Loop Activity* (post-tested) or by combining an *Exclusive Merge* and *exclusive Decision* as shown in Figure 3.1 (a) and (b).

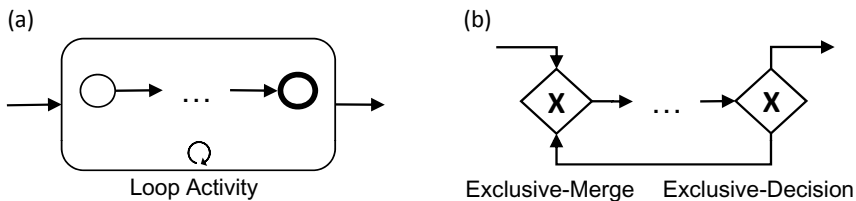


Fig. 3.1 An Example for a Syntactic Redundancy in the BPMN: Loop Activity (post-tested) and composed exclusive Merge and Decision

A further example, concerns control-flow splits in the BPMN, that can be modeled either implicitly or explicitly using control nodes, such as decision or fork. Figure 3.2 illustrates different ways to model control flow splits and joins in the BPMN. Here, the process models in Figure 3.2 (a) and (b) use explicit control flow splits and joins to specify parallel (a) and alternative (b) behavior. The process models given in the bottom of Figure 3.2 also specify parallel (c) and alternative (d) behavior. However, there the behavior is modeled by implicit control flow splits and joins or by a mixture of implicit and explicit elements. These syntactic redundancies need to be removed by an IR to ease the comparison of different process models.

Last but not least, also the representation of process models is a source of heterogeneity and hardens the comparison of process models. Generally, two representation paradigms can be distinguished: graph-oriented process modeling languages and block-oriented process modeling languages [Mendling et al., 2006]. The former languages use edges to define the execution order of activities contained in the process models. Examples for this type of process modeling languages are the BPMN, UML Activity Diagrams [OMG, 2010b], or Event-driven Process Chains (EPC) [Keller et al., 1992]. The latter type of languages specifies the execution order of activities by nesting basic control elements. A prominent example for a mainly block-oriented language is BPEL [OASIS, 2007].

In block-oriented languages the hierarchical structure of process models is explicitly modeled by the nested blocks. For instance, a process model in a

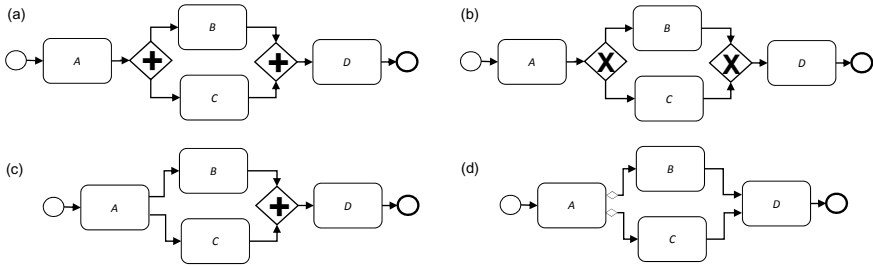


Fig. 3.2 Different Ways to model Parallel and Alternative Behavior

block-oriented modeling language may contain a parallel block (e.g. a *Parallel Flow* in BPEL) which in turn encloses two alternative blocks (e.g. *Switch* blocks in BPEL). This hierarchical structure created by these blocks enables an efficient comparison of block-structured process models, in particular since the beginning and the end of a block is well-defined.

In contrast to models in block-oriented languages, process models specified in graph-oriented languages are more difficult to compare, since their hierarchical structure is hidden in their graph-like representation and cannot be leveraged for the comparison. The hierarchical structure of a graph-oriented process model is hidden in subgraphs that are spanned by gateways that split and join the control-flow in a process model. In particular, the beginning and the end of such a subgraph in a process model is not directly given in a graph-oriented process model and needs to be analyzed afterwards. The absence of this structural information hardens the identification of corresponding elements or entire subgraphs in different process models. For instance, it is difficult to identify corresponding subgraphs with parallel or alternative behavior. To overcome these issues, the IR shall specify the hierarchical structure of process models explicitly.

Summarized, an intermediate representation that enables a language-independent solution for change management of process models has to fulfill the following requirements:

- R1 The intermediate representation shall serve as an abstraction of commonly used concrete process modeling languages, such as BPMN [OMG, 2011a], UML Activity Diagrams [OMG, 2010b], and BPEL [OASIS, 2007].
- R2 The intermediate representation shall not contain syntactic redundancies.
- R3 The intermediate representation shall make the implicit hierarchical structure of process models explicit.

We introduce the syntax and semantics of the intermediate representation and address the Requirements R1 and R2 in the next section. The later requirement is considered in Section 3.4. There, we decompose process models in the intermediate representation into fragments to make the hierarchical structure of graph-oriented process models explicit.

3.3 Intermediate Representation for Business Process Models

In this section, we specify the intermediate representation (IR), which serves as an abstraction of commonly used concrete process modeling languages, such as BPMN [OMG, 2011a], UML Activity Diagrams [OMG, 2010b], and BPEL [OASIS, 2007]. It shall be possible to abstract these concrete languages to the IR by mapping (a subset of) their elements to the IR. Based on models in the IR, difference, dependency, and conflict detection are performed on an abstract level enabling change management that is independent of language-specific details. In the following, we first introduce the meta-model of the IR. Then, we consider the semantics of IR process models.

3.3.1 Syntax of the IR

We develop the intermediate representation starting with generic workflow graphs (WFG) used e.g. in [van der Aalst et al., 2002, Sadiq and Orłowska, 2000, Vanhatalo et al., 2007] and an investigation of the Business Process Model and Notation (BPMN) as a language that shall be abstracted to the IR. A WFG is a directed graph consisting of nodes that are connected by edges. Having the abstraction of BPMN process models into a common representation and our requirements for an IR in mind, we evolved the generic WFGs into our intermediate representation. Figure 3.3 shows the meta-model for the IR. Models in the IR consist of a core set of nodes connected by edges. Nodes comprise activities, events, and gateways to split and join the control-flow.

The IR covers core elements that model the execution order of activities in a process model, such as *AND/XOR/Undefined-Splits* and *AND/XOR/Undefined-Joins*. These elementary elements are supported by nearly all process modeling languages and enable the modeling of sequential, parallel, alternative, looping, and complex behavior. In block-oriented languages [Mendling et al., 2006], elementary splits and joins are not modeled directly, but are instead supported by composed model elements (blocks), e.g. a BPEL *Switch* structure models alternative behavior. However, such composed model elements can be reduced to pairs of elementary splits and joins.

To ensure that IR process models are free of syntactic redundancies (Requirement R2), we assume that the following constraints hold:

1. *Activities* and *Events* have exactly one incoming and one outgoing edge. In the case, that an activity has multiple incoming/outgoing edges in a concrete modeling language, an appropriate gateway is used to replace the multiple edges.
2. Nodes are connected in such a way that each node is on a path from the IR Initial to the IR Final.
3. Control-flow splits and joins are modeled explicitly with the appropriate *Gateways*, e.g. *AND-Split*, *And-Join*, *XOR-Split*, *XOR-Join*, *Undefined-Split*, or *Undefined-Join*.

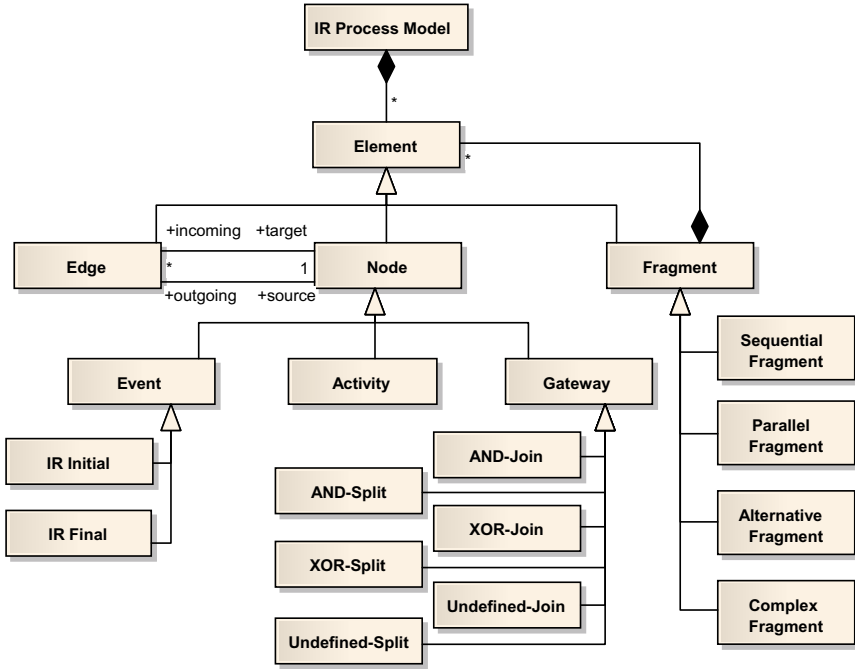


Fig. 3.3 Meta-model for the Intermediate Representation

4. Gateways have either exactly one incoming and at least two outgoing edges (*AND-Split*, *XOR-Split*, *Undefined-Split*) or at least two incoming and exactly one outgoing edge (*AND-Join*, *XOR-Join*, *Undefined-Join*).
5. An *IR Initial* has no incoming edge and exactly one outgoing edge and an *IR Final* has exactly one incoming edge and no outgoing edge.
6. An IR process model contains exactly one *IR Initial* and exactly one *IR Final*.

IR Initial and IR Final nodes are necessary to ensure that an IR process model has a unique start and end node. Unique start and end nodes are needed for the decomposition of IR process models into fragments [Vanhatalo et al., 2007] to make the hierarchical structure of the process models explicit. The decomposition of process models into fragments is addressed in detail in Section 3.4. Please note, that the restriction of IR process models to unique start and end nodes, does not exclude the merging of process models with multiple start and end nodes. In Section 3.5, we address this issue again, when we abstract BPMN processes to IR process models.

Since IR Initial and IR Final nodes are just a technical necessity to enable the decomposition of IR process models into fragments, we will not visualize them in every example process model shown in the remainder of this book. In particular, we do not visualize IR Initial and IR Final if an IR process model already unique start and end node.

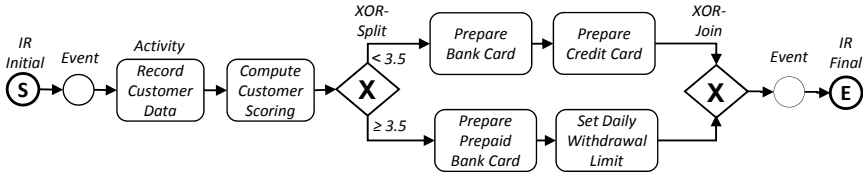


Fig. 3.4 Source Process Model of Figure 1.3 in the Intermediate Representation

Figure 3.13 shows the source process model *V* (Figure 1.3) in the IR. To ease the understandability of the IR, we use a subset of the BPMN’s concrete syntax also for the intermediated representation. Only for *IR Initial* and *IR Final*, we added suitable representations to the standard BPMN syntax. Figure 3.5 shows the concrete syntax for model elements of IR process models.

Having the syntax of the IR at hand, we introduced the semantics of IR process models in the next section.

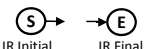
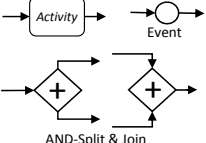
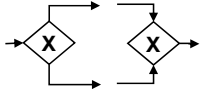

Concrete Syntax	Semantics
 <p>IR Initial IR Final</p>	<p>An <i>IR Initial</i> can fire if none of the edges carries a token (i.e. initial state of the <i>IR</i>). When it executes a single token is added to its outgoing edge. An <i>IR Final</i> can fire if its incoming edge carries at least one token. Firing of an <i>IR Final</i> removes all token from all edges in an <i>IR</i>.</p>
 <p>AND-Split & Join</p>	<p><i>Activities</i>, <i>Events</i>, and <i>AND-Splits</i> can fire if a token is on their incoming edge. <i>AND-Joins</i> require at least one token on each incoming edge, before they can fire. When an <i>Activity</i>, an <i>Event</i>, or an <i>AND-Split/Join</i> fires the number of tokens on each incoming edge is decreased by one and one token is added on each outgoing edge.</p>
 <p>XOR-Split & Join</p>	<p>An <i>XOR-Split</i> can fire whenever a token is on its incoming edge. When a split fires, one token is taken from its incoming edge and exactly one of its outgoing edges is selected to which the token is added. The selection of the outgoing edge is nondeterministic.</p> <p>An <i>XOR-Join</i> can fire if at least one of its incoming edges carries a token. When a join fires, an incoming edge that carries at least one token is selected non-deterministically. This token is taken from this incoming edge and is added to the outgoing edge of the <i>XOR-Join</i>.</p>
 <p>Undefined-Split & Join</p>	<p>The behavior of <i>Undefined-Splits</i> or <i>Joins</i> is not further specified. These elements are used to represent gateways in a concrete language, whose behavior is unknown or does not match to the <i>AND/XOR</i> logic of the gateways presented above. An <i>Undefined-Split</i> or <i>Join</i> is always enclosed by a <i>Complex Fragment</i>.</p>

Fig. 3.5 Concrete Syntax and Semantics of the Intermediate Representation

3.3.2 Semantics of the IR

We define the semantics of the IR similar to the semantics of Petri nets [Murata, 1989] in terms of token flow. The nodes of the IR represent the transitions of a Petri net, and the edges are the places of the Petri net. A state of the IR can then be described as the number of tokens carried by the edges of an IR. In Figure 3.5, we informally describe the behavior of important elements of the IR following mainly the semantics defined in [Vanhatalo et al., 2008].

The textual specification of the IR's semantic provides a first overview of the behavior of IR process models. However, the specification is too informal and imprecise to be helpful for the abstraction of concrete process modeling languages to the IR. As a consequence, we specify the semantics of the IR by applying the Dynamic Meta Modeling approach (see Section 2.2.3 in Chapter 2), to formally determine the behavior of IR process models.

For that purpose, we first integrate the concept of token-flow into the meta-model of the intermediate representation. Thereby, we obtain a runtime meta-model that can be used to describe the dynamic semantics of IR process models in terms of DMM rules. Figure 3.6 shows the runtime meta-model of the IR. The execution of an *IR Process* is controlled by an *IR ProcessExecution* consisting of *Tokens*. States of an IR process are described by *Tokens* that are carried by *Nodes*.

Based on the runtime meta-model of the IR, we can now specify DMM rules. DMM rules are typed graph transformation rules that specify the behavior of individual model elements of the IR. The rules shown in Figures 3.7 and 3.8 specify the semantics of *IR Initial* and *IR Final* nodes. The *IR Initial* rule starts the execution of an IR process model. For that purpose, it generates a token, which is carried by its outgoing edge if no token is carried by an edge or a node in an IR process model. Analogously, an *IR Final* terminates the execution of an IR process model.

The dynamic behavior of *Activities* and *Events* is described by the DMM rule shown in Figure 3.9. A token on the incoming edge of an activity or event is passed to the outgoing edge.

Analogously, the behavior is defined for *XOR-Splits* and *XOR-Joins*. Figure 3.10 shows the DMM rule of an *XOR-Split*. The rule is applied if a token arrives on an incoming edge of an *XOR-Split* and passes the token through the gateway on an outgoing edge in a non-deterministic way.

The respective DMM rules of *AND-Splits* and *AND-Joins* are specified in Figures 3.11 and 3.11.

Finally, we let the behavior of *Undefined-Splits* and *Undefined-Joins* of IR process models unspecified. As their naming suggests, the behavior of these gateways is not fixed, since they act as wildcards for gateways of concrete process modeling languages, whose behavior is either unknown or complex. In Section 3.5 of this chapter, we will exemplarily abstract BPMN *Inclusive Gateways* and *Complex Gateways* to *Undefined-Splits* and *Undefined-Joins* of IR process models.

In the next section, we show how an IR process model is decomposed into fragments.

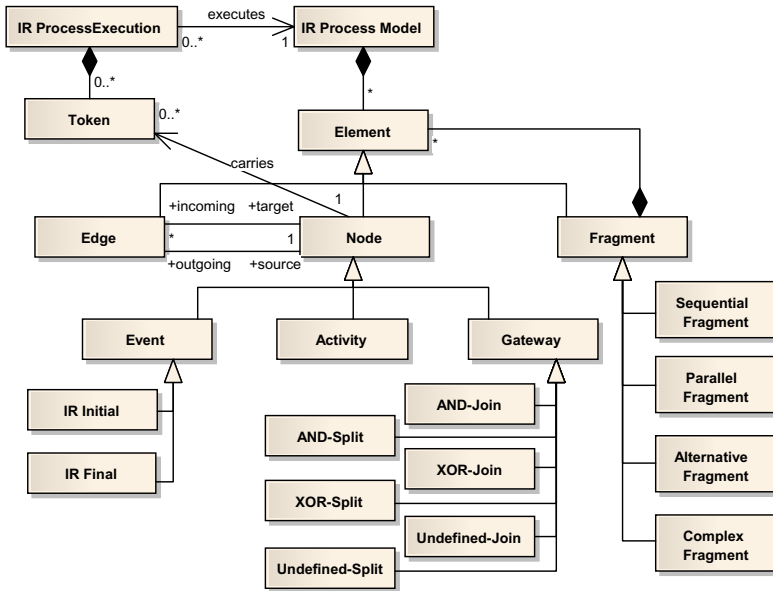


Fig. 3.6 Runtime Meta-model for the Semantics Specification of the Intermediate Representation

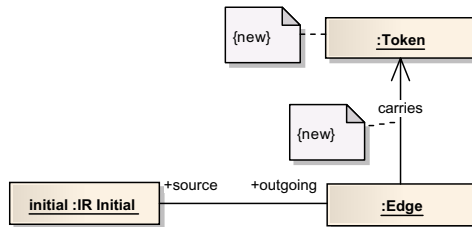


Fig. 3.7 DMM Rule that specifies the Behavior of an IR Initial

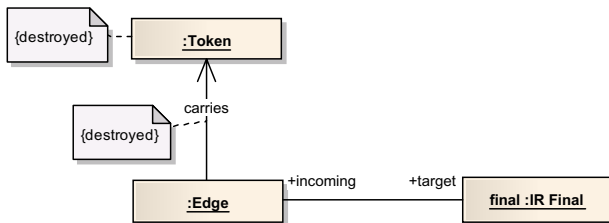


Fig. 3.8 DMM Rule that specifies the Behavior of an IR Final

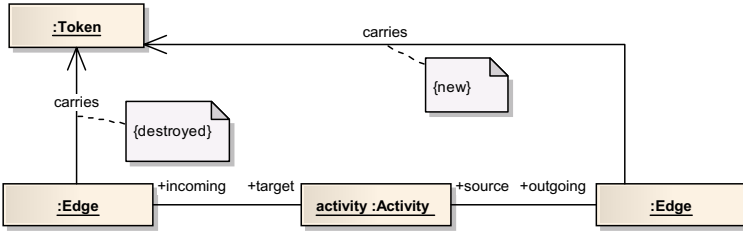


Fig. 3.9 DMM Rule that specifies the Behavior of Activities and Events

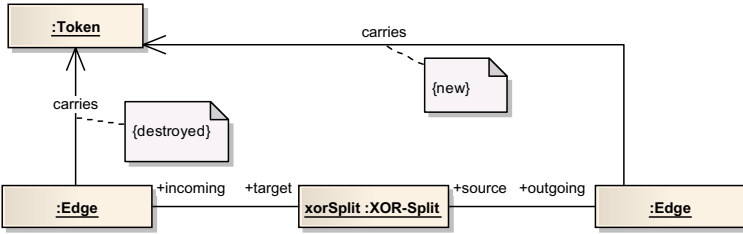


Fig. 3.10 DMM Rule that specifies the Behavior of an XOR-Split

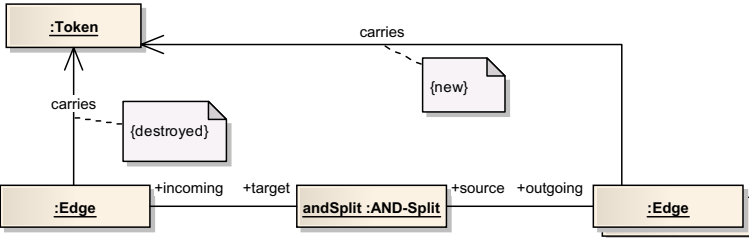


Fig. 3.11 DMM Rule that specifies the Behavior of an AND-Split

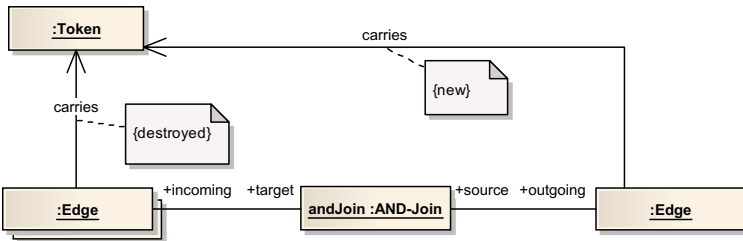


Fig. 3.12 DMM Rule that specifies the Behavior of an AND-Join

3.4 Decomposition into Fragments

So far, we have defined the syntax and semantics of the IR that shall serve as a common representation for process models (Requirement R1). By removing syntactic redundancies in the IR, we have addressed Requirement R2. In this section, we consider Requirement R3 and present an approach to make the hierarchical structure of process models explicit to provide a suitable base for process model comparison.

Since the intermediate representation is a graph-oriented language, the hierarchical structure of process models in the IR is hidden in subgraphs that are spanned by gateways that split and join the control-flow in the process models. These subgraphs need to be identified to make the hierarchical structure of a process model explicit for two reasons: First, the knowledge about distinct subgraphs that constitute the hierarchical structure of a process model is a prerequisite for the identification of corresponding subgraphs between different process models that is used in process model matching.

Second, based on the subgraphs, we can establish relationships between the gateways that begin and end such a subgraph, which is beneficial to merge different process models. To give an example, consider the subgraph f_A that specifies alternative branching shown in Figure 3.13. Further, this subgraph that begins with the *XOR-Split* and ends with the *XOR-Join* shall constitute a difference between two process models. If this difference shall be resolved during the merging of the two process models, we have to take care that the complete subgraph is inserted in the integrated process model. As a consequence, both gateways (*XOR-Split* and the *XOR-Join*) have to be inserted together, otherwise the integrated process model would not be connected.

To make the implicit hierarchical structure of IR process models explicit, we decompose IR process models into *single-entry-single-exit fragments* (SESE) that have a single entry edge and a single exit edge in IR process models. SESE fragments are known from compiler theory and are originally used to compute the control dependence equivalence relation. In [Johnson et al., 1993], an approach is described to compute SESE fragments in linear time. Within a SESE fragments more fragments can be enclosed. In [Johnson et al., 1994], a proof is presented showing that SESE fragments do not overlap, i.e. two fragments are either nested or disjoint. We define SESE fragments for IR process models as follows:

Definition 1 (Single-Entry-Single-Exit Fragment). *(based on [Johnson et al., 1994]) Let G be an IR process model with distinguished nodes IR Initial and IR Final, such that every node is on a path from IR Initial to IR Final. Two distinct nodes x and y in the IR process model G enclose a single-entry-single-exit fragment if*

- x dominates y , i.e. every path from IR Initial to y includes x , and
- y postdominates x , i.e. every path from x to IR Final includes y , and
- every cycle containing x also contains y and vice versa.

Recently, SESE fragments have been used successfully in the domain of process modeling [Vanhatalo et al., 2007] to check soundness of control-flow (i.e. to show the absence of deadlocks and lack of synchronization).

In general, process models can be decomposed into SESE fragments [Vanhatalo et al., 2007]. Figure 3.13 shows a SESE decomposition of the source process model V (Figure 1.3) into canonical fragments. Fragments are visualized by a surrounding of dotted lines. The alternative structure starting with the *exclusive Decision* and ending with the *exclusive Merge* is enclosed by the fragment f_A . Its branches are enclosed by the fragments f_B and f_C . The fragment f_{root} , which encloses the entire process model, is also considered as a SESE fragment which we refer to as *root fragment*.

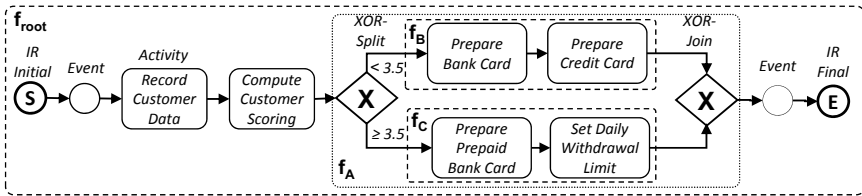


Fig. 3.13 Source Process Model of Figure 1.3 decomposed into Single-Entry-Single-Exit Fragments

For process merging, we define the set of canonical fragments [Vanhatalo et al., 2007] of process models and distinguish between different types of fragments as follows:

- a *sequence* has no AND/XOR/OR-Gateways as children. Further, a sequence is maximal, i.e., neither a preceding nor a succeeding model element can be added to the sequences. For example, in Figure 3.13, f_{root} , f_B , and f_C are sequences.
- a *parallel fragment* does not contain any cycles and has no XOR/OR-Gateways as children.
- an *alternative fragment* and an alternative loop have no AND/OR-Gateways as children. For example, in Figure 3.13, f_A is an alternative fragment.
- a *complex fragment* is any other fragment that is none of the above.

We denote the set of canonical SESE fragments $\mathcal{F}(V)$ for a given process model V . Further, we consider a fragment as being *structured* if it consists of matching pairs of nodes that split and join the control flow. Otherwise, it is considered as being *unstructured*. Given a fragment $f \in \mathcal{F}(V)$, we denote by $type(f)$ the type of the fragment and by $parent(f)$ the parent fragment. Similarly, given a node $x \in N$, we denote by $type(x)$ the type of the node and $parent(x)$ the parent fragment of x . For example, $type(\text{“Prepare Bank Card”}) = \text{Activity}$ means that “Prepare Bank Card” is an Activity node and $parent(\text{“Prepare Bank Card”}) = f_B$ means that “Prepare Bank Card” is contained in the fragment f_B .

By decomposing process models into canonical fragments, the hierarchical composition structure of fragments becomes explicit and can be used to compare process models efficiently. The hierarchical structure can be visualized by organizing the canonical fragments of a process model V into a process structure tree (PST) [Vanhatalo et al., 2007], denoted by $PST(V)$, according to the composition hierarchy of the fragments (see Figure 3.14 for the tree obtained for the source process model V from Figure 1.3). If a fragment f_1 contains another fragment f_2 (respectively node n), then f_1 will be the parent of fragment f_2 (node n) in this tree and fragment f_2 (node n) will be one of its children. Further, the root of the tree is the root fragment.

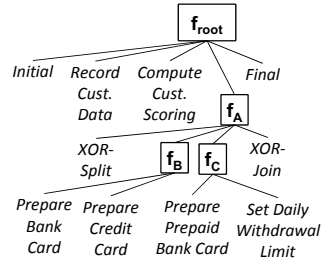


Fig. 3.14 Process Structure Tree (PST)

In the next section, we map BPMN processes to IR process models.

3.5 Abstraction of BPMN to the Intermediate Representation

In this section, we abstract exemplarily the Business Process Model and Notation (BPMN) to the IR by defining a mapping of a core subset of BPMN elements to IR elements. This section is partially based on our earlier publication [Gerth et al., 2009].

For the abstraction of a concrete modeling language into the IR, we have to define a mapping between elements of the concrete language and elements of the IR. To ensure that each process model in a concrete modeling language (here a core subset of BPMN) can be mapped to a model in the IR, each model element of the concrete modeling language needs to be mapped to an element in the IR. Otherwise models in a concrete modeling language can be created that cannot be merged based on the IR.

To ensure such a mapping between a concrete modeling language and the IR, we map iteratively each model element of a concrete language to the IR. In trivial cases this can be done one-by-one, e.g. a BPMN *Task* is mapped to an IR *Activity*. In other cases, single model elements cannot be mapped in isolation, because a group of model elements corresponds to an IR element or a group of IR elements corresponds to a concrete element. Then, those groups of elements need to be mapped together. For instance, a BPMN *Loop Activity* is mapped to several model elements in the IR.

For the abstraction of BPMN models into IR models, we consider a core subset of BPMN elements that covers fundamental *Activities*, such as *Tasks*, *Sub-Processes*, and *Loops*, *Events*, such as *Start Events*, *Intermediate Events*, and *End Events*, as well as *Gateways*, such as *Parallel Gateways*, *Exclusive Gateways*, *Inclusive Gateways*, and *Complex Gateways*. The elements are connected by BPMN *Sequence Flow* and may optionally be related by *Data Associations*.

The actual mapping of the BPMN elements to the IR elements is done in a semantic-driven way by inspecting the behavior of the BPMN model elements and

mapping them to suitable IR model elements. For that purpose, a precise and formal semantic specification of the concrete modeling language is beneficial that can be compared to the semantic specification of the IR introduced in Section 3.3. Thereby, semantically corresponding model elements between the concrete modeling language and the IR can be identified more efficiently and mapping errors can be avoided.













BPMN Element	IR Element	BPMN Element	IR Element	BPMN Element	IR Element
 Start  End  Intermediate	 Event	 Task  Service Task  Human Task  Send Task	 Activity	 Sequence Flow  Data Association	 Edge

Fig. 3.15 Mapping of BPMN Tasks, Events, and Connections to IR Elements

Figure 3.15 illustrates the mapping of BPMN atomic activities, events, and connections which are mapped onto corresponding IR elements. BPMN *Tasks* are mapped to IR activities. BPMN events are abstracted to the IR event element. Please note that BPMN *Start Events* and *End Events* are mapped to IR Events although their semantics slightly differs. In IR process models, the individual BPMN start and end events are treated like intermediate events, since the execution of an IR process model is started and terminated by a unique *IR Initial* and *IR Final* events, which precede (resp. succeed) BPMN *Start Events* and *End Events* in IR process models. As described above, unique start and end nodes are necessary to enable a decomposition of process models into fragments. In the case of BPMN processes that have multiple start or end nodes, the obtained IR process model must be refactored and completed. To that extend, the approach presented in [Vanhatalo et al., 2008] can be used, which rejoins multiple start and/or end nodes with unique *IR Initial* and *IR Final* events. Finally, BPMN *Sequence Flow* and *Data Associations* are abstracted to IR edges.

The mapping of BPMN gateways is shown in Figure 3.16. BPMN *Inclusive Gateways* and *Complex Gateways* are abstracted to *Undefined-Split/Join* elements of the IR. The mapping of BPMN *Exclusive Gateways* and *Parallel Gateways* is straightforward. Two or more incoming (outgoing) edges of a BPMN element, which is not a gateway, represent an implicit *Parallel Fork (Exclusive Merge)*. These implicit gateways are syntactically different from explicit exclusive and parallel gateways, but semantically equivalent. According to Requirement R2, we map semantically equivalent implicit and explicit gateways to the same IR elements, as illustrated in the bottom row of Figure 3.16.

Finally, BPMN compound activities, such as *Sub-Processes* and *Loops*, are mapped as illustrated in Figure 3.17. Compound activities are flattened during the abstraction, i.e. they are integrated in-line in the IR. However, their hierarchical information is preserved by enclosing the compound activities with fragments in the IR. BPMN *Sub-Processes* are represented by sequential fragments in the IR. The incoming and outgoing edge of a sub-process is directly connected to its start and end

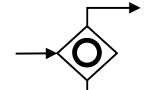
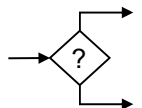
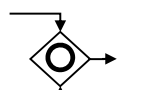
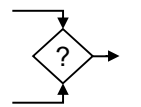
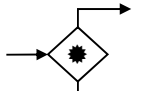
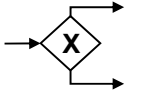
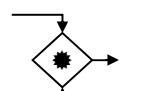
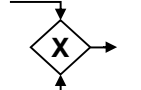
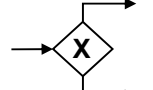
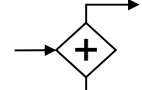
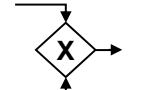
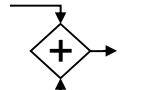
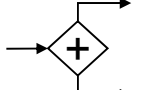
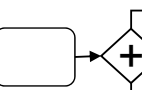
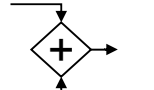
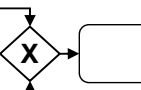
BPMN Element	IR Element	BPMN Element	IR Element
 Inclusive-Decision	 Undefined-Split	 Inclusive-Merge	 Undefined-Join
 Complex-Decision	 XOR-Split	 Complex-Merge	 XOR-Join
 Exclusive-Decision	 AND-Split	 Exclusive-Merge	 AND-Join
 Parallel-Fork	 Activity w. AND-Split	 Parallel-Join	 XOR-Join w. Activity

Fig. 3.16 Mapping between BPMN Gateways and IR Splits and Joins

events, represented by *IR Events*. BPMN *Loops* are abstracted into a combination of IR *XOR-Join* and *XOR-Split* that is enclosed by an alternative fragment as shown in Figure 3.17. The *XOR-Split* takes the decision whether the loop is repeated or the loop is exited.

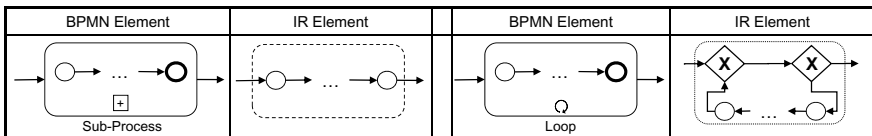


Fig. 3.17 Mapping of BPMN Sub-processes and Loops to IR Elements

The presented mapping fulfills the requirements for an abstraction of a concrete language to the IR, because each element of the core subset of BPMN is mapped to the IR (Completeness). In addition, Requirement R2 (Syntactic Redundancy

Elimination) is fulfilled, because different syntactic ways that model the same semantic concept (e.g. implicit/explicit BPMN *Parallel Fork* or *Exclusive Merge*) are abstracted to their respective counterparts in the IR. Using the mapping, models in the core subset of BPMN can be abstracted to IR process models.

3.6 Summary and Discussion

In this chapter, we have introduced the intermediate representation that serves as a common representation of process models in different modeling languages. Using the intermediate representation, we aim to generalize our solution for change management of process models to support the commonly used modeling languages BPMN [OMG, 2011a], UML Activity Diagrams [OMG, 2010b], and BPEL [OASIS, 2007].

First, we discussed different options for an intermediate representation and derived requirements for an IR. We defined the syntax of the IR in terms of a meta-model and specified the semantics of IR process models formally using typed graph transformation rules. We introduced an approach for the decomposition of process models into fragments, which enclose nested subgraphs with distinguished behaviors. Thereby, we made the implicit structure of IR process models explicit, which helps to harmonize block-oriented and graph-oriented process modeling languages. Finally, we described a mapping of a core subset of the BPMN to the IR.

The abstraction of concrete modeling languages to the IR enables us to compare and analyze process models for the purpose of change management - independent from the concrete modeling languages of the process models. However, an abstraction of a concrete language is always a trade-off between differences that can be detected on the level of the abstracted process models and differences that need further interpretation on the level of the process models in their concrete modeling language. For instance, on the level of the IR, we can identify a difference concerning an activity, however if the activity represents a BPMN human task or a BPMN service task must be determined in the level of the concrete modeling language. On this account, differences identified based on the IR need to be translated back into differences of process models in a concrete modeling language. We address this issue in Chapter 10.

In the next chapter, we introduce matching approaches and strategies for process models.

Matching

In the previous chapter, we have introduced the intermediate representation for business process models to enable change management of process models independent of their process modeling language. In this chapter, we present an approach to match process models in the intermediate representation. Matching considers the identification of related information, in order to identify corresponding model elements between two process models. The result of a matching is a mapping, which links related elements contained in different models. Based on a mapping differences and equivalences between process models can be computed.

The remainder of this chapter is structured as follows: First, we establish requirements for a solution to process model matching. Then, we evaluate existing strategies to model matching with respect to their usability for process model matching. In Section 4.3, we introduce the concept of correspondences to link related model elements. We present our approach to process model matching in versioning scenarios in Section 4.4. Finally, we conclude with a summary and discussion.

4.1 Requirements for Process Model Matching

In this section, we consider specific challenges that an approach for process model matching has to address. Based on these challenges, we derive general requirements for process model matching. The requirements are independent of the intermediate representation, which we use to abstract from process models in a concrete modeling language. However, we will show in the course of this chapter how the IR helps to fulfill our requirements for process model matching.

In general, merging different business process models requires the determination of relationships between process models and contained model elements. For that purpose, different process models need to be compared automatically to identify contained corresponding model elements. This comparison is typically called model matching and results in a mapping between two process models.

Based on such a mapping, differences between different process models are derived, which describe how one model can be transformed into the other. Thereby,

the quality of the mapping is important to ensure a correct set of differences. As a consequence, the matching of process models must result in a precise mapping that identifies all corresponding elements between two process models.

For that purpose, a solution to process model matching has to address the following challenges: First, process models typically contain several elements, which are difficult to distinguish since they basically share the same set of attributes. Examples for such elements are gateways, edges, or start and end events. These elements are difficult to match based on their own attributes.

A common approach to match these underspecified model elements is to identify them based on their environment. For instance, operations in class diagrams that share the same name, can usually be distinguished based on the following information: their input and output parameters, their privacy attribute, their parent class, and their parent package. Based on these parameters and the path information, two operations usually can be matched uniquely even if they share the same name.

In contrast to structured models, such as class diagrams, process models typically show a very flat hierarchical structure and often do not provide enough information that could be used to match equal elements. For instance, gateways are contained in a process, which may additionally be structured by nested sub-processes. However, since several gateways of the same type may be contained within a single (sub-)process, corresponding gateways cannot be identified based on the enclosing (sub-)process uniquely. Moreover, incoming and outgoing edges of gateways do not provide much help to match gateways too, since they are usually identified and matched based on the elements they connect, i.e. edges are matched after the matching of gateways.

A second issue that makes process model matching difficult are implicit relationships between elements contained in a single process model. To give an example, we consider a graph-oriented process model. An implicit relationship exists between a gateway that splits the control-flow of the process model into two or more flows and the gateway that joins these flows again. Differences between two process models that occur due to modifications of these gateways (e.g. as a result of their insertion into one of the process models) need to be resolved together, otherwise unconnected process models may be obtained. The knowledge about these implicit relationships should already be gained during model matching to simplify the later detection of differences.

To summarize, an approach to match different process models has to fulfill the following requirements:

- R1 (*Mapping between two process models*) A solution for process model matching shall compute a mapping between corresponding model elements in two given process models V and V_i automatically.
- R2 (*Underspecified model elements*) In particular, correspondences between underspecified process model elements, such as gateways, shall be identified.
- R3 (*Implicit relationships*) Implicit relationships between splitting and joining gateways within a single process model shall be identified.

In the next section, we evaluate existing approaches to model matching whether they are suitable for the matching of process models.

4.2 Evaluation of Existing Matching Approaches for Process Model Matching

In the following, we evaluate existing matching approaches with respect to our requirements for the matching of process models. We distinguish between *identity-based* and *similarity-based* matching approaches, following roughly the classification of model matching approaches proposed in [Kolovos et al., 2009].

4.2.1 Identity-Based Matching Approaches

Identity-based matching approaches match model elements based on a comparison of their static attributes, such as a unique model ID or based on equal names. If model elements do not have unique attributes, model elements can be matched based on a comparison of several of their attributes or their associations. The set of attributes and associations together is considered as the model elements signature [Kolovos et al., 2009] and may comprise a unique identifier for a model element. The result of identity-based approaches is a binary value, either two model elements match or they do not match.

Examples for identity-based matching approaches are [Alanen and Porres, 2003] or [Ohst et al., 2003], which rely on unique identifiers for the matching of MOF-based models. In [Reddy and France, 2005], model elements of UML class diagrams are identified and matched based on a comparison of several of their attributes.

The advantage of identity-based matching approaches is their simplicity and their speed. For the matching of process models, an initially applied identity-based matching approach can be used to compute a mapping between model elements with unique and equal names, such as activities and intermediate events. Moreover, model elements without a unique identifier but with a suitable signature based on several of their attributes that substitutes a unique identifier can be matched. An example for model elements in process models that can be matched by their signature are edges, whose source and target nodes often constitute a unique identifier. However, an identity-based approach is not suited to identify synonyms/homonyms or to identify correspondences between process model elements that usually do not have unique identifiers or a signature, such as gateways.

To summarize, an identity-based approach for process model matching partially fulfills Requirement R1 but does not fulfill Requirements R2 and R3.

4.2.2 Similarity-Based Matching Approaches

In contrast to the previous approach that results in a binary value, similarity-based matching approaches compute a quantified value between 0 (no

similarity) and 1 (identity) for model elements. A similarity value can be computed for single attributes such as the name of a model element, e.g. by computing the Levenshtein distance [Levenshtein, 1966]. For multiple attributes or associations of a model element a composed similarity value can be computed that may additionally be weighted. Examples for similarity-based matching approaches are [Ehrig et al., 2007, Nejati et al., 2007, Xing and Stroulia, 2005, Rosa et al., 2010]. EMF compare [Eclipse Foundation, 2011c] is a popular tool that uses a matching approach that is close to the similarity-based approach presented in [Xing and Stroulia, 2005], which computes a similarity value for model elements by analyzing the element's name, content, type, and its relations to other elements. The approach presented in [Treude et al., 2007] identifies similarities between UML models according to their tree-like structure. By iterating the tree representation of a model, a composed similarity measure is computed based on weighted similarities of model element attributes and relations. Similarly in [Chawathe et al., 1996], an algorithm for the matching of versions of tree-structured data is presented, which considers similarity of node names and their position in the tree-structure.

In [Nejati et al., 2007] state charts are matched in a similarity-based approach. In general, similarity-based matching approaches are well-suited to identify corresponding model elements between process models that are labeled with strings. In combination with ontologies, such as the Wordnet::Similarity package [Pedersen et al., 2004], even synonyms and homonyms can be identified [Ehrig et al., 2007, Nejati et al., 2007]. In the case of gateways and other model elements in process models that cannot be identified based on their own attributes, correspondences can be identified partially with this approach by measuring the similarity of their environment. For instance, by matching pairs of gateways of the same type, whose preceding and succeeding model elements have the most correspondences among each other [Rosa et al., 2010]. In [Weidlich et al., 2010] a comprehensive framework (ICOP) for the matching of activities in process models is presented. The approach is capable to identify correspondences between an activity and a group of activities. However, the suitability comes with the price of computational complexity, since potentially all model elements of a certain type need to be compared with each other to compute their similarity degree.

Concerning our set of requirements, Requirements R1 and R2 are fulfilled. Analogously, to the identity-based approach, a similarity-based matching approach cannot identify implicit relationships between model elements within a single process model and thus does not fulfill Requirement R3.

4.2.3 Summary

As we have seen, none of the presented approaches on its own is suitable to address all our requirements for process model matching completely. In particular, existing approaches miss to fulfill Requirements R2 and R3. That means, the approaches have difficulties to match gateways in graph-oriented process models and to establish their implicit relationships within a single model.

Based on models in the intermediate representation, we propose an approach that overcomes these issues. Our approach combines identity-based and similarity-based approaches for the matching of process models. We identify correspondences between underspecified model elements leveraging the decomposition of process models into fragments as introduced in Chapter 3 and establish mappings between the fragments. Thereby, gateways that belong together are contained in corresponding fragments that can be used to match gateways between different process model versions.

We give a general overview of matching in versioning scenarios and present our approach to match models in the IR in Section 4.4. In the next section, we introduce a model to represent correspondences between process models.

4.3 Data Structure for Model Matching

In this section, we introduce a model to express relationships between matched model elements of business process models. In the following, we refer to relationships between model elements as correspondences [Pottinger and Bernstein, 2003]. Correspondences are contained in a mapping that defines how two models and their contained elements are related.

To represent specific correspondences between model elements in order to describe the relation between two models, a model to represent correspondences is needed. Existing frameworks such as EMFcompare [Eclipse Foundation, 2011c] or Atlas Model Weaver (AMW) [Eclipse Foundation, 2009] provide standard solutions for the representation of correspondences.

Similar to these existing match models, we use a mapping model defined over the meta-model shown in Figure 4.1 to represent correspondences between different process model versions. A Mapping is created between two process model versions in the intermediate representation and consists of a set of Correspondences between different Elements in the IR process models. Mapping and correspondences are defined in the remainder of this section.

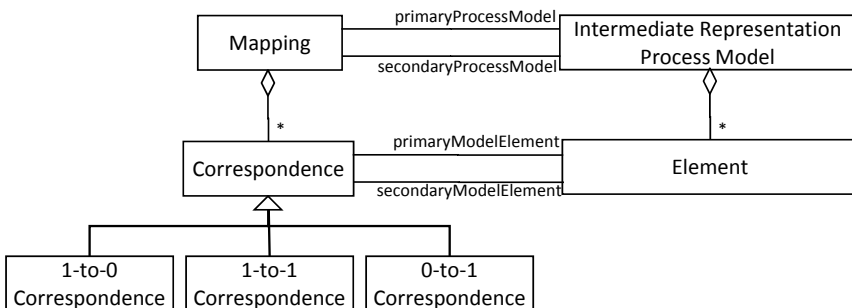


Fig. 4.1 Meta-model of a Mapping between IR Process Models

For the following discussion, we assume that two process models V and V_i in the intermediate representation (IR) are given. A correspondence is a link between two model elements in the business process model V and V_i . In general, a model element in one process model is connected by a correspondence to a model element in another process model if the first model element represents the other model element and vice versa. Based on the number of connected elements, we distinguish the following types of correspondences:

Definition 2 (Correspondences). *Let V and V_i be two business process models in the intermediate representation. Further let x and y be two model elements. Then the following types of correspondences can be established between x and y :*

- A $(1 - 1)$ **correspondence** connects two elements x, y in V and V_i if x represents y and vice versa.
- A $(1 - 0)$ **correspondence** is attached to an element x in V if x is not represented by an element y in V_i .
- A $(0 - 1)$ **correspondence** is attached to an element y in V_i if y is not represented by an element x in V .

Correspondences are bidirectional. That means if one model element x corresponds to another model element y , then y also corresponds to x .

In addition to the types of correspondences introduced in Definition 2, there may be correspondences representing relationships between sets of model elements. For instance, a $(1 - n)$ correspondence may represent the refinement of a single model element in one process model into a set of model elements in another model. Similarly, a $(n - 1)$ correspondence may represent the abstraction of a set of model elements into a single model element in the other process model. Finally, a $(n - m)$ correspondence may represent relationships between two sets of model elements. An automated computation of these types of relationships between model elements during matching is challenging and computational hard, due to the exponential increasing number of potential matching sets of model elements. In [Weidlich et al., 2010], a framework is described for the automated detection of $(1 - n)$ and $(n - 1)$ correspondences between activities in different process models based on different heuristics. The framework is in particular beneficial for the matching of process models that do not have a common source version.

In the versioning scenario considered in this book, we address relationships between sets of elements such as refinement and abstraction using several correspondences between single model elements. For instance, let us assume that a model element $x \in V$ corresponds to $y \in V_i$. Then V_i is altered by replacing y with v and w . In this case, x does not correspond to v and w , rather x has no counterpart since its former counterpart y was removed. Thus, x is attached to a $(1 - 0)$ correspondence. v and w however are attached to $(0 - 1)$ correspondences. In the remainder, we do not consider $(1 - n)$, $(n - 1)$, or $(n - m)$ correspondences.

We introduce the set of $(1 - 1)$ correspondences that connect model elements in V and V_i and denote this set by $C_{1-1}(V, V_i)$. Further, we denote the set of $(1 - 0)$

correspondences by $C_{1-0}(V, V_i)$. Similarly, we denote the set of $(0 - 1)$ correspondences as $C_{0-1}(V, V_i)$.

Correspondences can be classified according to the type of model elements they connect. We distinguish between correspondences that connect edges, nodes, and fragments. All correspondences between two process models together comprise a mapping between the process models. A mapping between two process models is defined next:

Definition 3 (Mapping). *Let two business process models V, V_i in the intermediate representation be given. We define mapping $\mathcal{M}(V, V_i)$ to be the following sets of correspondences between elements of V and V_i :*

- $C_{1-0}^E(V, V_i)$, $C_{0-1}^E(V, V_i)$, and $C_{1-1}^E(V, V_i)$ containing correspondences between edges.
- $C_{1-0}^N(V, V_i)$, $C_{0-1}^N(V, V_i)$, and $C_{1-1}^N(V, V_i)$ containing correspondences between nodes.
- $C_{1-0}^F(V, V_i)$, $C_{0-1}^F(V, V_i)$, and $C_{1-1}^F(V, V_i)$ containing correspondences between fragments.

Based on the correspondence types we are able to detect inserted and deleted model elements between business process models, which are examined in detail in Chapter 6. In the next section, we describe how a mapping is established in versioning scenarios and present a concrete example.

4.4 Matching in Versioning Scenarios

In this section, we consider the matching of different process models in versioning scenarios. Parts of the presented matching approach have been published in one of our earlier publications [Gerth et al., 2011b].

In a versioning scenario, different versions of a process model are matched by considering a common ancestor version. In contrast to matching scenarios where no common ancestor exists, in versioning scenarios a partial mapping can be computed automatically. This partial mapping is based on the model elements that already exist in the common ancestor and leverages the computation of a complete mapping. In the following, we first give an overview of versioning scenarios and describe which mappings need to be computed between versions of process models. Then, we present the steps of our matching approach in Section 4.4.2.

4.4.1 Overview

In versioning scenarios, different versions of a process model need to be matched by considering a common ancestor version. Figure 4.2 visualizes such a scenario (see also Figure 1.3). A source version V of a business process model is developed independently by different users. Therefore, V is first copied into the versions V', V'' , e.g. by checking V out of a repository into the local workspace of a user. Then, these

versions are individually developed into the versions V_1, V_2 by applying change operations. For the creation of a merged version V_M , the changes applied to V_1 and V_2 must be considered. For that purpose, the process model versions must be matched in order to identify corresponding model elements. In particular, we are interested in the following three mappings:

- a mapping $\mathcal{M}(V, V_1)$ between the process model versions V and V_1 ,
- a mapping $\mathcal{M}(V, V_2)$ between the process model versions V and V_2 ,
- and finally, a mapping $\mathcal{M}(V_1, V_2)$ between the process model versions V_1 and V_2 .

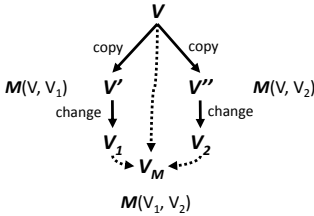


Fig. 4.2 Versioning Scenario

The mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$ are required for the detection of differences between the process models V, V_1 and V, V_2 . The mapping $\mathcal{M}(V_1, V_2)$ is a prerequisite for the identification of conflicting differences between the process model versions V_1 and V_2 in order to obtain a merged process model V_M .

Figure 4.3 gives an overview of our matching approach for process model versions. The output of the approach are three complete mappings between the process model versions V, V_1 , and V_2 . We first compute partial mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$. In contrast to matching scenarios where no common ancestor exists, in versioning scenarios such partial mappings can be computed automatically. We consider a mapping to be partial if it only contains $(1 - 1)$ correspondences between model elements that are already existing in the common ancestor version V and are unchanged in the versions V_1 or V_2 .

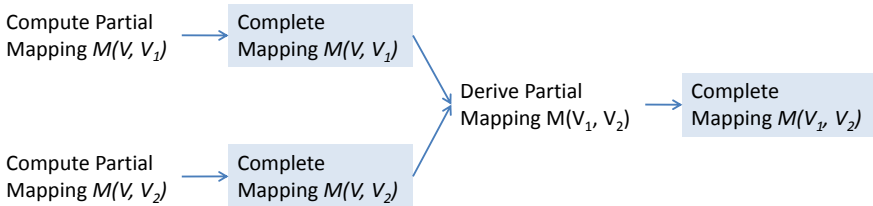


Fig. 4.3 Overview of our Matching Approach in Versioning Scenarios

In a second step, we complete the partial mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$ by matching model elements that were newly added or modified in one of the versions V_1 or V_2 . Thirdly, we automatically derive a partial mapping $\mathcal{M}(V_1, V_2)$ between the versions V_1 and V_2 based on the complete mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$. Finally, we complete the mapping $\mathcal{M}(V_1, V_2)$.

The following sections, introduce each step in detail. We begin with the computation of partial mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$ in the next section. In

Section 4.4.3, we complete these mappings and derive a partial mapping $\mathcal{M}(V_1, V_2)$ in Section 4.4.4.

4.4.2 Computation of Partial Mappings

The creation of partial mappings between the process models V, V_1 , and V, V_2 is divided into two steps. In a first step, we initially create the partial mappings, when new versions of a process model V are created. In the second step, we updated the partial mappings after the modification of the new versions V_1 and V_2 and obtain mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$. The two steps are described in the following.

Step 1: Creation of a Partial Mapping

In a versioning scenario, a partial mapping is constructed when the business process model version V is copied, e.g. into the local workspace of a developer during the check-out process. (see Figure 4.2). After the copying, identical pairs of process models V, V' and V, V'' exist¹. For each edge, node, and fragment contained in V a $(1 - 1)$ correspondence is created, which connects the model element in V with its counterpart in V' (or V'' respectively). All $(1 - 1)$ correspondences together constitute the initial mappings $\mathcal{M}(V, V')$ and $\mathcal{M}(V, V'')$ of the identical pairs of process models V, V' and V, V'' .

Figure 4.4 shows the source process model V of our example and its copy V'' . Arrows between identical model elements represent $(1 - 1)$ correspondences. $(1 - 1)$ correspondences also exist between edges and fragments of V and V'' but are not visualized due to readability reasons.

In the following section, we propose an algorithm that updates these mappings after the modification of the versions V', V'' into versions V_1 and V_2 .

Step 2: Update of a Partial Mapping

In the versioning scenario presented in Figure 4.2, we assume that the process model version V' is modified into version V_1 and V'' is modified into version V_2 . In order to reflect the applied modifications, the initially created partial mappings $\mathcal{M}(V, V')$ and $\mathcal{M}(V, V'')$ need to be updated into the mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$. That means, for each correspondence we have to check whether the model elements it connects, still exist in both versions of the process model and add new correspondences for newly inserted model elements, which are not attached by a correspondence. A mapping can be updated automatically by the following algorithm given in Listing 1.

The update algorithm checks for each $(1 - 1)$ correspondence c contained in $\mathcal{M}(V, V_i)$, whether the underlying model elements of the correspondence still exist in V_i and was not modified. If a model element no longer exists in V_i , we assume that the element was deleted from this version and remove the correspondence c from

¹ We assume that the functionality of a model element does not change when it is copied.

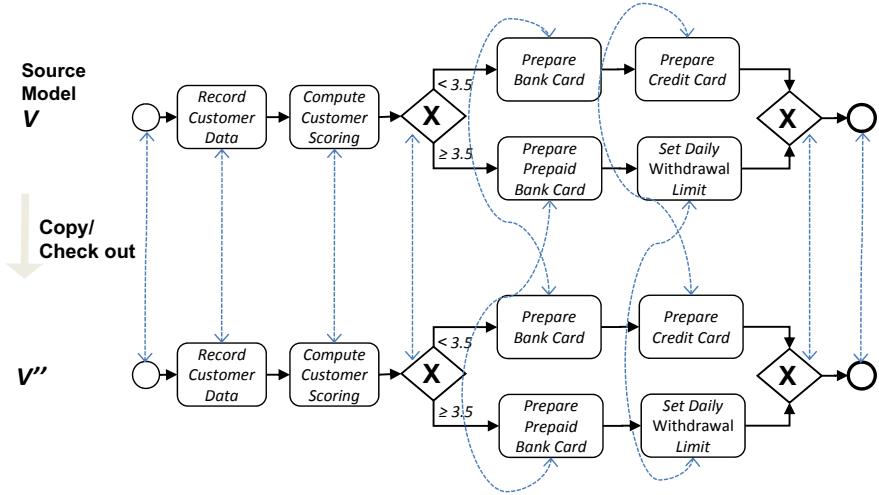


Fig. 4.4 Initial Mapping created between two Versions V and V'' when V is copied during Check-out

Listing 1. Algorithm for the Update of a Partial Mapping $\mathcal{M}(V, V_i)$

```

Input: Mapping  $\mathcal{M}$ 
Input: Process Model  $V$ 
Input: Process Model  $V_i$ 
Output: updated Mapping  $\mathcal{M}$ 

updateMapping( $\mathcal{M}, V, V_i$ )
     $N_i = V_i.getModelElements()$ ;
    // find deleted and modified model elements
    foreach (1 – 1) correspondence  $c \in \mathcal{M}$  do
         $e = c.getModelElement(V_i)$ ;
        if  $e \notin N_i \vee e.isModified()$  then
            // remove correspondence  $c$ 
             $\mathcal{M}.remove(c)$ 
        end
    end
    return  $\mathcal{M}$ ;
end
    
```

the mapping $\mathcal{M}(V, V_i)$. Similar, in the case that a model element in V_i was modified, the correspondence c is removed, too.

Figure 4.5 provides an example for an updated partial mapping $\mathcal{M}(V, V_2)$ between the process models V and its succeeding version V_2 (introduced in Figure 1.2). The arrows represent (1 – 1) correspondences and connect model elements with the same functionality. Highlighted model elements in process models V_2 do not have a counterpart in process model V and are attached to (0 – 1) correspondences in the updated

mapping. The activity “Set Daily Withdrawal Limit” in V is no longer existing in process model version V_2 , respectively a $(1 - 0)$ correspondences is attached to this model element in the mapping. Again, correspondences between edges and fragments of V and V_2 are not visualized due to readability reasons.

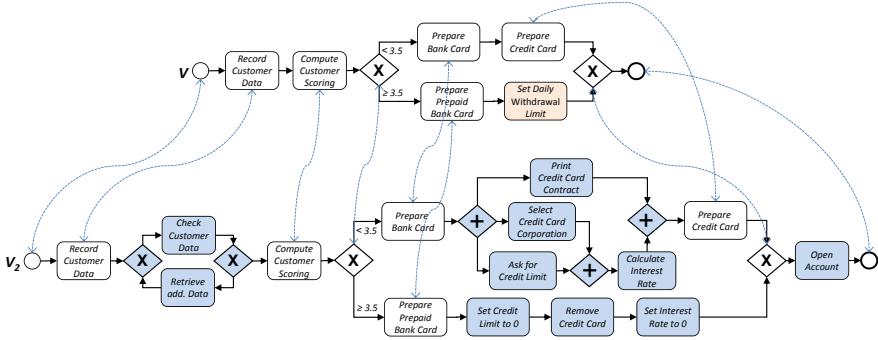


Fig. 4.5 Updated Partial Mapping of the Process Models V and V_2 (introduced in Figure 1.2)

So far, we have created and updated the partial mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$. We complete these mappings in the next section.

4.4.3 Completion of the Partial Mappings

Based on a partial mapping between two process models V and V_i , we present an approach to obtain a complete mapping between the process models.

A partial mapping $\mathcal{M}(V, V_i)$ contains only $(1 - 1)$ correspondences between model elements that exist in both process models V and V_i and are unchanged in the version V_i . To complete a partial mapping, we have to assign correspondences to unmatched model elements. That means, we have to assign $(1 - 1)$ correspondences to model elements that actually match, assign $(1 - 0)$ correspondences to model elements that only exist in version V , and assign $(0 - 1)$ correspondences to model elements that only exist in version V_i .

A model element is unmatched in a partial mapping if it was newly inserted in the version V_i or if it was modified in version V_i and a former existing $(1 - 1)$ correspondence was removed from the partial mapping.

We match unmatched model elements according to the following strategies by leveraging existing model matching strategies and the knowledge given in the partial mappings. First, we match nodes. Based on the obtained node mapping, we then match edges. Finally, we match fragments.

Matching Nodes and Edges

In the following, we describe an approach to match nodes and edges between two given process models V and V_i . The approach identifies correspondences by

identifying similarities between nodes and edges in different business process models². We first match nodes to obtain a node mapping. Afterwards, we match edges based on this node mapping.

For the matching of nodes, we use two strategies that are applied sequentially. First, we use an ID-based strategy and compare the names of nodes. If the names of two nodes of the same type are equal, we establish a $(1 - 1)$ correspondence between the two nodes. After the name comparison, we apply a similarity-based strategy that computes a Levenshtein [Levenshtein, 1966] distance between the names of the remaining nodes and match nodes whose distance is under a certain threshold. The matching of nodes could further be improved by adding a step that tries to identify corresponding nodes using an ontology. Thereby, correspondences between nodes can be identified those names contain synonyms.

Finally, we classify unmatched nodes that do not have a corresponding counterpart by adding $(1 - 0)$ correspondences to the mapping $\mathcal{M}(V, V_i)$ if the unmatched node exists in V or a $(0 - 1)$ correspondence if the node exists in V_i .

Based on the node mapping, we match edges using a signature-based strategy. Therefore, edges are matched based on the source node and the target node that they connect. In the first step, we try to match edges those source and target node correspond to each other and add a $(1 - 1)$ correspondence to the mapping. In a second step, we match the remaining edges where either the source or the target nodes are corresponding and add $(1 - 1)$ correspondences to the mapping, too. Analogously to the node mapping, we classify edges without a counterpart in the other model by adding a $(1 - 0)$ correspondence to the mapping if an edge only exists in version V or a $(0 - 1)$ correspondence if an edge only exists in V_i .

After the node and edge matching, an appropriate correspondence is attached to all edges and nodes in the mapping $\mathcal{M}(V, V_i)$. Based on the mapping of nodes and edges, we compute a mapping between fragments in the following.

Matching Fragments

Similar to the node and edge matching, we have to match fragments between two process models V and V_i without a correspondence in the mapping $\mathcal{M}(V, V_i)$. In general, two unmatched fragments f_V and f_{V_i} shall be matched if they fulfill the following requirements:

- f_V and f_{V_i} are of the same type, e.g. sequential, alternative, parallel, etc., and
- f_V and f_{V_i} contain corresponding model elements.

To match fragments, we apply a similarity-based matching strategy and iterate over all unmatched fragments of the same type in V and V_i to identify potentially matching pairs of fragments that contain corresponding model elements. As discussed in Section 3.4 in Chapter 3, the type of a fragment is determined by the execution logic of its contained gateways. We add $(1 - 1)$ correspondences to the mapping for pairs

² Note that gateways are not matched during node matching, they are considered during the matching of fragments.

of fragments of the same type if most of their contained nodes correspond to each other. In the case that for a fragment several potential matching candidates exists, we additionally consider the position of these candidates and match the fragment with the candidate that is in its vicinity.

During the fragment matching, we additionally establish correspondences between unmatched gateways that serve as entry or exit nodes of corresponding fragments. Finally, we add a $(1 - 0)$ correspondence to the mapping for fragments that only exists in version V and a $(0 - 1)$ correspondence for fragments that only exists in V_i .

Using this approach, a partial mapping $\mathcal{M}(V, V_i)$ between two process models can be completed such that every model element in V, V_i is attached to an appropriate correspondence. Please note that the approach to fragment matching presented here, is mainly based on the syntax of process models and their fragments. Only the type information of the fragment represents semantics. As a consequence, the obtained fragment mapping may be imprecise, since fragments may be matched whose contained elements are executed in different execution orders resulting in different sets of execution traces. To overcome this issue, we present an approach to identify equivalent fragments based on their execution traces in Chapter 8.

In the next section, we describe how the partial mapping $\mathcal{M}(V_1, V_2)$ between the process model versions V_1 and V_2 can be derived from the complete mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$.

4.4.4 Derivation of the Mapping $\mathcal{M}(V_1, V_2)$

The partial mapping $\mathcal{M}(V_1, V_2)$ can be constructed based on the common ancestor version V referenced in the complete mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$. To that extent, we iterate over the correspondences contained in the complete mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$. Depending on the type of the correspondence, we add new correspondences to $\mathcal{M}(V_1, V_2)$ as specified in Table 4.1. For instance, we add a $(1-1)$ correspondence between two model elements $x_1 \in V_1$ and $x_2 \in V_2$ if x_1 is connected to an element x by a $(1 - 1)$ correspondence in $\mathcal{M}(V, V_1)$ and x_2 is connected to x by a $(1 - 1)$ correspondence in $\mathcal{M}(V, V_2)$.

Table 4.1 Derivation of a Partial Mapping $\mathcal{M}(V_1, V_2)$

$\mathcal{M}(V, V_1)$	$\mathcal{M}(V, V_2)$	$\mathcal{M}(V_1, V_2)$
$(1 - 1)$	$(1 - 1)$	$(1 - 1)$
$(1 - 1)$	$(1 - 0)$	$(1 - 0)$
$(1 - 0)$	$(1 - 1)$	$(0 - 1)$
$(1 - 0)$	$(1 - 0)$?
$(0 - 1)$	$(0 - 1)$?

In the case, that a model element x only exists in the source process model V and no longer in V_1 and V_2 (see fourth row in Table 4.1), no correspondence is added to the mapping $\mathcal{M}(V_1, V_2)$. Similar, for newly added model elements that

exist in V_1 and V_2 but not in the source version V (see fifth row in Table 4.1), no correspondences are added to the mapping $\mathcal{M}(V_1, V_2)$. Accordingly, $\mathcal{M}(V_1, V_2)$ is also a partial mapping and needs to be completed.

Analogously to the completion of the partial mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$ described in Section 4.4.3, the mapping $\mathcal{M}(V_1, V_2)$ is completed by first matching unmatched nodes between the process model versions V_1 and V_2 . Based on the node mapping, an edge matching is performed and finally unmatched fragments are matched. After the completion, for every model element in V_1 and V_2 an appropriate correspondence is contained in the mapping $\mathcal{M}(V_1, V_2)$.

Based on the complete mappings $\mathcal{M}(V, V_1)$ and $\mathcal{M}(V, V_2)$ differences between the process models can be inferred from the contained (1–0) and (0–1) correspondences to merge different process model versions.

4.5 Summary and Discussion

In this chapter, we have established requirements a mapping between process model versions has to fulfill. With respect to these requirements, we have evaluated existing approaches to model matching classified into two different strategies: identity-based and similarity-based matching strategies. We have presented our model for the representation of correspondences between related model elements. We have introduced model matching in versioning scenarios and the concept of a partial mapping that can be created and updated automatically in such scenarios. Based on the partial mapping, we have then proposed an approach to compute complete mappings between versions of process models.

The outputs of this chapter are mappings containing sets of correspondences between related model elements contained in different business process model versions. In the next chapter, we consider possible options to represent differences between of different process model versions.

Difference Representation

For the merging of different process model versions into an integrated version, differences between the versions must be identified and represented appropriately that a human user can inspect the differences and can select a subset of the differences that shall be resolved in an integrated process model version. In this chapter, we introduce difference representations for process model change management.

To that extent, we begin by establishing requirements a difference representation for process model change management has to fulfill in Section 5.1. In Section 5.2, we first introduce a difference representation in terms of elementary change operations and show their completeness to represent all kinds of differences that can occur between two process models. In Section 5.3, we present an improved difference representation based on compound change operations. Finally, we conclude with a summary and discussion in Section 5.4.

5.1 Requirements for Difference Representation

In this section, we discuss requirements a difference representation between process models has to fulfill.

In general, a difference representation must be able to represent all possible differences that can occur between two process models in order to transform a source process model into a target process model. In addition, based on a representation it must be possible to resolve a difference. Further, similar to the merging of textual documents, process models are merged by a business user, who usually is not a computer scientist. The business user inspects and resolves certain differences in order to obtain an integrated process model version. For that purpose, the difference representation has to fulfill specific requirements concerning user-friendliness. For instance differences must be displayed in a form that is understandable by a business user, e.g. by grouping related differences that need to be resolved together.

In summary, we obtain the following two general requirements for difference representations:

- R1 (*Completeness*) The difference representation must be complete that every possible difference between two process models in the IR can be represented and based on the representation the difference can be resolved.
- R2 (*Understandability*) The representation of differences shall be user-friendly and intuitively understandable by business users.

For the representation of differences between models, typically two different techniques exist [Cicchetti et al., 2007]: Either in terms of a change log (or edit script) [Alanen and Porres, 2003, Rinderle et al., 2004, Xing and Stroulia, 2005, Rinderle et al., 2006] that contains change operations to transform one model into the other, or by representing differences visually by overlapping common parts of the models [Ohst et al., 2003].

The former kind of difference representation is operational and describes in terms of change operations how a source model can be transformed into a target model. The latter kind is a declarative difference representation [Ohst et al., 2003] that describes differences between models, e.g. by overlapping common parts of models. In [Dijkman, 2007], a declarative classification of differences between process models is presented. In contrast to an operational difference representation, declarative difference representations do not describe how one model is transformed into the other.

Examples for operational difference representations are UMLDiff [Xing and Stroulia, 2005] or the EMF Compare plugin [Eclipse Foundation, 2011c]. There, differences between models are captured in terms of change operations that can be applied directly to resolve differences between models. Change operations support modifications of single model elements such as the *addition*, *deletion*, *renaming*, and *movement*. The granularity of the change operations is by default on an elementary level, i.e. every modification of a single element results in an elementary change operation. Cicchetti et al. propose a meta-model independent approach for the representation of differences in [Cicchetti et al., 2007]. For every concrete class in a given meta-model, three individual meta-classes are added: one for the insertion, one for the deletion, and one to represent other modifications.

For the difference representation in change management of process models, an operational difference representation has several benefits compared to a declarative difference representation. For instance, an operational difference representation in terms of change operations can directly be applied to resolve the differences they describe. Further, in state-based versioning scenarios, an operational difference representation of individual differences is easier to obtain than a declarative representation of individual representations. For instance, to obtain a declarative representation of individual differences, for each difference, two process models have to be computed based on the source process model and the target process model at hand. Out of these reasons, we consider in the following only operational difference representations in terms of change operations that can directly be applied to resolve differences.

Finally, as described in Chapter 3, we assume that process models are connected, i.e. every element in a process model is on a path from a start node to an end node.

Consequently, we require that an operational difference representation supports the creation of connected merged process models.

To summarize, we capture the following two further requirements a solution for process model change management has to fulfill:

- R3 (*Directly Resolvable*) Differences between process models shall be directly resolvable based on their operational representation.
- R4 (*Connected Process Model*) The difference representation shall support the creation of connected merged process models.

In the course of our research, we first approached the problem of finding a suitable difference representation by capturing differences in terms of elementary change operations. This approach is described in Section 5.2. In Section 5.3, we then improve the difference representation based on elementary change operations and introduce the concept of compound change operations that comprise several related, elementary change operations.

5.2 Difference Representation Based on Elementary Change Operations

In this section, we introduce an approach for the representation of differences between process models in terms of elementary change operations. Then, we prove that elementary change operations are sufficient to express all differences between two process models. Finally, we evaluate elementary change operations according to the requirements for difference representations.

5.2.1 Elementary Change Operations

An elementary change operation modifies a single element in a process model. For instance, an element may be inserted into or deleted from a process model. Elementary change operations are usually supported by process modeling editors that allow users to connect and combine iteratively all kinds of model elements to develop process models.

Several model versioning approaches exist that rely on elementary change operations to represent differences between models. For instance, differences between MOF-based models are identified and represented in terms of elementary change operations in [Alanen and Porres, 2003]. Similar, the approaches [Ohst et al., 2003, Pottinger and Bernstein, 2003, Kelter et al., 2005, Eclipse Foundation, 2011c, Cicchetti et al., 2008], or [Murta et al., 2007] rely in elementary change operations. For a more complete overview, we refer to Section 2.4 in Chapter 2.

Based on the meta-model of the intermediate representation (IR), we derive a difference meta-model consisting of elementary change operation types to represent differences between process models. Such a difference meta-model can be constructed

as described in [Cicchetti et al., 2007] or in [Rivera and Vallecillo, 2008]. For every selected class in the meta-model of the IR, we add an individual meta-class for the insertion and deletion to the difference meta-model. For instance, for the class *Edge*, we add the classes *InsertEdge* and *DeleteEdge* to the difference meta-model. Figure 5.1 (a) visualizes the meta-model for elementary difference models. For convenience, the meta-model of the intermediate representation (IR) is shown next to the meta-model of the elementary difference model.

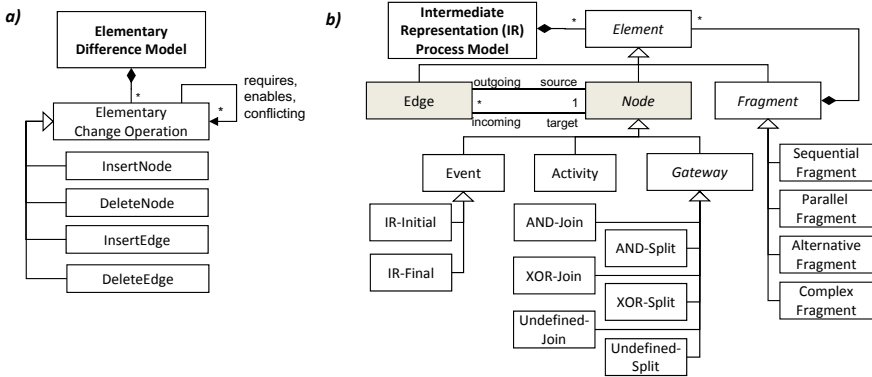


Fig. 5.1 (a) Meta-Model for Difference Models based on elementary Change Operations together with (b) the Meta-Model of the Intermediate Representation

We distinguish between different types of elementary change operations: *InsertNode*, *InsertEdge*, *DeleteNode*, and *DeleteEdge*. This set of elementary change operations can be used to represent differences caused by the insertion and deletion of Edges and Nodes in IR process models (see highlighted elements in Figure 5.1 (b)). Differences caused by the insertion and deletion of concrete nodes, such as Events, Activities, or Gateways are also represented by *InsertNode* and *DeleteNode* operations. Further, it is worth to mention that additional elementary change operation types for the representation of Fragments differences are not needed. A fragment consists of several model elements, such as edges and gateways. Hence, fragment differences are already represented by elementary change operations for Nodes and Edges.

The elementary change operations are typed over the meta-model of the intermediate representation and are defined as follows:

- $InsertNode :: IR\ Process\ Model \times Node \rightarrow IR\ Process\ Model$
- $DeleteNode :: IR\ Process\ Model \times Node \rightarrow IR\ Process\ Model$
- $InsertEdge :: IR\ Process\ Model \times Edge \times Node \times Node \rightarrow IR\ Process\ Model$
- $DeleteEdge :: IR\ Process\ Model \times Edge \times Node \times Node \rightarrow IR\ Process\ Model$

In the following, we describe the semantics of the elementary change operations informally by describing the impact of their application and give a concrete example.

InsertNode

An *InsertNode*(IR Process Model, Node) operation inserts a single Node, e.g. an Activity or a Gateway, in an IR Process Model. After the insertion, the node is not connected to any other node in the process model until an *InsertEdge* operation is applied to connect the newly inserted node with another node in the process model. The inverse operation of *InsertNode* is the *DeleteNode* operation. Figure 5.2 shows the application of an *InsertNode*(V , “Compute Customer Scoring”) operation that inserts the Activity “Compute Customer Scoring”.

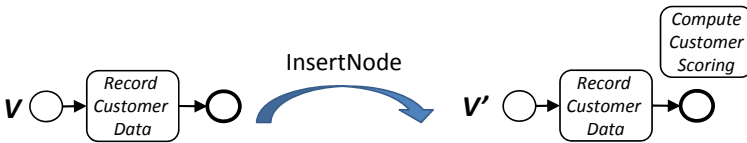


Fig. 5.2 Application of an elementary *InsertNode* Operation that inserts the Activity “Compute Customer Scoring”

DeleteNode

The *DeleteNode*(IR Process Model, Node) operation removes a Node from an IR Process Model. In approaches that do not allow dangling edges, the application of a *DeleteNode* operation will additionally delete all incoming and outgoing edges (by *DeleteEdge* operations). The inverse operation of *DeleteNode* is the *InsertNode* operation¹. In Figure 5.3, the Activity “Record Customer Data” is deleted by a *DeleteNode*(V , “Compute Customer Scoring”) operation.

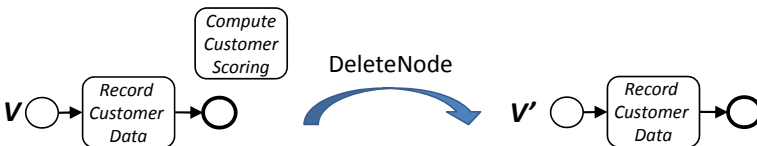


Fig. 5.3 Application of an elementary *DeleteNode* Operation that deletes the Activity “Compute Customer Scoring”

¹ In the case that additional delete operations were applied to delete dangling edges, appropriate *InsertNode* operations have to be added to the inverse operation.

InsertEdge

The $InsertEdge(IR\ Process\ Model, Edge, Node, Node)$ operation adds an Edge between two Nodes in an IR Process Model. The node s , where the edge starts, is called source node of the edge and the node t , where the edge ends, is the target node of the edge. After the insertion, the source node s and the target node t are directly connected. The inverse operation of $InsertEdge$ is the $DeleteEdge$ operation. The application of an $InsertEdge(V, e, \text{“Record Customer Data”}, \text{“Compute Customer Scoring”})$ operation is visualized in Figure 5.4 by connecting the Activities “Record Customer Data” and “Compute Customer Scoring”.



Fig. 5.4 Application of an elementary $InsertEdge$ Operation

DeletedEdge

The $DeleteEdge(IR\ Process\ Model, Edge, Node, Node)$ operation removes an Edge between two Nodes in an IR Process Model. Its inverse operation is the $InsertEdge$ operation. An example for the $DeleteEdge$ operation is given in Figure 5.5. There, the outgoing edge e of the activity “Record Customer Data” is deleted by the $DeleteEdge(V, e, \text{“Record Customer Data”}, \text{“Compute Customer Scoring”})$ operation.



Fig. 5.5 Application of an elementary $DeleteEdge$ Operation that disconnects the Activities “Record Customer Data” and “Compute Customer Scoring”

In the next section, we evaluate whether the elementary change operations introduced here are sufficient to represent all possible differences between two IR process models.

5.2.2 Completeness of Elementary Change Operations

Having introduced elementary change operations for the representation of differences between process models in the intermediate representation (IR), one question to ask is whether all possible differences that can occur between two process models

V and V_i can be represented using elementary change operations. If this is the case, then the set of elementary change operations is complete.

To proof the completeness of elementary change operations, we first reason about possible modifications that can be applied to a process model. Based on these modifications, we define two classes of differences between process models, namely *InsertDifferences* and *DeleteDifferences*. Finally, we show that these classes of differences can be represented by elementary change operations.

For the following discussion, we assume that two syntactically equal process models V and V_i are given. Based on this pair of process models, we introduce a difference between the two models by modifying V_i . To that extent, we have to consider the meta-model of the intermediate representation and derive modifications resulting in differences between V and V_i . The modifications have to be derived in such a way that after the modification, V_i is still an instance of the IR meta-model. We can derive the following three different modifications:

1. **(Addition of a model element):** A concrete model element specified in the meta-model can be added to the process model V_i . In the case of the IR, we can add an *Edge* or a concrete *Node* to the model V_i ².
2. **(Removal of a model element):** A model element that already exists in the process model V_i can be removed from V_i . For the IR, we can remove an *Edge* or a concrete *Node* from the model V_i .
3. **(Update of a model element):** A model element that already exists in the process model V_i can be updated by changing one of its attributes. For instance, we can change the name of an *Activity* in the IR *Process Model* V_i or alter the source of an *Edge* by reconnecting it to a different *Node*.

Apparently, these modifications comprise all possible differences that can occur between two IR *Process Models*. For convenience, we further assume that the last modification, which updates existing model elements, can be reduced to a combination of the first and second modification. That means, instead of updating an existing model element in a process model, the model element can be removed from the process model and afterwards added again with updated attributes.

Accordingly, the first and the second modifications are sufficient to create all possible differences between two process models. We distinguish the obtained differences into two types *InsertDifference* and *DeleteDifference*, which are defined next.

Definition 4 (InsertDifference). *Given two IR Process Models V, V_i and a mapping $\mathcal{M}(V, V_i)$ containing the set $\mathcal{M}_{0-1}(V, V_i)$ that consists of $(0-1)$ correspondences in $\mathcal{M}(V, V_i)$ to represent *Elements* that only exist in V_i , then an *InsertDifference* is defined as an *Element* $x \in \mathcal{M}_{0-1}(V, V_i)$.*

² *Fragments* are not directly modified in an IR process model. They are computed based on the *Edges* and *Nodes* in an IR *Process Model* as described in Chapter 3.

Definition 5 (DeleteDifference). Given two IR Process Models V , V_i and a mapping $\mathcal{M}(V, V_i)$ containing the set $\mathcal{M}_{1-0}(V, V_i)$ that consists of $(0 - 1)$ correspondences in $\mathcal{M}(V, V_i)$ to represent Elements that only exist in V , then a Delete-Difference is defined as an Element $y \in \mathcal{M}_{1-0}(V, V_i)$.

To prove the completeness of the set of elementary change operations, we have to show that using elementary changes these two types of differences can be represented and resolved based on the representation. The following theorem establishes a relationship between the difference types and our elementary change operations:

Theorem 1 (Completeness of Elementary Change Operations). Given two IR Process Models V, V_i and a set of elementary change operations consisting of *InsertNode*, *DeleteNode*, *InsertEdge*, and *DeleteEdge*. For each possible difference between the process models V and V_i a sequence of appropriate elementary change operations $op_1 \dots op_n$ exists that resolves the difference.

Proof: As mentioned above, possible differences between two process models can be distinguished into two difference types: *InsertDifference* and *DeleteDifference*. In the following, we show how elementary change operations can be used to represent differences of these types. Let a difference δ between the process models V and V_i be given and $type(\delta)$ shall be the difference type of δ .

- If $type(\delta) = \textit{InsertDifference}$: There exists a model element e in V_i that does not exist in process model V . The difference can be represented by an elementary change operation that resolves the difference by inserting the model element e also into process model V . Depending on the type of the model element e one of the following elementary change operation is used: *InsertNode* or *InsertEdge*.
- If $type(\delta) = \textit{DeleteDifference}$: There exists a model element e in V that does not exist in process model V_i . The difference can be represented by an elementary change operation that resolves the difference by deleting the model element e also from process model V . Depending on the type of the model element e one of the following elementary change operation is used: *DeleteNode* or *DeleteEdge*.

Theorem 1 shows that elementary change operations fulfill the property of completeness. That means, all differences between process models can be represented and resolved using elementary change operations. In the following section, we provide an example of an elementary difference model.

5.2.3 An Example of an Elementary Difference Model

Table 5.1 shows an elementary difference model $\Delta(V, V_2)$ that represents the differences between the process models V and V_2 from our example (see Figure 1.3) in terms of elementary change operations. The operations are arranged according to their appearance in the process model V_2 going through the process model from left to right. To enable the distinction between different inputs and outputs of gateways, we labeled the inputs with $I1..In$ and the outputs with $O1..On$.

Table 5.1 Change Log $\Delta(V, V_2)$ consisting of Elementary Change Operations that represent the Differences between the Process Models V and V_2

$\Delta(V, V_2)$ DelEdge(V, e ₂ , "Rec. Cust. Data", "Comp. Cust. Scoring") InsNode(V, "XOR - Join fLoop") InsNode(V, "XOR - Split fLoop") InsEdge(V, e ₁₁ , "Recorl Cust. Data", "XOR - Join fLoop") InsEdge(V, e ₁₂ , "XOR - Split fLoop", "Comp. Cust. Scoring") InsNode(V, "Check Cust. Data") InsNode(V, "Retrieve add. Data") InsEdge(V, e ₁₃ , "XOR - Join fLoop", "Check Cust. Data") InsEdge(V, e ₁₄ , "Check Cust. Data", "XOR - Split fLoop") InsEdge(V, e ₁₅ , "Retrieve add. Data", "XOR - Join fLoop") InsEdge(V, e ₁₆ , "XOR - Split fLoop", "Retrieve add. Data") DelEdge(V, e ₅ , "Prep. Bank Card", "Prep. Credit Card") InsNode(V, "AND - Split fPar") InsNode(V, "AND - Join; 2 fPar") InsEdge(V, e ₁₇ , "Prep. Bank Card", "AND - Split fPar")	... InsEdge(V, e ₁₈ , "AND - Join; 1 fPar", "Prep. Credit Card") InsNode(V, "Print Cr. C. Contract") InsNode(V, "Select Cr. C. Comp.") InsNode(V, "Ask for Cr. Limit") InsNode(V, "Calc. Interest Rate") InsEdge(V, e ₁₉ , "AND - Split fPar", "Print Cr. C. Contract") InsEdge(V, e ₂₀ , "Print Cr. C. Contract", "AND - Join; 1 fPar") InsEdge(V, e ₂₁ , "AND - Split fPar", "Select Cr. C. Comp.") InsEdge(V, e ₂₂ , "Select Cr. C. Comp.", "AND - Join; 2 fPar") InsEdge(V, e ₂₃ , "AND - Split fPar", "Ask for Cr. Limit") InsEdge(V, e ₂₄ , "Ask for Cr. Limit", "AND - Join; 2 fPar") InsEdge(V, e ₂₅ , "AND - Join; 2 fPar", "Calc. Interest Rate") InsEdge(V, e ₂₆ , "Calc. Interest Rate", "AND - Join; 1 fPar") DelEdge(V, e ₈ , "Prep. P. Bank Card", "Set D. Withd. Limit") DelEdge(V, e ₉ , "Set D. Withd. Limit", "XOR - Join fAlt") DelNode(V, "Set D. Withd. Limit") InsNode(V, "Set Cr. Limit to 0") InsNode(V, "Remove Cr. Card") InsNode(V, "Set Interest Rate to 0") InsEdge(V, e ₂₇ , "Prep. P. Bank Card", "Set Cr. Limit to 0") InsEdge(V, e ₂₈ , "Set Cr. Limit to 0", "Remove Cr. Card") InsEdge(V, e ₂₉ , "Remove Cr. Card", "Set Interest Rate to 0") InsEdge(V, e ₃₀ , "Set Interest Rate to 0", "XOR - Join fAlt") DelEdge(V, e ₁₀ , "XOR - Join fAlt", "End") InsNode(V, "Open Account") InsEdge(V, e ₃₁ , "XOR - Join fAlt", "Open Account") InsEdge(V, e ₃₂ , "Open Account", "End")
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Such a difference model can be shown to a business user, who then applies selected change operations in order to resolve differences between process models. In change management, a difference model is typically referred to as a change log. Accordingly, we will use the terms difference model and change log synonymously in the remainder of this book. In the next section, we evaluate the suitability of a difference representation based on elementary change operations for process model change management.

5.2.4 Discussion

In this section, we evaluate the use of elementary change operations with respect to our requirements for differences representation that we have introduced in Section 6.1.

All possible differences between two process models can be represented by an appropriate elementary change operation and the application of an elementary change operation resolves the difference it represents.

However, looking at the change log presented in Table 5.1, the total number of elementary change operations required to represent the differences between the process models V and V_2 is overwhelming. Based on the elementary change operations it is difficult to grasp the actual high-level logical/structural change that was applied to a process model. Even simple differences result in a multitude of elementary change operations. For instance, the insertion of a single node in a connected process model results in four elementary change operations: First, the new node is inserted, resulting in an *InsertNode* change operation. Then, a *DeleteEdge* change operation occurs by the removal of the edge that connects the predecessor and the successor of the newly inserted node. Finally, the new node is connected to its predecessor and successor, rising two *InsertEdge* operations. Based on these four elementary change operations, it is difficult to understand the intention of the difference (i.e. a single node was inserted between a predecessor and a successor).

In addition, based on elementary change operations it is difficult to identify, which differences can be resolved independently, i.e. without the necessity to resolve other differences in advance. That means for the small example from above (insertion of an activity), in order to obtain a connected process model, a business user has to ensure that all four elementary change operations are applied together.

Table 5.2 summarizes the suitability of elementary change operations for the purpose of difference representation in process model change management. The granularity of elementary change operations is too fine grained to describe the actual intention of changes that are applied to process models.

In the next section, we introduce an improved approach for difference representation that considers differences on a higher level.

Table 5.2 Features of Elementary Change Operations according to the Requirements for Difference Representations (Section 5.1)

Requirements for Difference Representation	Elementary Change Operations
[R1] <i>Completeness</i>	✓
[R2] <i>Understandability</i>	✗
[R3] <i>Directly Resolvable</i>	✓
[R4] <i>Connected Process Model</i>	✗

5.3 Difference Representation Based on Compound Change Operations

In this section, we present an improved approach for difference representation between process models that overcomes the issues of elementary change operations. The approach represents differences in terms of *compound change operations* that are composed of several related elementary changes.

Analogously to the introduction of elementary change operations in the previous section, we first describe compound change operations and then show the completeness of compound change operations in Section 5.3.2. In Section 5.3.3, we provide an example of a compound difference model describing the differences between the process models V and V_2 (see Figure 1.3). Finally, we discuss compound change operations according to the requirements for difference representation.

5.3.1 Compound Change Operations

In contrast to elementary change operations, that modify atomic model elements, compound change operations comprise several elementary change operations. Thereby, compound change operations represent differences on a higher level and enable us to abstract from differences due to single edges and gateways.

Resolving differences using compound change operations is improved in two ways: First, compound change operations take care of an automatic reconnection of the control-flow in the process model. For instance, an activity is not only inserted but it is also connected to its preceding and succeeding node. Second, compound change operations comprise related elementary changes that must be applied to obtain a connected process model. For instance, a difference due to the insertion of an `AND-Split` is usually accompanied with at least a difference caused by the insertion of an `AND-Join`, which together form a parallel fragment. These related differences are represented together in terms of a compound fragment operation. If such a compound fragment operation shall be applied to resolve the difference it represents, the operation ensures that the fragment is inserted completely and is also connected to its preceding and succeeding node in the obtained integrated process model.

Figure 5.6 (a) visualizes the meta-model for compound difference models based on compound change operations. For convenience, the meta-model of the intermediate representation (IR) is shown next to the meta-model of the difference model.

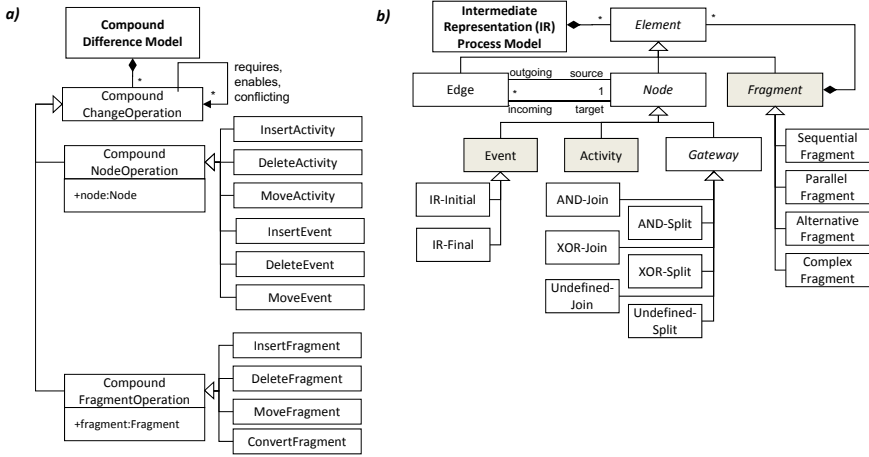


Fig. 5.6 (a) Meta-Model for Difference Model based on CompoundChangeOperations together with (b) the Meta-Model of the Intermediate Representation

We distinguish between *compound activity operations*, *compound event operations* and *compound fragment operations* that are used to represent differences between to process models caused by modifications of the highlighted elements in the meta-model of the IR.

In the following, we introduce compound change operations for activities and fragments in detail. For every compound change operation, we describe the semantics informally³ by describing the impact of its application in terms of elementary change operations and give an example for clarification. Note that we do not describe *compound event operations* separately, since they are identical to *compound activity operations* except that they modify events instead of activities.

Insert-Operations

An *InsertActivity* operation takes as input an IR Process Model, an Activity, and two Nodes and produces a modified IR Process Model.

$$InsertActivity :: IR \text{ PM} \times Activity \times Node \times Node \longrightarrow IR \text{ PM}$$

The *InsertActivity*(V, a, x, y) operation inserts a single Activity a into the IR Process Model V and connects the Activity with a preceding Node x and succeeding Node y . The operation comprises a sequence of elementary change operations: In the case, that the predecessor x and the successor y are already connected by a control-flow edge, this edge is removed. Then, the new activity a is inserted in the process model V and it is connected by two *InsertEdge* operations that connect

³ A formal definition of the semantics of compound change operations in terms of typed attribute graph transformation rules can be found in Section 7.2.3 of Chapter 7.

the predecessor x and the successor y with the newly inserted activity. The inverse operation of $InsertActivity(V, a, x, y)$ is the $DeleteActivity(V, a, x, y)$ operation. An example for the application of an $InsertActivity$ operation that inserts the activity “*Compute Customer Scoring*” is shown in Figure 5.7.



Fig. 5.7 Application of an $InsertActivity$ Compound Change Operation

An $InsertFragment$ operation takes as input an IR Process Model, a Fragment, and two Nodes and produces a modified IR Process Model.

$$InsertFragment :: IR\ PM \times Fragment \times Node \times Node \longrightarrow IR\ PM$$

The $InsertFragment(V, f, x, y)$ operation inserts an entire Fragment f into the IR Process Model V . A fragment is specified by a 4-tuple $f = (G, R, entry, exit)$, where G is a list of contained Gateways that split and join the control-flow within the fragment f . R is a relation that specifies how the contained Gateways are connected by edges. $Entry$ and $exit$ determine the entry and exit Nodes of f . To obtain a connected process model after the application of the operation, the $entry$ and the $exit$ Nodes are connected with the preceding Node x and the succeeding Node y of f . In addition, the Nodes contained in f are connected by edges according to the relation R .

The behavior of the operation can be described by a sequence of elementary change operations: First, the edge that connects the predecessor x with the successor y is removed. Then, the new fragment f is inserted by inserting its gateways specified in G and the $entry$ and $exit$ nodes in the process model using $InsertNode$ operations. The $entry$ node is then connected to the predecessor x and, analogously, the $exit$ node is connected to the predecessor y by two $InsertEdge$ operations. Finally, the contained gateways in the fragment are connected according to relation R in order to obtain a connected process model. The inverse operation of $InsertFragment(V, f, x, y)$ is the $DeleteFragment(V, f, x, y)$ operation. Figure 5.8 gives an example for the insertion of an alternative fragment f_a into the process model V .

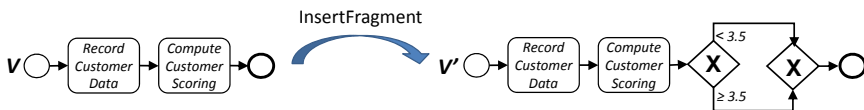


Fig. 5.8 Application of an $InsertAlternativeFragment$ Compound Change Operation

To distinguish between *InsertFragment* operations for different fragment types, we refer to an *InsertFragment* operation by adding the type of the inserted fragment to the name of the operation, e.g. *InsertCyclicFragment* or *InsertConcurrent-Fragment*.

Delete-Operations

A *DeleteActivity* operation takes as input an IR Process Model, an Activity, and two Nodes and produces a modified IR Process Model.

$$DeleteActivity :: IR\ PM \times Activity \times Node \times Node \longrightarrow IR\ PM$$

The *DeleteActivity*(*V*, *a*, *x*, *y*) operation deletes a single Activity *a* from the IR Process Model *V* and reconnects the former predecessor Node *x* and successor Node *y*. The behavior of the operation comprises a sequence of elementary change operations: First, activity *a* is disconnected from its predecessor *x* and its successor *y* by applying two *DeleteEdge* operations. Then, a *DeleteNode* operation removes activity *a* from the process model. Finally, the predecessor *x* and successor *y* are connected by executing an *InsertEdge* operation. The inverse operation of *DeleteActivity*(*V*, *a*, *x*, *y*) is the *InsertActivity*(*V*, *a*, *x*, *y*) operation. Figure 5.9 gives a concrete example of the application of a *DeleteActivity* operation that deletes the activity “Compute Customer Scoring” from process model *V*.



Fig. 5.9 Application of a *DeleteActivity* Compound Change Operation

A *DeleteFragment* operation takes as input an IR Process Model, a Fragment, and two Nodes and produces a modified IR Process Model.

$$DeleteFragment :: IR\ PM \times Fragment \times Node \times Node \longrightarrow IR\ PM$$

The *DeleteFragment*(*V*, *f*, *x*, *y*) operation deletes an entire Fragment *f* from the IR Process Model *V* and reconnects the control flow. Analogously to *Insert-Fragment*, a fragment is specified as a 4-tuple $f = (G, R, entry, exit)$.

For the deletion of a fragment *f*, we assume that the fragment is empty, i.e. *f* only contains the model elements specified in $f = (G, R, entry, exit)$. This assumption potentially requires that other compound change operation have been applied in advance to remove the contents of the fragment, e.g. by deleting or moving model elements. Such dependencies between compound change operations are discussed separately in their own Chapter 7. For the moment, we assume that a fragment that shall be deleted is empty.

The behavior of a *DeleteFragment* operation comprises a sequence of elementary change operations: First, the *entry* is disconnected from its predecessor x and the *exit* node is disconnected from its successor y by two *DeleteEdge* operations. Then, all edges that connect the gateways in the fragment are deleted by applying a *DeleteEdge* operation for each edge determined by the relation R . For every gateways $g \in G$ a *DeleteNode* operation is executed to delete the gateway from the process model. Finally, to obtain a connected process model the predecessor x and the successor y of fragment f are reconnected. The inverse operation of *DeleteFragment*(V, f, x, y) is the *InsertFragment*(V, f, x, y) operation. In Figure 5.10, a concrete *DeleteFragment* operation that deletes an alternative fragment is applied on process model V .

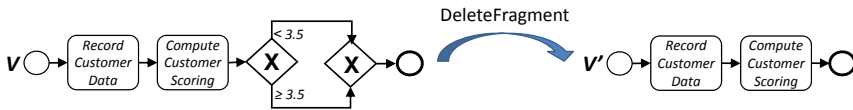


Fig. 5.10 Application of a *DeleteAlternativeFragment* Compound Change Operation

To distinguish between *DeleteFragment* operations for different fragment types, we refer to a *DeleteFragment* operation by adding the type of the deleted fragment to the name of the operation, e.g. *DeleteCyclicFragment* or *DeleteConcurrent-Fragment*.

Move-Operations

A *MoveActivity* operation takes as input an IR Process Model, an Activity, and four Nodes and produces a modified IR Process Model.

$$MoveActivity :: IR\ PM \times Activity \times Node \times Node \times Node \times Node \longrightarrow IR\ PM$$

The operation *MoveActivity*(V, a, v, w, x, y) gives an example. It moves a single Activity a from a position specified by its current preceding Node v and succeeding Node w to a new position between the new predecessor x and successor y in the IR Process Model V .

The behavior of the operation comprises the following sequence of elementary change operations: First, activity a is disconnected from its current predecessor v and its successor w by applying two *DeleteEdge* operations. Afterwards, the current predecessor v and successor w are connected again by an *InsertEdge* operation. In the case, that the new predecessor x and the successor y of activity a are already connected by a control-flow edge, this edge is removed. To complete the compound change operation, activity a is connected by two *InsertEdge* operations to its new predecessor x and its new successor y .

The operation *MoveActivity*(V, a, v, w, x, y) can be inverted by exchanging its position parameters resulting in the operation *MoveActivity*(V, a, x, y, v, w). An

example of the application of a concrete *MoveActivity* operation is visualized in Figure 5.11. There, the activity “*Compute Customer Scoring*” is moved behind the alternative fragment.



Fig. 5.11 Application of a *MoveActivity* Compound Change Operation

A *MoveFragment* operation takes as input an IR Process Model, a Fragment, and four Nodes and produces a modified IR Process Model.

$$MoveFragment :: IR\ PM \times Fragment \times Node \times Node \times Node \times Node \longrightarrow IR\ PM$$

The *MoveFragment*(*V*, *f*, *v*, *w*, *x*, *y*) operation moves the Fragment *f* from a position specified by its current predecessor Node *v* and successor Node *w* to a new position between predecessor Node *x* and successor Node *y* in the IR Process Model *V*.

The behavior of the operation is described by the following sequence of elementary change operations: First, fragment *f* is disconnected from its current position by applying two *DeleteEdge* operations that disconnect the *entry* and *exit* nodes from the predecessor *v* and the successor *w*. Afterwards, the current predecessor *v* and successor *w* are connected again by an *InsertEdge* operation. In the case, that the new predecessor *x* and the successor *y* of fragment *f* are already connected by a control-flow edge, this edge is removed. The compound change operation is completed by applying two *InsertEdge* operations that connect the new predecessor *x* of the fragment with the *entry* node and the new successor *y* with the *exit* node.

The operation *MoveFragment*(*V*, *f*, *v*, *w*, *x*, *y*) can be inverted by the operation *MoveFragment*(*V*, *f*, *x*, *y*, *v*, *w*) whose current and new position parameters are exchanged. Figure 5.12 gives an example of the application of a concrete *MoveFragment* operation.

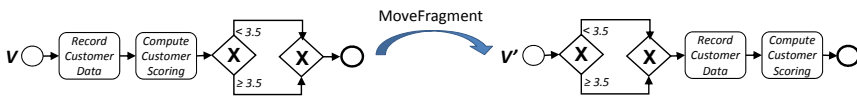


Fig. 5.12 Application of a *MoveFragment* Compound Change Operation that moves an alternative Fragment

Analogously to the other fragment operations, we distinguish between *MoveFragment* operations for different fragment types, by referring to *MoveFragment* operations by adding the type of the moved fragment to the name of the operation, e.g. *MoveAlternativeFragment* or *MoveConcurrentFragment*.

ConvertFragment-Operation

A *ConvertFragment* operation takes as input an IR Process Model, two Fragments, and two Nodes and produces a modified IR Process Model.

$$\text{ConvertFragment} :: \text{IR PM} \times \text{Fragment} \times \text{Fragment} \times \text{Node} \times \text{Node} \longrightarrow \text{IR PM}$$

The *ConvertFragment*(V, f, f_c, x, y) operation gives an example. It substitutes an existing Fragment f by a Fragment f_c in an IR Process Model V . Analogously to the former operations for fragments, fragments are specified as 4-tuples ($G, R, \text{entry}, \text{exit}$). Since a *ConvertFragment* modifies the structure of an existing fragment, we have to consider two fragments f and f_c for the application of the operation, whereas f specifies the existing fragment and f_c the converted fragment.

For the conversion of a fragment generally three different cases exist: First, the set of the contained sequential fragments in fragment f is changed by inserting or deleting gateways and/or edges. Second, the type of the fragment f may be changed by adding new gateways to the fragment or substituting existing gateways. To give an example, the AND-split and join gateways of a parallel fragment may be substituted by XOR gateways resulting in a type change of the parallel fragment to an alternative fragment. Third, a mixture of the first and the second case may be identified.

The behavior of the *ConvertFragment* operation can be described based on elementary change operations: First, we disconnect the gateways of the existing fragment f from the control-flow by applying *DeleteEdge* operations. Then, we substitute the gateways of the existing fragments by the gateways of the converted fragment f_c . To that extent, we first delete the existing gateways applying *DeleteNode* operations and then we insert the gateways from the converted fragment using *InsertNode* operations. Finally, we connect the inserted gateways according to the relation R to reestablish a connected fragment. For the reconnection, the mapping M between the fragments f and f_c must be considered. This behavior can be improved, by deleting only the gateways from fragment f that were actually modified in the converted fragment f_c .

An example for the application of a *ConvertFragment* operation is shown in Fig. 5.13. There, an existing alternative fragment f_a is converted into a fragment f_c by adding a new XOR-split gateway into the fragments structure. The application of this operation does not result in a fragment type change, i.e. both fragments f_a and f_c are alternative fragments. A fragment type change occurs if the logic of the gateways changes in a fragment, e.g. an AND-split is inserted in an alternative fragment.

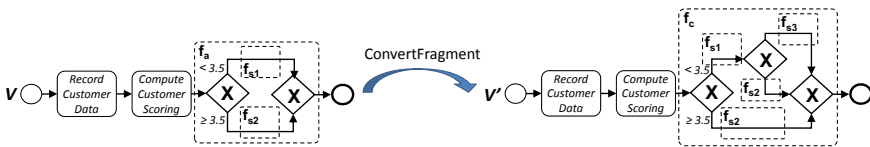


Fig. 5.13 Application of a *ConvertFragment* Compound Change Operation

Having introduced our compound difference meta-model based on compound change operations, we reason about the completeness of compound change operations in the next section.

5.3.2 Completeness of Compound Change Operations

Similar to elementary change operations, we have to show that all possible differences that can occur when a process model V is changed into a process model V_i , can be represented and resolved using compound change operations. If this is the case, then the set of compound change operations is complete.

To prove the completeness of compound change operations, we leverage the completeness of elementary change operations that we have shown in Section 5.2.2. We assume an elementary change log $\Delta(V, V_i)$ (or difference model) is given consisting of elementary change operations that represent the differences between two given process models V and V_i . As introduced in Section 5.2, the set of elementary change operations consists of *InsertNode*, *DeleteNode*, *InsertEdge*, and *DeleteEdge*. Further, we assume that the change log is minimal, i.e. $\Delta(V, V_i)$, does not contain elementary change operations that are redundant or overwrite each other.

Given such a minimal change log $\Delta(V, V_i)$, we have to show that each elementary change operation in this change log gives rise to a compound change operation involving activity, event, or fragments and no elementary change operation will be ignored. The following theorem establishes a relationship between the minimal change log and our compound change operations:

Theorem 2 (Completeness of Compound Change Operations). *Given two business process models V, V_i and two change logs $\Delta_{elem}(V, V_i)$ consisting of elementary change operations and $\Delta_{comp}(V, V_i)$ consisting of compound change operations. Further, let both change logs represent the differences between the process models V and V_i .*

For each elementary change operation $op_e \in \Delta_{elem}(V, V_i)$ there exists a compound change operations $op_c \in \Delta_{comp}(V, V_i)$ such that op_c comprises op_e .

Proof sketch: Given $op_e \in \Delta_{elem}(V, V_i)$:

- If $op_e = \text{InsertNode}$ we can distinguish two cases:
 - If op_e inserts an activity then there exists a dedicated *InsertActivity* op_c exists that comprises op_e . Analogously if op_e inserts an event a dedicated *InsertEvent* op_c exists that comprises op_e .
 - If op_e inserts a gateway then the gateway either creates a new fragment or is inserted into an existing fragment. In the first case, the insertion of the gateway is comprised in an *InsertFragment* compound change operation op_c , the second case results in a *ConvertFragment* operation op_c . In both cases, op_c (*InsertFragment* or *ConvertFragment*) comprises op_e .
- If $op_e = \text{InsertEdge}$ then this involves integrating new nodes (gateways, activities, or events) into the process model, reordering of existing fragments or nodes, or reconnection of existing nodes in case of deletions.

- In the case of an insertion, there must be a related elementary *InsertNode* operation, resulting in an appropriate *InsertActivity*, *InsertEvent*, *InsertFragment*, or *ConvertFragment* compound change operations op_c comprising op_e .
 - In the case of an reordering of existing fragments or nodes, the elementary *InsertEdge* operation (possibly together with other *InsertEdge* operations) gives rise to appropriate *MoveActivity*, *MoveEvent*, *MoveFragment*, or *ConvertFragment* compound change operations op_c comprising op_e .
 - Finally, in the case of a deletion, there must be a suitable *DeleteActivity*, *DeleteEvent*, *DeleteFragment*, or *ConvertFragment* operation op_c comprising op_e .
- The cases $op = DeleteNode$ or $DeleteEdge$ can be treated analogously.

This result shows that the set of compound change operations fulfills the completeness requirement for difference representation. In the next section, we present a change log consisting of compound change operations representing the differences between two real world process models.

5.3.3 A Change Log with Compound Change Operations

In this section, we give an example of a concrete change log $\Delta(V, V_2)$ that represents the differences between the process models V and V_2 introduced in Chapter 1 in Figure 1.3. Figure 5.14⁴ shows the concrete change log $\Delta(V, V_2)$.

The operations in $\Delta(V, V_2)$ are arranged according to their appearance in the process model V_2 going through the process model from left to right. To enable the distinction between different inputs and outputs of gateways, we labeled the inputs with $I1..In$ and the outputs with $O1..On$. The application of all change operations contained in the change log resolves the differences between the two process models completely. That means, the application of all changes on process model V transforms V into V_2 .

Next, we evaluate compound change operations according to our requirements for difference representations.

5.3.4 Discussion

Not surprisingly, the change log $\Delta(V, V_2)$ based on compound change operations requires far less change operations to represent the differences than a change log consisting of elementary change operations. (compare Figures 5.1 and 5.14).

Analogously to elementary change operations, we have shown that the set of compound change operations is complete and all possible differences between two process models can be represented by an appropriate compound change operation.

⁴ To prevent line breaks in printed change logs, we may abbreviate the names of change operations and model elements. For instance, we write *MoveAct* instead of *MoveActivity* or “Check Cust. Data” instead of “Check Customer Data”.

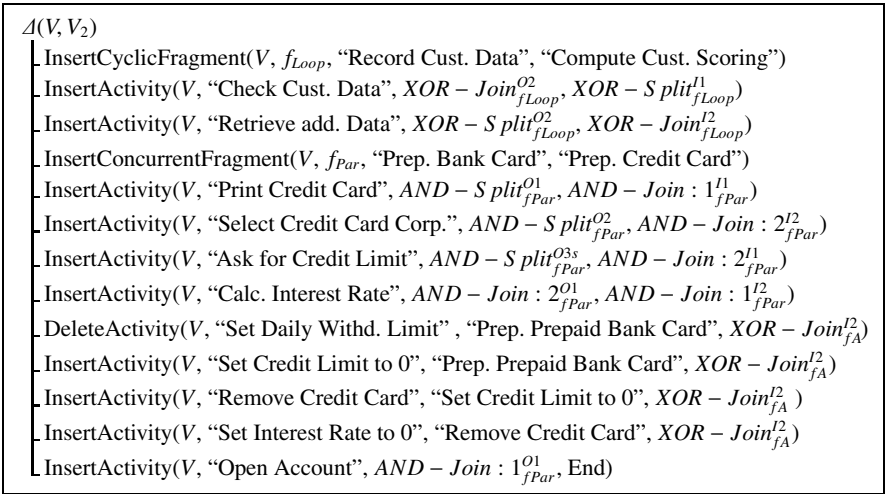


Fig. 5.14 Concrete Change Log $\Delta(V, V_2)$ consisting of Compound Change Operations that represent the Differences between Process Model V and V_2

The application of all compound change operations that describe the differences between two process models V and V_i , transforms V into V_i .

In contrast to elementary change operations, compound change operations turned out to be more intuitive to human users. An evaluation has shown that the granularity of compound change operations is suitable for a user-friendly resolution of differences between process models. By abstracting from individual edge changes and an automatic reconnection of the control flow in the process models, the application of compound change operations results in connected process models. As a consequence, the merging of different process model versions requires far less user interaction than merging approaches based on elementary change operations. We present the result of the evaluation in detail in Appendix A.

Table 5.3 summarizes the suitability of compound change operations for the purpose of difference representation in process model change management.

Table 5.3 Comparison of Elementary and Compound Change Operations according to Requirements for Difference Representations

Requirements for Difference Representation	Elem. Change Operations	Compound Change Operations
[R1] <i>Completeness</i>	✓	✓
[R2] <i>Understandability</i>	✗	✓
[R3] <i>Directly Resolvable</i>	✓	✓
[R4] <i>Connected Process Model</i>	✗	✓

Overall, a difference representation in terms of compound change operations fulfills all our requirements regarding user-friendliness and applicability to be suitable in change management of process models.

5.4 Summary and Discussion

In this chapter, we have considered the representation of differences between process models. We first have established requirements such a representation has to fulfill. Then, we approached the problem of difference representation by introducing a difference model based on elementary change operations and showed their completeness to represent all possible difference.

Since elementary change operations did not fulfill all of our requirements, we came up with an improved difference model based on compound change operations. Compound change operations turned out to be more suitable for the representation of differences in change management of process models. In particular, due to the coarser granularity of compound change operations the merging of process models requires far less user interaction than merging approaches based on elementary changes. In addition, compound change operations ease understandability of the actual differences between two process models, since they are close to the intention a business user has in mind when modifying a process model.

In the next chapter, we introduce our approach for the detection of differences that results in a change log consisting of compound change operations.

Difference Detection

In the previous chapter, we have introduced our difference model based on compound change operation as an appropriate means to represent differences between process models. In this chapter, we present an approach to actually identify differences between two process models.

As input, the approach expects two process models in the intermediate representation and a mapping between them as introduced in Chapter 4 (see Figure 6.1). The result of the difference detection is a reconstructed change log consisting of compound change operations that represent the differences between two process models. The compound change operations can directly be applied to resolve the differences they represent. In contrast to a mapping that relates corresponding model elements, a change log describes how one process model can be transformed into the other.

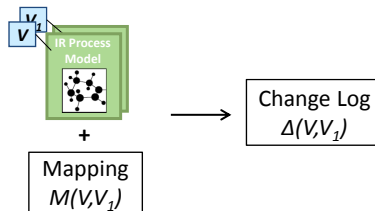


Fig. 6.1 Difference Detection Overview

In the next section, we establish requirements our approach to difference detection has to fulfill. In Section 6.2, we present our approach that adds a compound change operation for each detected difference into a reconstructed change log. In Section 6.3, we arrange the change log according to the hierarchical structure of the underlying process models and assign each change operation to the fragment, which is affected by the operation. We complete the difference detection by specifying position parameters of compound change operations in Section 6.4. Finally, we conclude with a summary and discussion.

6.1 Requirements for Difference Detection

In this section, we discuss requirements a solution for difference detection in process model change management has to fulfill.

In general, the detection of differences introduced into a process model is straightforward in a process-aware information system [Dumas et al., 2005, Reichert and Dadam, 1998] that provides change logs (see, e.g. [Rinderle et al., 2004, Rinderle et al., 2006]). In these scenarios differences between process models are given and do not need to be detected.

However, in scenarios where process models are developed independently in a distributed environment, a change log is usually not available. Reasons for this are either the use of modeling tools that do not provide logging mechanisms or the exchange of process models across tool boundaries. In such situations, the detection of differences has to be performed in a state-based manner by comparing process models before and after changes have been made.

For this purpose, several approaches exist that can roughly be divided into generic approaches that can deal with different models and approaches that focus on models in a specific language. A generic approach for matching and difference detection of UML models is presented in [Kelter et al., 2005]. In this approach, UML class diagrams are abstracted to a generic data model comparable to our intermediate representation, which is then used for matching and difference detection. The EMF-Compare Framework [Eclipse Foundation, 2011c] can be used for matching and difference detection of EMF-based models. Alanen et al. [Alanen and Porres, 2003] present algorithms to calculate the difference and union of models based on Meta Object Facility (MOF) [OMG, 2010c] assuming model elements with unique IDs. These approaches focus on structural diagrams, such as class diagrams, rather than on graph-like process models. In addition, they result in elementary changes that are inconvenient for process model change management.

In our approach, the result of the difference detection shall be a reconstructed change log consisting of compound change operations that transforms one process model into the other. To that extent, every detected difference is represented by an appropriate compound change operation in the reconstructed change log.

For two versions of a process model V and V_1 , generally multiple change logs exist that transform one process model version into the other. Figure 6.2 gives an example.

The process model V describes necessary steps to open a banking account for a customer. This process model was transformed into process model version V_1 by moving the activity “*Open Account*” and the highlighted fragment f_{Loop} . A correct change log $\Delta(V, V_1)$ is shown in Figure 6.3¹ consisting of two compound change operations that transform process model V into V_1 .

In Figure 6.4, another correct change log $\Delta'(V, V_1)$ is shown, consisting of four compound change operations. In contrast to the change log $\Delta(V, V_1)$, here the activity

¹ To prevent line breaks in printed change logs, we abbreviate the names of change operations and model elements. For instance, we write *MoveAct* instead of *MoveActivity* or “Rec. Cust. Data” instead of “Record Customer Data”.

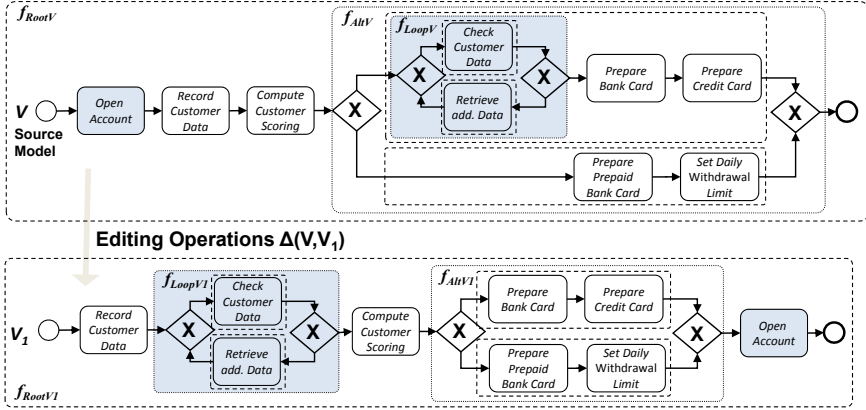


Fig. 6.2 Two Process Model Versions V and V_1

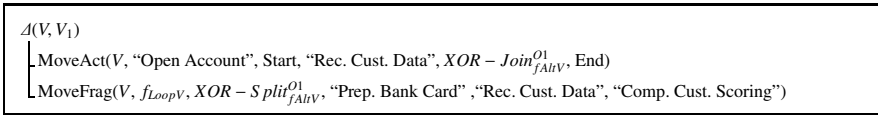


Fig. 6.3 Correct Change Log $\Delta(V, V_1)$ consisting of Compound Change Operations that transforms the Process Model V into V_1 (see Figure 6.2)

“Open Account” is not moved to its new position. Instead, all preceding model elements of “Open Account” are moved before the activity until “Open Account” is at its new position. Obviously, $\Delta'(V, V_1)$ contains more compound change operations than necessary to transform process model V into V_1 and is therefore an undesired change log. With regards to understandability of the difference representation, a desired change log shall be minimal, i.e. it only consists of change operations that are essential to transform one process model into the other.

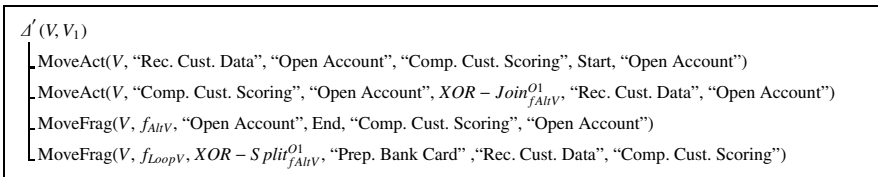


Fig. 6.4 Correct Change Log $\Delta'(V, V_1)$ consisting of Compound Change Operations that transforms the Process Model V into V_1 (see Figure 6.2)

To distinguish between desired and undesired change logs, we define the concept of costs of a change log similar to the cost model introduced in [Chawathe et al., 1996]. The cost of a change log is based on the costs of

individual compound change operations. We denote the costs of a compound change operation by $Cost(CompoundChangeOperation)$. For convenience, we assume that the costs for each compound change operations are equal, i.e. $Cost(InsertActivity) = Cost(DeleteActivity) = \dots = Cost(MoveFragment) = Cost(ConvertFragment) = 1$, however, every other cost model is possible. The cost of a change log is then defined as the sum of the costs of its contained compound change operations, i.e. $Cost(\Delta(V, V_i)) = \sum_{op \in \Delta(V, V_i)} Cost(op)$. Based on this simple cost model, we define a desired minimal change log as follows:

Definition 6 (Minimal Change Log). *Given two business process models V and V_i and a change log $\Delta(V, V_i)$ that represents the differences between the process models in terms of compound change operations and transforms V into V_i . The change log $\Delta(V, V_i)$ is minimal if there exists no other change log $\Delta'(V, V_i)$ with lower costs $Cost(\Delta'(V, V_i)) < Cost(\Delta(V, V_i))$ and also transforms process model V into V_i .*

To summarize, an approach to difference detection between process models has to fulfill the following requirements:

- R1 (*Reconstruction of a Change Log*). The solution for difference detection between two process models V and V_i must provide a technique to reconstruct one possible change log $\Delta(V, V_i)$ consisting of compound change operations. Applying all compound change operations contained in $\Delta(V, V_i)$ transforms process model V into V_i .
- R2 (*Minimal Change Log*). The reconstructed change log $\Delta(V, V_i)$ is minimal according to Definition 6.

In the following, we introduce our approach to difference detection between process models in the intermediate representation.

6.2 Approach to Difference Detection

In this section, we present an approach to difference detection between two process models that results in a change log consisting of compound change operations. Our approach builds upon the approach presented by Chawathe et al. in [Chawathe et al., 1996]. There, an approach is presented that computes a minimal cost edit script between two ordered trees T_1 and T_2 that transforms T_1 into T_2 . In contrast to normal trees, in ordered trees the children of inner nodes have a fixed order. In their approach edit scripts are generated that consist of four different edit operations (Insert, Delete, Update, and Move) for the modification of ordered trees.

In general, process models are directed graphs. However, by decomposing process models in the intermediate representation into fragments as described in Chapter 3, models in the intermediated representation can be considered as ordered trees (compare Figure 3.13 and Figure 3.14). Thereby, the difference detection approach presented in [Chawathe et al., 1996] can be applied. Specifically, we leverage their approach to identify inserted, deleted and moved model elements between different

process models. We extend the approach by the detection of converted fragments to cope with structural changes of fragments that are specific for process models and are obtained when a single gateway is inserted into or deleted from an existing fragment. Further, we do not fix the execution order of compound change operations in our reconstructed change log to a specific order, as it is the case for generated edit scripts [Chawathe et al., 1996]. By considering dependencies between compound change operations and dynamically computing position parameters, we enable that change operations can be applied in an arbitrary order to resolve differences between process models.

In the following, we first give an overview of our approach, before we describe the individual steps in detail.

6.2.1 Approach Overview

Figure 6.5 sketches our approach to difference detection. As input, we expect two process models V, V_i together with a mapping $\mathcal{M}(V, V_i)$. The mapping $\mathcal{M}(V, V_i)$ has been created during the matching of two process models as introduced in Chapter 4. As output of the approach a minimal change log $\Delta(V, V_i)$ is returned that contains all required compound change operations to transform process model V into V_i .

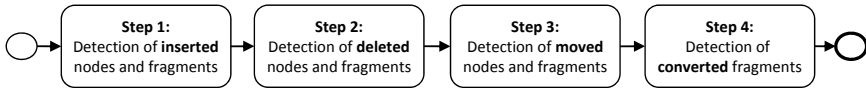


Fig. 6.5 Steps of our Approach to Difference Detection between Process Models

The approach consists of four steps: In Step 1 & 2, we identify differences due to newly inserted and deleted model elements. Step 3 comprises the detection of moved model elements and is divided into two sub-steps: First, elements that were moved between fragments are identified and afterwards, elements that were moved within a fragment are identified. In Step 4, we identify converted fragments, those execution orders or execution logics were changed. When a difference is detected in a step, an appropriate compound change operation is added to the change log $\Delta(V, V_i)$. Note that we do not consider the detection of differences due to updated attributes of model elements in our approach. The identification of updated attributes of model elements is generally straight-forward by iterating over all corresponding model elements and by comparing their attributes. A step to identify such differences could be easily added to our approach, e.g. as an additional Step 5.

In a three-way merge scenario, the difference detection is performed twice. First, we compute differences between the source process model V and version V_1 based on the mapping $\mathcal{M}(V, V_1)$ and we obtain the change log $\Delta(V, V_1)$. Afterwards, we compute differences between the source version V and version V_2 based on the respective mapping $\mathcal{M}(V, V_2)$ resulting in a change log $\Delta(V, V_2)$.

In the following sections, we present the individual steps of our approach. We first consider the specific differences that are detected in the individual steps and then describe in detail how these differences can be identified. For each identified difference an appropriate compound change operation is added to the change log.

6.2.2 Step 1: Detection of Inserted Model Elements

In Step 1, we identify differences due to newly inserted activities, events, and fragments between two process models V and V_i . For each newly inserted model element a dedicated *InsertActivity*, *InsertEvent*, or *InsertFragment* compound change operation is added to the change log $\Delta(V, V_i)$.

According to Definition 4 an *InsertDifference* between two process models V and V_i is defined as a model element that exists in process model V_i but not in process model V . The identification of *InsertDifferences* caused by the addition of activities, events, or fragments is straightforward by iterating over the correspondences in the sets $\mathcal{M}_{0-1}^N(V, V_i)$ and $\mathcal{M}_{0-1}^F(V, V_i)$. For each correspondence $c \in \mathcal{M}_{0-1}^N(V, V_i)$ attached to an activity or event an *InsertActivity* operation (*InsertEvent* respectively) is added to the change log $\Delta(V, V_i)$. Analogously for each $c \in \mathcal{M}_{0-1}^F(V, V_i)$ attached to a fragment an *InsertFragment* operation is added to $\Delta(V, V_i)$.

Obviously, the detection of inserted model elements leads to a minimal number of insert compound change operations in the reconstructed change log $\Delta(V, V_i)$, since for every inserted activity, event, or fragment an individual operation is required.

In our example introduced in Figure 1.3 the following *InsertActivity* and *InsertFragment* operations are identified between the process models V and V_2 :

$\Delta(V, V_2)$	
	InsertActivity(V , “Check Customer Data”, , ,)
	InsertActivity(V , “Retrieve add. Data”, , ,)
	InsertActivity(V , “Print Credit Card”, , ,)
	InsertActivity(V , “Select Credit Card Corp.”, , ,)
	InsertActivity(V , “Ask for Credit Limit”, , ,)
	InsertActivity(V , “Calc. Interest Rate”, , ,)
	InsertActivity(V , “Set Credit Limit to 0”, , ,)
	InsertActivity(V , “Remove Credit Card”, , ,)
	InsertActivity(V , “Set Interest Rate to 0”, , ,)
	InsertActivity(V , “Open Account”, , ,)
	InsertCyclicFragment(V , f_{Loop} , ,)
	InsertConcurrentFragment(V , f_{Par} , , ,)

Fig. 6.6 Detected *InsertActivity* and *InsertFragment* Compound Change Operations between the Process Models V and V_2 (Figure 1.3)

The compound change operations are added to the change log without specifying their position parameters, i.e. their position in the process model (see Chapter 5). In our approach, we compute position parameters after the detection of differences.

Further, the operations are added to the change log in such a way that they are directly applicable to resolve the differences between the process model versions V and V_i . For instance, the activity “*Check Cust. Data*” from our example constitutes a difference between the two process model versions V, V_2 , since the activity only exists in V_2 . To represent this difference, we add the operation $\text{InsertActivity}(V, \text{“Check Customer Data”}, ,)$ to the change log that will insert the activity “*Check Cust. Data*” also in process model V .

6.2.3 Step 2: Detection of Deleted Model Elements

In Step 2, we identify differences caused by deleted activities, events, and fragments between two process models V and V_i . For each deleted model element a dedicated *DeleteActivity*, *DeleteEvent*, or *DeleteFragment* compound change operation is added to the change log $\Delta(V, V_i)$.

Analogously to the identification of *InsertDifferences*, the detection of *DeleteDifferences* (Definition 5) that are caused by removing activities, events, or fragments from process model V_i is straightforward by iterating over the correspondences in the sets $\mathcal{M}_{1-0}^N(V, V_i)$ and $\mathcal{M}_{1-0}^E(V, V_i)$. For each correspondence $c \in \mathcal{M}_{1-0}(V, V_i)$ attached to an activity (or event) a *DeleteActivity* operation (respectively a *DeleteEvent* operation) is added to the change log $\Delta(V, V_i)$. For each $c \in \mathcal{M}_{1-0}^F(V, V_i)$ attached to a fragment a *DeleteFragment* operation is added to $\Delta(V, V_i)$.

Also the detection of deleted model elements results by default in a minimal change log $\Delta(V, V_i)$ with a minimal number of compound change operations, since for every deleted activity, event, or fragment exactly one operation is added to the change log.

In our example (Figure 1.2), we obtain the following *DeleteActivity* operation between the process models V and V_2 :

$\Delta(V, V_2)$
 $\perp \text{DeleteActivity}(V, \text{“Set Daily Withdrawal Limit”}, ,)$

Fig. 6.7 Detected *DeleteActivity* Compound Change Operation between Process Models V and V_2 (Figure 1.3)

6.2.4 Step 3: Detection of Moved Model Elements

In the previous steps, we have identified *InsertDifferences* and *DeleteDifferences* due to newly inserted or deleted activities, events, and fragments. In this step, we consider the movement of model elements. Typically, an activity, event, or fragment is moved in a process model by modifying its incoming and outgoing edges. The removal and the addition of edges also results in *InsertDifferences* and *DeleteDifferences* that can be identified by iterating over the mapping $\mathcal{M}^E(V, V_i)$

between edges in the process models V and V_i analogously to the approaches in Step 1 and Step 2.

However, in contrast to the insertion and deletion of activities, events, or fragments, where each detected *InsertDifferences* and *DeleteDifferences* is represented by an appropriate compound change operation (e.g. *InsertActivity*, *DeleteActivity*, ...), this is not the case for every *InsertDifference* or *DeleteDifference* caused by the modification of an edge. First, to move a model element several insertions and/or deletions of edges are necessary. In addition, *InsertDifferences* and *DeleteDifferences* due to newly inserted or deleted edges cannot be assigned uniquely to individual *MoveActivity*, *MoveEvent*, or *MoveFragment* compound change operations. As a consequence, an approach to detect moved elements cannot be based on an analysis of correspondences between edges.

For the detection of moved model elements, we propose an approach based on a comparison of the relative position of model elements in the process models. Our approach leverages the decomposition of process models into fragments. In general, a model element such as an activity, event, or fragment in an IR process model can be moved in two ways: Either a model element is moved within fragment or a model element is moved from one fragment into another. We denote the difference that is caused by the former move type as an *Intra-Fragment Move Difference* and we denote the difference that is obtained by the latter move type as an *Inter-Fragment Move Difference*. Based on this distinction, we propose detection approaches for both types of differences next. We begin with *Inter-Fragment Move Differences*, followed by *Intra-Fragment Move Differences*.

Step 3(a): Inter-fragment Move Difference

A model element that is moved from its parent fragment to another fragment causes a inter-fragment move difference. In Figure 6.2, the movement of the fragment f_{Loop} in process model V_1 from the upper branch of the alternative fragment into the root fragment results in an inter-fragment move difference. Whenever such an inter-fragment move difference is detected an appropriate *MoveActivity*, *MoveEvent*, or *MoveFragment* compound change operation is added to the reconstructed change log to represent the difference.

The identification of *Inter-Fragment Move Differences* is performed by iterating over the correspondences in the sets $\mathcal{M}_{1-1}^N(V, V_i)$ and $\mathcal{M}_{1-1}^F(V, V_i)$. For each correspondence between a pair of activities (or events) $(x, y) \in \mathcal{M}_{1-1}^N(V, V_i)$, we compare whether their parent fragments also correspond to each other, i.e. we check whether $(parent(x), parent(y)) \in \mathcal{M}_{1-1}^F(V, V_i)$. If the parent fragments of the corresponding nodes x, y do not correspond to each other, the nodes y and x are in different fragments and we have identified an *Inter-Fragment Move Difference*. To resolve the difference an *MoveActivity* operation (*MoveEvent* respectively) is added to the change log $\Delta(V, V_i)$. Analogously, for each pair of corresponding $(f, f_i) \in \mathcal{M}_{1-1}^F(V, V_i)$ whose parent fragments do not correspond to each other an *Inter-Fragment Move Difference* is obtained and a *MoveFragment* operation is added to $\Delta(V, V_i)$.

The number of compound change operation for the representation of detected *Inter-Fragment Move Differences* is optimal and results in a minimal change log according to Definition 6. For every *Inter-Fragment Move Difference* exactly one move operation is added to the change log $\Delta(V, V_i)$.

In our example introduced in Figure 6.2, the following *MoveFragment* operation is identified to represent the *Inter-Fragment Move Difference* between the process models V and V_1 :

$$\Delta(V, V_1) \\ \perp \text{MoveFragment}(V, f_{LoopV}, \dots)$$

Fig. 6.8 *MoveFragment* Compound Change Operation that resolves the detected *Inter-Fragment Move Difference* between Process Models V and V_1 (see Figure 6.2)

In the following section, we describe an approach to detect model elements that were moved within fragments.

Step 3(b): Intra-fragment Move Difference

Changing the order of corresponding model element within their parent fragments results in intra-fragment move differences. In Figure 6.2, the movement of the activity “*Open Account*” within the root fragment f_{RootV_1} in process model V_1 leads to an intra-fragment move difference between the process models V and V_1 . Whenever such an intra-fragment move difference is detected an appropriate *MoveActivity*, *MoveEvent*, or *MoveFragment* compound change operation is added to the reconstructed change log to represent the difference.

To identify *Intra-Fragment Move Differences*, we consider the relative order of corresponding model elements in sequences with respect to the control flow of the process model. For that purpose, we first iterate over corresponding sequences. For every corresponding pair of sequences (f, f_i) , we compare the order of their contained corresponding children. If there exist two pairs of corresponding children $(a, a_i) \in \mathcal{M}(V, V_i)$ and $(b, b_i) \in \mathcal{M}(V, V_i)$ that are in different orders (i.e. a before b in f and b_i before a_i in f_i or vice versa) an *Intra-Fragment Move Differences* is detected. To resolve the difference a *MoveActivity*, *MoveEvent*, or *MoveFragment* operation (depending on the type of the child) is added to the change log $\Delta(V, V_i)$.

In contrast to the presented detection approaches for the previous differences, *Intra-Fragment Move Differences* may be represented and resolved by different numbers of move operations. For instance, the *Intra-Fragment Move Differences* between the process models V and V_1 are correctly resolved by the compound change operation $\text{MoveActivity}(V, \text{“OpenAccount”}, \text{Start}, \text{“Rec.Cust.Data”}, \text{XOR-Join}_{f_{AltV}}^{O1}, \text{End})$. However, the differences could also be resolved by three compound change operations that move the activities “*Record Customer Data*”, “*Compute Customer Scoring*” and the alternative fragment f_{AltV} before the activity “*Open Account*”.

Obviously, the latter change log contains more operations than necessary and the former change log shall be preferred, since it is minimal according to Definition 6. To obtain a minimal change log, we have to detect *Intra-Fragment Move Differences* and represent them with a minimal number of compound change operations. In [Chawathe et al., 1996], an approach is presented to align children of inner nodes in ordered trees that results in a minimal number of edit operations. The approach is based on the concept of a *longest common subsequence* (LCS). The direct children of an inner node in an ordered tree constitute a sequence of nodes. To align corresponding nodes of two such sequences, a LCS is computed. A subsequence is obtained from a sequence by deleting nodes. The LCS is then iteratively extended by moving nodes until all corresponding nodes between the two sequences are in the same order. In the following, we describe how this approach can be used for the detection of *Intra-Fragment Move Differences* between process models in the intermediated representation.

In a process model in the intermediate representation, a sequential fragment f consisting of model elements that are executed sequentially can be considered as a sequence of direct children of an inner node in an ordered tree. Analogously, a subsequence f' can be obtained from a sequential fragment f by deleting model elements contained in f . A *longest common subsequence* (LCS) for process models in the intermediate representation is then defined as follows:

Definition 7 (Longest Common Subsequence (LCS)). (*inspired by [Chawathe et al., 1996]*) Given two versions V, V_i of a business process model in the intermediate representation and a mapping $\mathcal{M}(V, V_i)$ that relates corresponding edges, nodes, and fragments between V, V_i . Further, let two sequential fragments f, f_i that contain the model elements x_1, \dots, x_n and y_1, \dots, y_m be given. A longest common subsequence *LCS* (f, f_i) of the sequential fragments f and f_i is defined as a sequence $(x_i, y_i), \dots, (x_k, y_k)$ of model element pairs, such that

1. x_i, \dots, x_k is a subsequence of the sequential fragment f ,
2. y_i, \dots, y_k is a subsequence of the sequential fragment f_i ,
3. $\forall 1 \leq i \leq k \leq n (x_i, y_i) \in \mathcal{M}(V, V_i)$,
4. and there are no subsequences x_i, \dots, x_l in f and y_i, \dots, y_l in f_i that satisfy conditions 1, 2, and 3 and are longer than x_i, \dots, x_k and y_i, \dots, y_k .

We denote the length of a LCS of f and f_i by $|LCS(f, f_i)|$. For the computation of an LCS of two sequential fragments f, f_i an algorithm [Myers, 1986] with a quadratic worst case runtime $O(N^2)$ exists, where $N = |f| + |f_i|$ is the number of model elements in the fragments.

In our example introduced in Figure 6.2, an LCS for the sequential root fragments f_{RootV} and f_{RootV_1} is computed using the mapping $\mathcal{M}(V, V_1)$. The LCS consists of the activities “Record Customer Data”, “Compute Customer Scoring”, and the alternative fragment f_{AltV} in process model V and their matching counterparts in V_1 . The algorithm computes *Intra-Fragment Move Difference* of the activity “Open Account” that is represented by the following *MoveActivity* operation:

$\Delta(V, V_1)$ $\perp \text{MoveActivity}(V, \text{"Open Account"}, , , ,)$

Fig. 6.9 *MoveActivity* Compound Change Operation that resolves the detected *Intra-Fragment Move Difference* between Process Models V and V_1 (see Figure 6.2)

A proof that the identification of *Intra-Fragment Move Differences* based on LCSs results in minimal change logs can be found in [Chawathe et al., 1996].

6.2.5 Step 4: Detection of Converted Fragments

In Step 4, we identify *InsertDifferences* and *DeleteDifferences* that change the structure of corresponding fragments between two process models V and V_i or change the type of corresponding fragments. Typically, such differences are obtained by inserting or deleting gateways and edges in or from existing fragments. To resolve and represent the differences in the reconstructed change log $\Delta(V, V_i)$, *ConvertFragment* compound change operations are used that align corresponding fragments between two process models.

As introduced in Section 5.3.1, for the modification of an existing fragment generally three different cases exist: First, in a fragment the number of contained sequential fragments is changed by inserting or deleting gateways and or edges. Second, the type of the fragment may be changed by adding new gateways to the fragment or substituting existing gateways. Third, a mixture of the first and the second case may be identified. All three different cases are represented and resolved by *ConvertFragment* compound change operation.

An example for the first case is shown in Figure 6.10. Due to the reconnection of the activities “*Prepare Debit Card*” and “*Prepare Credit Card*” a new sequential fragment f_{DV_1} was created in process model V_1 .

To give an example for the second case if the XOR-split and/or the XOR-join gateway of the alternative fragment f_{AltV_1} in Figure 6.10 would have been substituted by gateways with AND-logic, the type of fragment f_{AltV_1} would have been changed.

The identification of converted fragments is performed by iterating over the correspondences between fragments in the set $\mathcal{M}_{1-1}^F(V, V_i)$. For each pair of corresponding fragments $(f, f_i) \in \mathcal{M}_{1-1}^F(V, V_i)$, we first check, whether the number of contained sequential fragments differs. That means, we iterate over the children of the fragments and try to find a contained sequential fragment that does not have a corresponding counterpart in the other fragment. Thereby, we identify fragment differences due to structural modifications. In our example presented in Figure 6.10, the fragment f_{DV_1} does not have a corresponding counterpart in f_{AltV} . Accordingly, the structures of the corresponding parent fragments f_{AltV}, f_{AltV_1} differ and a *Convert-Fragment* operation is added to the reconstructed change log $\Delta(V, V_1)$.

In a second check, we evaluate for every pair of corresponding fragments $(f, f_i) \in \mathcal{M}_{1-1}^F(V, V_i)$, whether the type of the fragment was changed. Therefore, we iterate over contained gateways in the fragments f, f_i . If a gateway is found that does

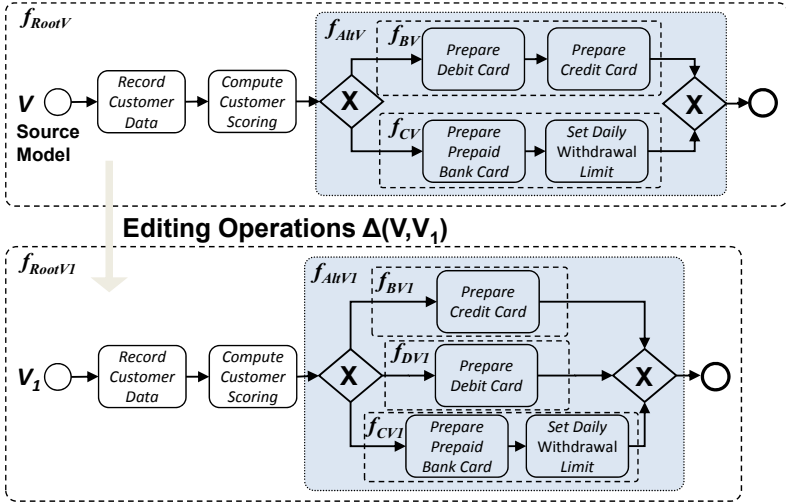


Fig. 6.10 Example for Differences between the Fragments f_{AltV} and f_{AltV1} in Process Models V and V_1 that are represented and resolved by a *ConvertFragment* Operation

not have a corresponding counterpart in the other process model and no *ConvertFragment* operation for this fragment was added to the change log before, we add a *ConvertFragment* operation to the reconstructed change log $\Delta(V, V_i)$.

The detection of converted fragments leads to a minimal number of *ConvertFragment* compound change operations in the reconstructed change log $\Delta(V, V_i)$, for every converted fragment exactly one *ConvertFragment* operation is added to $\Delta(V, V_i)$.

In our example introduced in Figure 6.10, the structure of the fragment f_{AltV1} was modified by inserting and deleting edges. Thereby, a new fragment f_{DV1} is created that does not have a corresponding counterpart in f_{AltV} . To represent the differences between the process model V and V_1 , a *ConvertFragment* operation is added to the change log $\Delta(V, V_1)$ that adds a new sequential fragment f_{DV} as a new branch in the alternative fragment f_{AltV} . For completeness, a *MoveActivity* operation is also added to the change log that moves the activity “*Prepare Debit Card*” from the upper branch in the newly created f_{DV} . It is worth to mention, that this *MoveActivity* operation would have been detected in Step 3(a) of our approach. The reconstructed change log $\Delta(V, V_1)$, which transforms the process model V into V_1 is shown next:

6.2.6 Summary

In the previous sections, we have introduced our approach for difference detection between business process models and the representation of differences in terms of compound change operations. Based on two process models V, V_i and a mapping $M(V, V_i)$ between them, we first have identified differences due to newly inserted

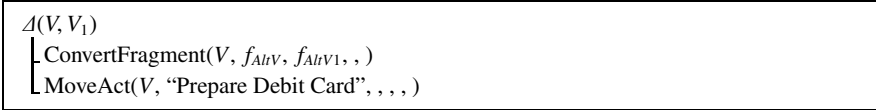


Fig. 6.11 *ConvertFragment* and *MoveActivity* Compound Change Operations that represents the Difference between Process Models V and V_1 from Figure 6.10)

and deleted model elements. Then, we have identified moved model elements. Finally, we have considered the identification of converted fragments, those execution order or execution logic was changed. As described above, we do not consider the detection of differences due to updated attributes of model elements in our approach.

In the case of our example, we obtain the reconstructed change log $\Delta(V, V_2)$ shown in Figure 6.12 that represents the differences between the process models V and V_2 from Figure 1.3.

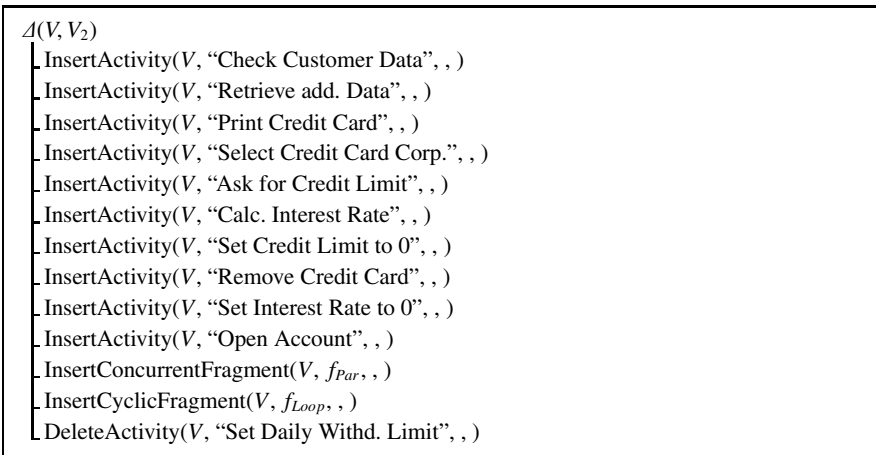


Fig. 6.12 Detected Compound Change Operations between the Process Models V and V_2

The reconstructed change log is at the moment a simple list consisting of compound change operations as introduced in Chapter 5. In contrast to a change log that is recorded during the modification of process model versions, a valid execution order of the change operations and information about the precise position where a change operation takes place is missing.

In the remainder of this chapter, we first introduce an approach to structure change operations in a change log according to the hierarchical structure of the underlying business process models. Then, in Section 6.4, we consider position parameters of change operations to complete the reconstruction of a change log.

6.3 Hierarchical Change Log

At the moment, our reconstructed change log is a simple list consisting of compound change operations (see Figure 6.12). Although compound change operations are way more intuitive than elementary change operations, since they comprise related elementary changes, it is still sometimes difficult to grasp the actual differences between the process models and their relationships. In particular if the process models differ to a large extent. For instance, from the change log shown in Figure 6.12 it is not clear that the activity “*Check Customer Data*” is inserted in the fragment f_{Loop} .

Inspired by the approaches for differences visualization presented in [Ohst et al., 2003] and [Chawathe et al., 1996], we aim to enable a more intuitive and natural understanding of the differences between process models. For that purpose, we arrange change operations according to the structure of the underlying process models. The structure of process models is given by the composition hierarchy of their contained fragments. Based on the composition hierarchy of fragments in process models, change operations can be associated to the fragment in which they occur. In Chapter 3, we have made the fragment hierarchy of process models explicit in terms of process structure trees (PST).

In the following, we first introduce a joint process structure tree (*Joint-PST*) that is constructed by overlapping the *PST*s of the underlying process models. Then we assign change operations to the fragments of the *Joint-PST* to obtain a hierarchical change log.

Definition 8 (Joint Process Structure Tree (*Joint - PST*)). *Given two business process models V, V_i in the intermediate representation and their process structure trees $PST(V), PST(V_i)$. Further, let a mapping $M(V, V_i)$ between the process models V, V_i be given. A *Joint - PST*(V, V_i) of the process models V, V_i is then defined as the union of the process structure trees $PST(V)$ and $PST(V_i)$. A *Joint - PST*(V, V_i) can be constructed as follows:*

- *for a corresponding pair for fragments $(f, f_i) \in M_{1-1}^F(V, V_i)$, a new fragment f_j is inserted into *Joint - PST*(V, V_i) with $parent(f_j) = parent(f)$.*
- *for a fragment $f \in M_{1-0}^F(V, V_i)$, a new fragment f_j is inserted into *Joint - PST*(V, V_i) with $parent(f_j) = parent(f)$.*
- *for a fragment $f_i \in M_{0-1}^F(V, V_i)$, a new fragment f_j is inserted into *Joint - PST*(V, V_i) with $parent(f_j) = parent(f_i)$.*

Based on the *Joint - PST*, we can define a hierarchical change log. The idea of the hierarchical change log is to arrange change operations according to the structure of the process model by associating to each fragment the compound change operations that affect it or take place in the fragment. A hierarchical change log is defined as follows:

Definition 9 (Hierarchical Change Log). *Given two business process models V, V_i , their decomposition into fragments $PST(V), PST(V_i)$, and a change log $\Delta(V, V_i)$ representing the differences between V, V_i in terms of compound change operations.*

A hierarchical change log that transforms V into V_i is the joint process structure tree *Joint* – $PST(V, V_i)$ whose nodes are enriched with compound change operations as follows:

- If $op = InsertActivity, InsertEvent, DeleteActivity, \text{ or } DeleteEvent$ then op is associated to the node representing the fragment in which op takes place.
- If $op = MoveActivity \text{ or } MoveFragment$ then op is associated to the node representing the fragment into which the element is moved and to the node representing the fragment out of which the element is moved.
- If $op = InsertFragment, DeleteFragment, \text{ or } ConvertFragment$, then op is associated to the node in the *Joint* – $PST(V, V_i)$ representing this fragment.

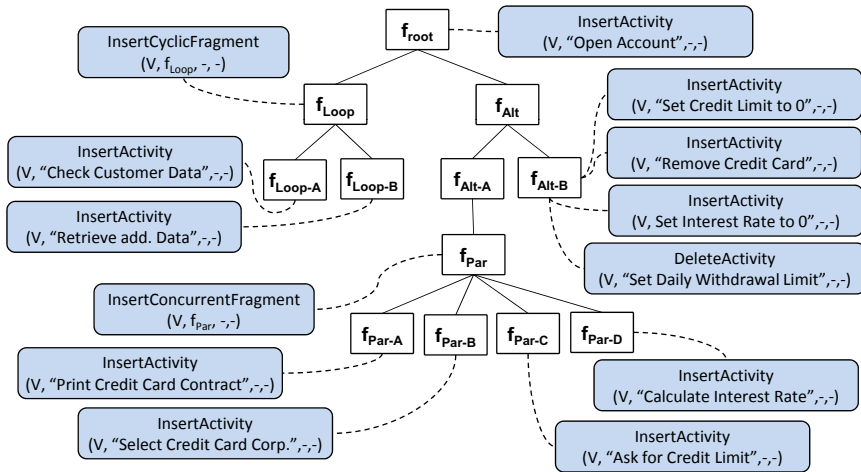


Fig. 6.13 Hierarchical Change Log that represents the Differences between the Process Models V and V_2 (see Figure 1.3)

Figure 6.13 shows a hierarchical change log for the two process model versions V and V_2 introduced in Figure 1.3 of Chapter 1. For example, the *InsertCyclicFragment* operation inserts the fragment f_{Loop} in the root fragment f_{root} . The *InsertConcurrentFragment* inserting the fragment f_{Par} , occurs in the upper branch f_{Alt-A} of the alternative fragment f_{Alt} . Within the newly inserted unstructured parallel fragment f_{Par} are several *InsertActivity* operations. Further operations such as the *DeleteActivity* operation is also associated to its fragment.

In some scenarios, for instance due to space limitations, a textual representation of the hierarchical change log is more suitable than the visual representation shown in Figure 6.13. A hierarchical change log can be transformed into a textual representation by printing the fragment hierarchy and contained compound change operations in terms of an indented list. In the case that a fragment is directly affected

by a compound change operation, the fragment is represented by the operation itself. Figure 6.14 shows the textual representation of the hierarchical change log from above.

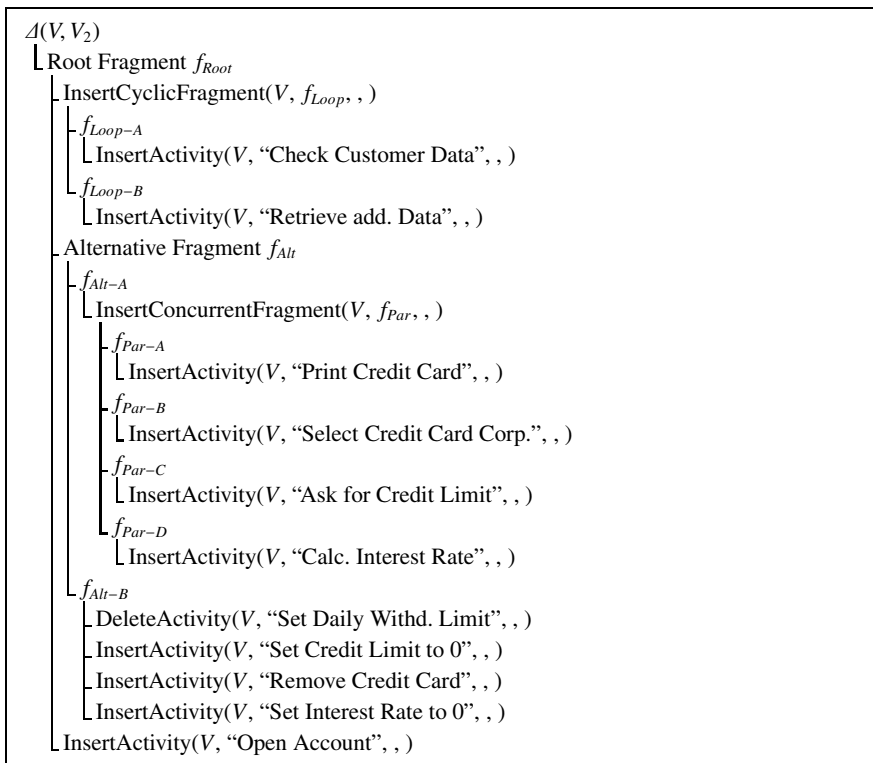


Fig. 6.14 Textual Representation of the Hierarchical Change Log representing the Differences between the Process Models V and V_2 (see Figure 1.3)

In existing model versioning approaches, differences between models are visualized differently. Some approaches use textual representation change operations, e.g. simple edit scripts containing change operations are used in [Alanen and Porres, 2003]. Also in ADEPT [Rinderle et al., 2006, Rinderle et al., 2007], simple change logs in terms of lists are used. A difference representation in terms of a simple list may harden the understandability of differences, as described above. More elaborated approaches are based on an overlapping of the underlying models. For instance, in [Ohst et al., 2003], the differences between versions of UML models (e.g. class or object diagrams) are visualized by computing a unified model for given versions of a UML diagram. In this unified model, common model elements of the underlying versions are overlapped and specific parts are highlighted. Thereby, newly added or

deleted model elements are directly visible. By coloring model elements that are specific to a certain version, also version specific differences can be represented. In [Chawathe et al., 1996], a visual delta tree for two given ordered trees is computed. Differences between the ordered trees are represented in the delta tree by annotating nodes with change operations.

In both approaches, differences are visualized based on the complete underlying models, resulting in difference visualizations that potentially contain several unchanged model elements. These unchanged model elements harden the actual understandability of the difference representation, in particular if large models are compared. To circumvent this problem, in [Ohst et al., 2003] a filtering mechanism is presented that can be used to restrict the visualization of differences to a certain type.

In contrast to these approaches, we construct a hierarchical change log by abstracting from the underlying models and focusing on the fragment hierarchy in the process models. Thereby, we obtain difference visualizations that are significantly smaller compared to the underlying process models. In addition to the visual representation of differences, we propose the use of a textual version of the hierarchical change log that represents nested fragments and change operations by an indented list as shown in Figure 6.14.

Using the hierarchical change log, either in visual or textual representation, a business user can easily identify the areas of the process model that have been modified. Moreover, the actual intention of the changes is easier to grasp. A hierarchical change log supports a business user to concentrate on those differences that are relevant for a certain area in the process model.

In the next section, we complete the detection of differences by specifying position parameters of change operations.

6.4 Position Parameters of Compound Change Operations

During the detection of differences, compound change operations are added to a reconstructed change log $\Delta(V, V_i)$. These change operations are initially partially specified. For example, for the compound operation *InsertActivity*(V , “Open Account”, $-$, $-$) the last two parameters, which we denote as *position parameters*, are not defined yet. That means, the operations are underspecified and cannot be applied directly. To make change operations applicable, we have to specify their *position parameters*. *Position parameters* of compound change operations consist of two nodes in the process model: a preceding node (predecessor) and a succeeding node (successor) that specify possible positions in a process model. If predecessor and successor are directly connected they specify a unique position in a process model. If predecessor and successor are not directly connected, a set of possible positions is specified.

In the case of an *InsertActivity* or *InsertFragment*(V, f, x, y) operation, position parameters specify the new position to which an activity or fragment is inserted. In the case of a *DeleteActivity* or *DeleteFragment* operation, position parameter specify the position from which an activity or fragment is removed from. In the case

of a *MoveActivity* or *MoveFragment* operation, two positions are specified: An old position from which an activity or fragment is moved from and a new position to which an activity or fragment is moved to. Finally, for *ConvertFragment* operations their current (i.e. old) position is specified.

For clarification, Figure 6.15 shows the reconstructed change log of our example with specified position parameters. For the moment, we assume that position parameter can be computed. For instance using the approach presented in [Chawathe et al., 1996], which specifies position parameters in the order in which change operations are detected between two model. In the next chapter, we will present an algorithm for position parameter computation of compound change operations, which is especially suited for process model change management.

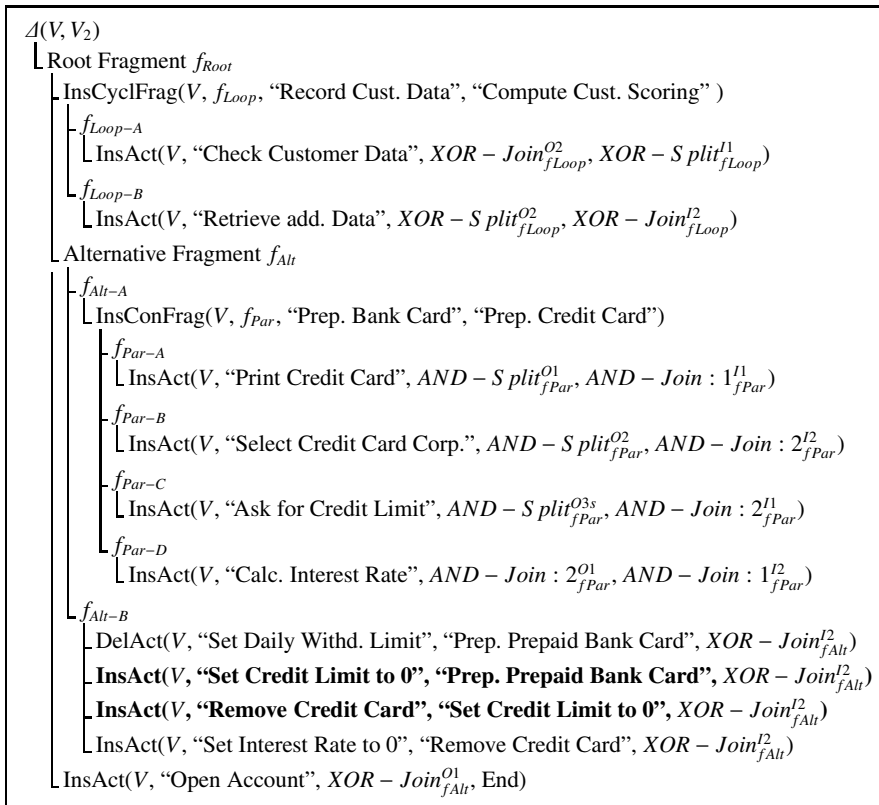


Fig. 6.15 Hierarchical Change Log consisting of Compound Change Operations with specified Position Parameters.

Based on the change log $\Delta(V, V_2)$ and the contained compound change operations with specified position parameters as shown in Figure 6.15, the differences between the process model V and V_2 can be resolved. By applying the compound change operation on the process model V , V is transformed into process model V_2 .

However, the compound change operations cannot be applied in any order, since the position parameters introduce dependencies between some of the operations. For instance, the bold printed operation $\text{InsertActivity}(V, \text{“Set Credit Limit to 0”}, \text{“Prep. Prepaid Bank Card”}, \text{XOR-Join}_{f_{Alt}}^2)$ must be applied before operation $\text{InsertActivity}(V, \text{“Remove Credit Card”}, \text{“Set Credit Limit to 0”}, \text{XOR-Join}_{f_{Alt}}^2)$, because the latter operation uses the inserted activity “*Set Credit Limit to 0*” of the former operation as position parameter. That means, the latter operation is dependent on the application of the former operation. Further if position parameters of compound change operations would have been specified differently, we would obtain other dependencies between the change operations.

As a consequence, dependencies between compound change operations have to be taken into account before change operations can be applied in order to merge to process model. We discuss dependencies between change operations and the computation of position parameters extensively in the next chapter.

6.5 Summary and Discussion

In this chapter, we presented an approach to detect differences between different process model versions that results in a reconstructed change log consisting of compound change operations. First of all, we introduced requirements a solution for difference detection has to fulfill. Then, we proposed our approach to difference detection that is divided into four steps. Each step is dedicated to identify a certain type of difference between two process models, which is represented by an appropriate compound change operation in the reconstructed change log.

To enable an intuitive and natural understanding of the differences between process models, we transformed the reconstructed change log into a hierarchical change log. The idea of a hierarchical change log is to arrange compound change operations according to the structure of the underlying process models. Thereby, differences are directly located to the fragments of a process model, which are affected by the differences. A hierarchical change log can also be beneficial for identifying groups of change operations that can be applied together, e.g. in terms of a change transaction.

Finally, as an outlook for the next chapter, we specified position parameter for compound change operations in a reconstructed change log $\mathcal{A}(V, V_i)$. Based on the reconstructed change logs from this chapter, we consider dependencies between compound change operations in the next chapter. There, we show how the computation of position parameters directly influences the number of dependencies between compound changes and how a dynamic specification of compound change operations enables business users to resolve differences between business process models without being unnecessarily restricted to a certain execution order of compound change operations.

Dependency Analysis

In the previous chapter, we reconstructed a change log consisting of compound change operations that represent differences between different process model versions. Before we can apply the compound change operations in order to merge different process model versions, possible dependencies between change operations must be identified.

Informally if two change operations are dependent, then the second one requires the application of the first one. For instance, before an activity can be inserted into a new fragment, the fragment itself must be inserted. Otherwise it can happen that applying a dependent change operation leads to a potentially unconnected process model and problems when applying following change operations. For example, inserting an activity into a fragment that does not exist yet, leads to an unconnected activity and problems when later inserting the fragment.

In this chapter, we introduce our approach to dependency analysis between compound change operations of process models. We begin by defining requirements for dependencies in Section 7.1. We approach the identification of dependencies by applying existing theory on dependent graph transformations and establish the notion of transformation dependencies between compound change operations in Section 7.2. In Section 7.3, we then show how the dependency detection can be further improved and introduce the concept of *Joint – PST* dependencies between change operations. Using dynamic specification of compound change operations, this approach results in fewer dependencies between change operations and thus more freedom when merging different process model versions.

Finally, we conclude with a summary and discussion in Section 7.4. The following sections of this chapter are partially based on our earlier publications [Küster et al., 2009, Küster et al., 2010].

7.1 Requirements for Dependency Analysis

In this section, we establish requirements for dependency analysis between change operations of business process models.

We assume that a reconstructed change log $\Delta(V, V_i)$ consisting of compound change operations is given, which can be used to create a consolidated model V_M out of a source process model V and a descendant version V_i . In an exemplary distributed modeling scenario, a process model representative will inspect each change operation in the change log and decide which operation to apply in order to construct a consolidated model V_M . Thereby, he applies the changes in an iterative way and continues to do so until he is satisfied with the resulting model V_M .

To that extent, a dependency concept for change operations is needed to ensure that only operations that do not depend on other operations can be applied at once. Otherwise it can happen that applying a change operation leads to a potentially unconnected process model and problems when applying following change operations.

With regards to the reconstructed change log from the previous chapter (see Figure 6.15), the process model representative might apply Operations A and B as shown below. The application of Operation B requires that Operation A was applied before, because B uses the activity “Set Credit Limit to 0” that is inserted by A. In other words, it is not possible to insert the activity “Remove Credit Card” without having inserted the activity “Set Credit Limit to 0”, since their operations depend on each other.

- (A) $\text{InsAct}(V, \text{“Set Credit Limit to 0”}, \text{“Prep. Prepaid Bank Card”}, \text{XOR} - \text{Join}_{fAlt}^2)$
 (B) $\text{InsAct}(V, \text{“Remove Credit Card”}, \text{“Set Credit Limit to 0”}, \text{XOR} - \text{Join}_{fAlt}^2)$

The detection of dependencies between change operations heavily relies on the specified position parameters of the change operations. That means, depending on the specified position parameters of change operations different dependencies may be computed. For instance, in our example from above, the application of Operation B depends on the application of Operation A. If the position parameters of both operations would have been specified as follows, then the dependency would change and the application of Operation A would depend on a prior application of Operation B.

- (A) $\text{InsAct}(V, \text{“Set Cr. Limit to 0”}, \text{“Prep. Prepaid Bank Card”}, \text{“Rem. Credit Card”})$
 (B) $\text{InsAct}(V, \text{“Rem. Credit Card”}, \text{“Prep. Prepaid Bank Card”}, \text{XOR} - \text{Join}_{fAlt}^2)$

As a consequence, the specification of position parameters must be taken into account, when developing a solution for dependency detection between compound change operations. Position parameters must be chosen in such a way that each change operation, which potentially can be applied in isolation, is not dependent on any other operation.

We have already discussed that the application of all change operations in the reconstructed change log $\Delta(V, V_i)$ transforms the process model V into process model V_i . That means, the two process models V and V_i are merged by applying change operations and the consolidated process model V_M is obtained. In the case that all change operations in $\Delta(V, V_i)$ are applied, V_M will be equivalent to the process model version V_i . However, the consolidation of different process models V, V_i into a consolidated model V_M shall also support the scenario, where just a subset $S \subseteq \Delta(V, V_i)$

of the change operations is applied to obtain V_M . This requires that a business user shall be able to select only some of the compound change operations that are applied to obtain the consolidated process model V_M . To that extent, the selection of a subset of change operations shall not be unnecessarily restricted by the detected dependencies.

Similarly, the application of compound change operations to consolidate different process model versions shall not be prescribed unnecessarily by dependencies. A user shall have the freedom to apply change operations, which can be applied independently in an arbitrary order.

To summarize, an approach to dependency analysis between compound change operations has to fulfill the following requirements:

- R1 (*Dependency Detection*) The dependency analysis must identify all dependencies between the compound change operations in a change log.
- R2 (*Application of a Subset of Change Operations*) A business user shall be able to select only some of the compound change operations that are applied to obtain a consolidated process model. This selection shall not be restricted unnecessarily by the detected dependencies.
- R3 (*Arbitrary Application Order*) A consolidated version of a process model can be created by applying independent operations in an arbitrary order.

Based on the reconstructed change log that we have computed in Chapter 6, we present an approach to compute dependencies between compound change operations based on dependent model transformations in the next section.

7.2 Transformation Dependent Compound Change Operations

In this section, we present an approach to compute dependencies between compound change operations with specified position parameters. In the following, we give an overview of the approach. This section and its subsections are based on our earlier publications [Küster et al., 2009, Küster et al., 2010].

7.2.1 Approach Overview

As a running example for dependency detection, we consider the reconstructed change log that we have introduced in the previous chapter. For convenience, this change log is shown again in Figure 7.1. For each compound change operation position parameters have been computed. These position parameters specify the position where the application of the change operation takes place in a process model.

In this section, we present an approach for the computation of dependencies between change operations with specified position parameters. For that purpose, we will leverage the notion of dependencies between model transformations and describe how dependent model transformations are identified in Section 7.2.2. In Section 7.2.3, we formalize compound change operation types in terms of model transformations. Based on this formalization, we derive dependencies between

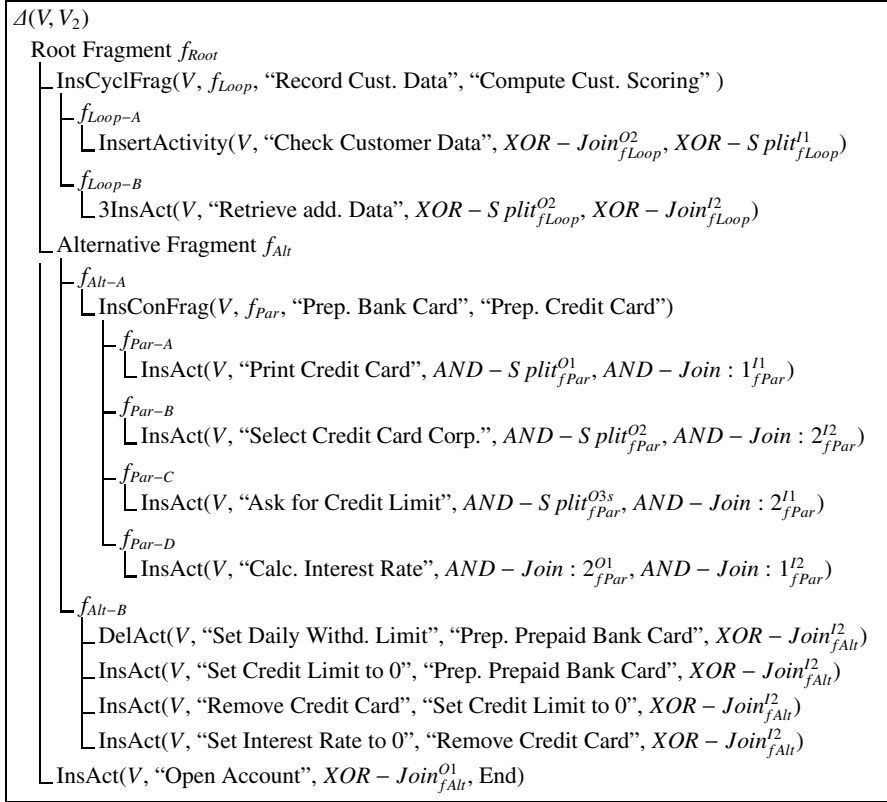


Fig. 7.1 Compound Change Operations with specified Position Parameters representing the Differences between the Process Models V and V_2 (see Figure 1.3).

change operation types and capture them in a dependency matrix in Section 7.2.4. In addition, we compute dependencies for our running example and come up with an execution order determining how the operations can be applied while considering their dependencies. Finally, we evaluate this approach for dependencies analysis whether it fulfills our requirements.

7.2.2 Compound Change Operations and Model Transformation Rules

In this section, we relate compound change operations to model transformations. For that purpose, we briefly recap the existing theory of model transformations and show how a change operation can be formalized in terms of a model transformation.

Each compound change operation op for a model V can be viewed as a model transformation rule on the process model V transforming it to a process model V_M . A model transformation rule can be formalized as a typed attributed graph transformation rule [Küster, 2006, de Lara et al., 2007, Mens et al., 2007], where the typed

graph is represented by the meta-model of the intermediate representation (see Chapter 3).

We distinguish between change operation type and a concrete change operation: A change operation type (such as $InsertActivity(v, a, x, y)$) describes a set of concrete change operations. By replacing the parameters of a change operation type with model elements of the models V and V_i , a concrete change operation is obtained. Examples for concrete compound change operations can be found in the reconstructed change log $\Delta(V, V_2)$ shown in Figure 7.1.

The behavior of a change operation type op can be specified using a typed attributed graph transformation rule op_r . A typed graph transformation rule $op_r : L \rightarrow R$ consists of a pair of typed instance graphs L, R such that the union is defined. A graph transformation step from a graph G to a graph H , denoted by $G \xRightarrow{op_r(o)} H$, is given by a graph homomorphism $o : L \cup R \rightarrow G \cup H$, called occurrence, such that the left hand side L is embedded into G and the right hand side R is embedded into H and precisely that part of G is deleted which is matched by elements of L not belonging to R , and, that part of H is added which is matched by elements new in R . Figure 7.2 shows the typed attributed graph transformation rule for $InsertActivity(V, a, x, y)$.

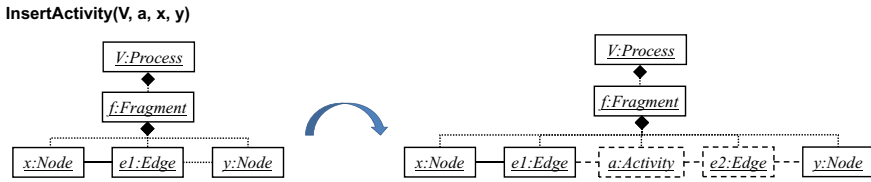


Fig. 7.2 Compound Change Operation Type: InsertActivity

The theory of graph transformation provides the basis for defining the semantics of a change operation type as follows: Given a change operation type op together with its rule op_r , a concrete change operation on a model V leading to a model V_i conforming to the type op is modeled by a change operation application of the rule op_r to V transforming it to V_i . Formally, this is represented by a graph transformation $G_V \xRightarrow{op_r(o)} H_{V_i}$ where op_r is applied at an occurrence o to the graph G_V leading to a new graph H_{V_i} (where G_V and H_{V_i} are represented as typed graphs obtained from the models V and V_i). We also write $V \xRightarrow{op} V_i$ or $V \xRightarrow{op(o)} V_i$. To represent a concrete change operation, we write $op(o)$.

Formally, the occurrence morphism o represents a binding between the change operation type and the models V and V_i . It maps nodes and edges of L and R to G and H . An occurrence morphism can be specified by a set of parameters x_1, \dots, x_n in the change operation type op and their instantiation in the concrete change operation $op(o)$. For each rule op_r , we distinguish between parameters that are preserved, deleted or newly created, so $x_i \in pres(op_r) \cup del(op_r) \cup new(op_r)$.

As an example, consider the change operation type $InsertActivity(v, a, x, y)$ and the change operation $InsertActivity(V, \text{“Set Credit Limit to 0”}, \text{“Prep. Prepaid Bank Card”}, XOR - Join_{fAlt}^I)$. This implies an occurrence morphism mapping v, a, x and y to the process model V and its contained model elements. In this case, v is mapped to the process model V , x to “Prep. Prepaid Bank Card”, y to $XOR - Join_{fAlt}^I$ and a is mapped to the activity “Set Credit Limit to 0”, which is newly created.

For the formalization of our set of compound change operation types, we use a shorthand which only includes those elements of the occurrence morphism such that the morphism is uniquely determined. For example, we write $InsertActivity(v, a, x, y)$ instead of $InsertActivity(v, f, a, e1, b, x, e2)$, where $f, a, e1, b, x, e2$ refers to the elements defined in the transformation rule (see Figure 7.2).

In the next section, we formalize the compound change operation types from our compound difference model introduced in Chapter 5.

7.2.3 Formalization of Compound Change Operation Types

In the following, we briefly consider the semantics of compound change operation types by formalizing them in terms of graph transformation rules.

The semantics of the $InsertActivity$ operation type is formally specified by the following operational graph transformation rule given in Figure 7.3. Applying this rule creates a new activity a and connects it with a preceding node x and a succeeding node y . Similarly, the graph transformation in Figure 7.4 formalizes the semantics of the $InsertFragment$ change operation type. First a new fragment f is created that is integrated in the control flow of the process model V by connecting it to a preceding node x and a succeeding node y .

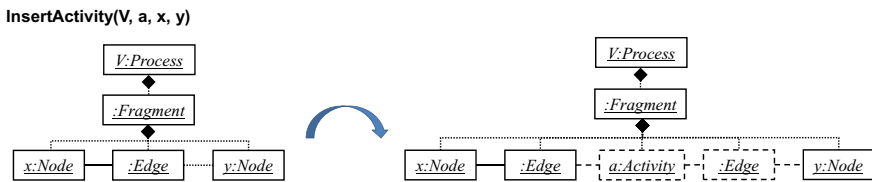


Fig. 7.3 Graph transformation rule describing the behavior of the $InsertActivity$ operation

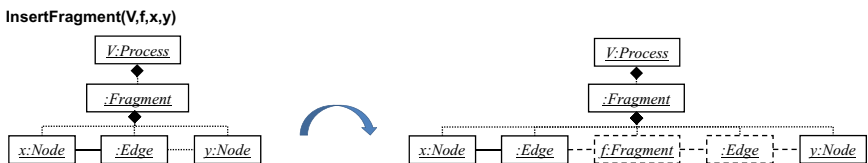


Fig. 7.4 Graph transformation rule describing the behavior of the $InsertFragment$ operation

Figures 7.5 and 7.6 visualize the graph transformation rules for the *DeleteActivity* compound change operation and the *DeleteFragment* change operation. In both rules, an existing activity a or fragment f is removed from a process model V and the control flow between the former predecessor x and successor y is reestablished.

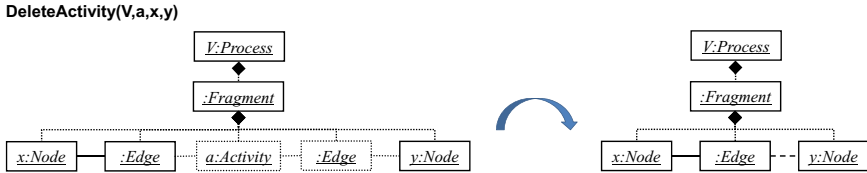


Fig. 7.5 Graph transformation rule describing the behavior of the *DeleteActivity* operation

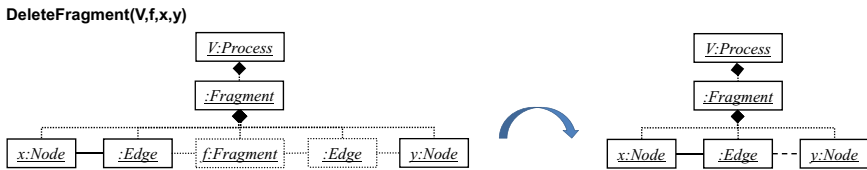


Fig. 7.6 Graph transformation rule describing the behavior of the *DeleteFragment* operation

The *MoveActivity* change operation type is formalized by the graph transformation rule presented in Figure 7.7. Figure 7.8 visualizes a graph transformation rule that determines the semantics of the *MoveFragment* operation. Looking at the behavior, the *MoveActivity* and the *MoveFragment* change operation types are a composition of the previously presented compound change operation types. That means, an activity a (or fragment f) is first removed from its previous position in a process model V and then introduced at a new position in V . The control-flow in V is reestablished by connecting the former predecessor v and successor w as well as the new predecessor and successor x, y with a (or f).

Finally, the model transformation rule in Figure 7.9 is a shorthand formalization of the *ConvertFragment* operation type. In general, a *ConvertFragment* operation can be described by an arbitrary sequence of elementary change operations as introduced in Section 5.2.1. That means, whenever the structure of the fragment f is changed by adding or deleting a contained sequence, a *ConvertFragment* operation is obtained. To change the structure of the fragment f generally two ways exist: Either, a control node is added to (or removed from) f or a path between two existing control nodes is introduced in f (or removed from f).

Based on the formalized compound change operations, we present an approach to compute dependencies between different compound change operations in the next section.

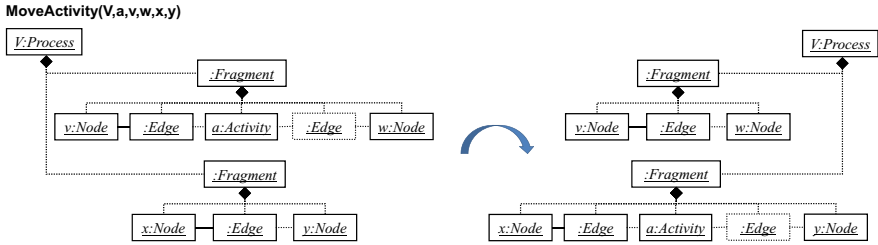


Fig. 7.7 Graph transformation rule describing the behavior of the *MoveActivity* operation

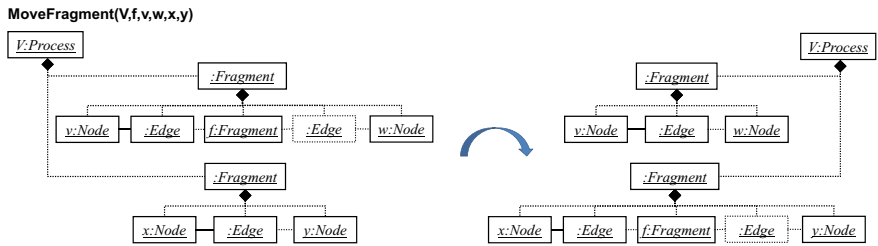


Fig. 7.8 Graph transformation rule describing the behavior of the *MoveFragment* operation

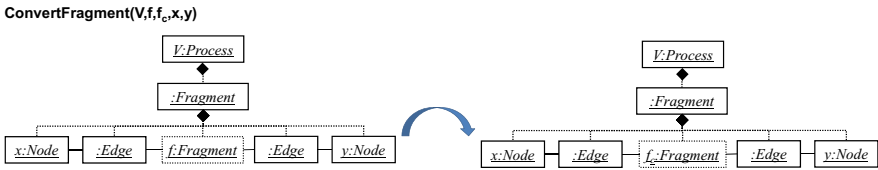


Fig. 7.9 Graph transformation rule describing the behavior of the *ConvertFragment* operation

7.2.4 Transformation Dependencies

Having specified our set of compound change operations as typed attributed graph transformations, we now define transformation dependent compound change operations and show how dependencies between compound change operations can be computed in this section.

Informally if two changes are dependent, then the second one requires the application of the first one. This is usually the case if the first change creates model structures that are required by the second change. Formally, we define:

Definition 10 (Transformation Dependent Compound Change Operations). [Küster et al., 2010] Let two compound change operations op_1 and op_2 with specified position parameters be given such that $V \xrightarrow{op_1} V'$ and $V' \xrightarrow{op_2} V''$. Then we call op_2 transformation dependent (TR-dependent) on op_1 if op_2 is not applicable on V and op_2 is applicable on V' .

For the computation of dependencies between compound change operations, we leverage the notion of dependencies between graph transformations that has been defined in [Corradini et al., 1997, Hausmann et al., 2002, Mens et al., 2007]. Dependencies between graph transformations are based on the concept of *weakly sequential independence* that states when two graph transformation rules can be applied independently of each other and their application order does not matter. Formally, given a sequence of graph transformations $G \xrightarrow{p_1(o_1)} H_1 \xrightarrow{p_2(o_2)} X$, $H_1 \xrightarrow{p_2(o_2)} X$ is *weakly sequential independent* of $G \xrightarrow{p_1(o_1)} H_1$ if the occurrence $o_2(L_2)$ is already present before the application of p_1 . This is the case if $o_2(L_2)$ does not overlap with objects created by p_1 . If in addition p_2 does not delete objects that are needed for the application of p_1 , then p_1 and p_2 can be exchanged and are called sequentially independent.

Based on the sequential independence, we can derive whether two particular transformation rules are sequentially dependent. Given two rules p_1 and p_2 , the computation of dependencies can be done using critical pairs. A critical pair is a pair of transformation steps $H_1 \xleftarrow{p_1(o_1)} G \xrightarrow{p_2(o_2)} H_2$ which are in conflict and with the property that G is minimal. Two transformation steps are in conflict if one can only be applied after/before the other or one step disables the other one. In order to compute the sequential dependencies between compound change operation types, given two rules p_1 and p_2 , we compute critical pairs of p_1 and p_2^{-1} and p_1^{-1} and p_2 [Hausmann et al., 2002]. In other words, for all possible pairs of compound change operation types formulated as model transformations, we overlap the right hand side of the first operation with the left hand side of the second operation and vice versa.

The critical pairs obtained by overlapping compound change operation types are then encoded by specifying conditions on the parameters of the operations and captured in a dependency matrix¹. An excerpt of the dependency matrix specifying situations in which compound change operation types are dependent on the operation *InsertActivity* operation type is shown in Figure 7.10.

A dependency between two change operation types occurs for instance between *InsertActivity*(V, a, x, y) and *InsertActivity*(V, b, v, w) if $v = a \ \& \ w = y$ or $v = x \ \& \ w = a$, where $\&$ means AND and $|$ means OR. In other words, *InsertActivity*(V, b, v, w) depends on operation *InsertActivity*(V, a, x, y) if either the newly inserted activity a is the predecessor or the successor of the activity b , which is inserted by the operation *InsertActivity*(V, b, v, w). The complete dependency matrix is given in the Appendix B.1.

Based on the dependency matrix for compound change operation types, we can easily identify dependencies between concrete compound change operations in a reconstructed change log, whose position parameters have been specified. With respect to the dependencies between concrete change operations, a possible execution order of the compound change operations can be identified that transforms a process model V into V_i .

¹ We used the AGG tool [Taentzer, 2003] to partially compute the entries of the matrices.

Transformation Dependencies	InsertActivity (V,b,v,w)	DeleteActivity (V,b,v,w)	MoveActivity (V,b,ov,ow,nv,nw)
InsertActivity (V,a,x,y)	[IA(a), IA(b)]: (v = a & w = y) (v = x & w = a)	[IA(a), DA(b)]: (b = x & w = a) (v = a & b = y)	[IA(a), MA(b)]: (nv = x & nw = a) (nv = a & nw = y) (ov = a & b = y) (b = x & ow = a)

Transformation Dependencies	InsertFragment (V,f2,v,w)	DeleteFragment (V,f2,v,w)	MoveFragment (V,f2,ov,ow,nv,nw)	ConvertFragment (V,f2,f2c,v,w)
InsertActivity (V,a,x,y)	[IA(a), IF(f2)]: (v = a & w = y) (v = x & w = a)	[IA(a), DF(f2)]: (v = a & entry(f2) = y) (exit(f2) = x & w = a)	[IA(a), MF(f2)]: (nv = x & nw = a) (nv = a & nw = y) (ov = a & entry(f2) = y) (exit(f2) = x & ow = a)	[IA(a), CF(f2)]: (v = a & entry(f2) = w) (exit(f2) = x & w = a)

Fig. 7.10 Excerpt of the Transformation Dependency Matrix for Compound Change Operations

For the compound change operations from our example introduced in Figure 1.3 in Chapter 1, we obtained nine dependencies between in total thirteen operations. The reconstructed change log $\Delta(V, V_2)$ with dependencies and one possible execution order² of the change operations is shown in Figure 7.11. Dependent operations are marked by squared brackets [\rightarrow *OperationNumber*] meaning that the execution of this operation depends on \rightarrow the operation *OperationNumber*.

7.2.5 Discussion

In the following, we evaluate whether the notion of transformation dependent compound change operations is suitable for process model change management according to the requirements introduced in Section 7.1. Before that, let us first recap the approach briefly.

We started by formalizing our set of compound change operations in terms of model transformations. Based on the existing notion of dependent model transformations, we defined transformation dependencies between our change operation types and encapsulated scenarios that result in dependencies between change operations into a dependency matrix. Using this matrix, it can be checked whether any two change operations with specified position parameters depend on each other. Using the reconstructed change log that we obtained as an result in the previous chapter, we computed dependencies between the contained compound change operations.

Apparently, the presented approach is capable to identify dependencies between fully specified compound change operations (i.e. operations whose position parameters have been specified). The application of compound change operations that are not dependent, results in a connected process model. For instance, after the application of Operation 11 (see Figure 7.11), the activity “*Set Credit Limit*

² Please note that this is just one execution order among several other possible execution orders.

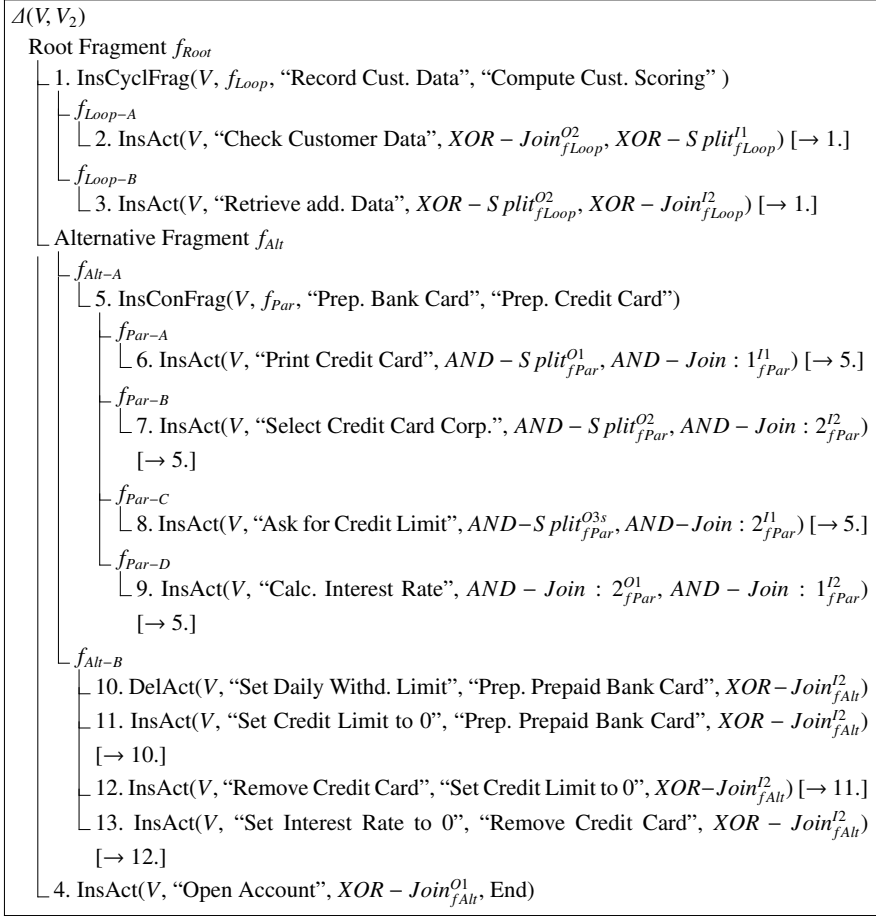


Fig. 7.11 Reconstructed Change Log $\Delta(V, V_2)$ of our running Example with Dependencies between Compound Change Operations and an Execution Order

to 0” is connected to its predecessor “Prep. Prepaid Bank Card” and successor “ $XOR - Join_{f_{Alt}}^{I2}$ ”.

However, according to Requirement 2 the approach is too restrictive and results in dependencies between change operations that potentially can be applied in isolation. To give an example, let us consider a scenario where the consolidated process model shall be created by applying just a subset of the compound change operations in change log $\Delta(V, V_2)$ given in Figure 7.11. Let us assume that a user wants to select Operation 12 InsertActivity(V , “Remove Credit Card”, “Set Credit Limit to 0”, $XOR - Join_{f_{Alt}}^{I2}$) that shall be applied to obtain the consolidated process model V_M . In this case, also Operation 11 InsertActivity(V , “Set Credit Limit to 0”, “Prep. Prepaid

Bank Card”, $XOR - Join_{fAlt}^{I2}$) must be applied, since Operation 12 depends on this operation. Actually, it is not possible to apply Operation 12 without Operation 11.

Similarly, the third requirement is not fulfilled, since dependencies that are computed for change operations with specified position parameters, restrict the application order of change operations unnecessarily. For clarification, let us again consider the example from above. Even if both Operations 11 and 12 shall be applied, it is not possible to apply Operation 12 before Operation 11, because Operation 12 uses the inserted activity “Set Credit Limit to 0” of Operation 11 as position parameter.

Table 7.1 summarizes which requirements are fulfilled by the presented approach to compute transformation dependent compound change operations.

Table 7.1 Evaluation of the Dependency Analysis based on Model Transformations according to the Requirements for Dependencies (Section 7.1)

Requirements for Dependency Analysis	Approach based on Model Transformations
[R1] <i>Dependency Detection</i>	✓
[R2] <i>Application of a Subset of Change Operations</i>	✗
[R3] <i>Arbitrary Execution Order</i>	✗

In the next section, we present an improved approach for the computation of dependencies that can be applied on compound change operations without the need to specify their position parameters in advance.

7.3 J-PST Dependent Compound Change Operations

In the previous section, we introduced an approach to compute dependencies between compound change operations based on dependent model transformations. As a prerequisite, the approach requires that position parameters of change operations have been specified before. According to the requirements for dependency computation, this approach turned out to be too restrictive and resulted in unnecessary dependencies between compound change operations.

In this section, we propose an approach to overcome these issues by computing dependencies between compound change operations, whose position parameters have not been specified yet. Our approach relies on the concept of dynamic specification of compound change operations, where concrete position parameters are computed dynamically when change operations are applied. Using our approach, different business process models can be integrated by applying change operations without being unnecessarily restricted to a certain order. This section and its subsections are based on our earlier publications [Küster et al., 2009, Küster et al., 2010].

In Section 7.3.1, we first introduce the concept of dynamic specification and present an algorithm that computes position parameters dynamically. We define the notion of *Joint-PST* dependencies in Section 7.3.2 and show that each *Joint-PST*

dependency implies a transformation dependency. Finally, we evaluate this approach whether it fulfills our requirements.

7.3.1 Dynamic Specification

In the following, we first give an overview on the concept of dynamic specification of compound change operations. Then, we define how position parameters of compound change operations are specified correctly and provide an algorithm for their computation.

After the detection of differences, the compound change operations in a reconstructed change log $\Delta(V, V_i)$ are underspecified, i.e. their position parameters have not been specified yet. In contrast to the former approach presented in the previous section, these partially specified compound change operations will serve in the following as our starting point for the computation of differences. To that extent, we will leverage the *Joint - PST* and the hierarchical change log that has been annotated with change operations as introduced in Section 6.3. Figure 7.12 shows the hierarchical change log $\Delta(V, V_2)$ from our example. Based on the hierarchical change log, dependencies between compound change operations are computed. We define the notion of *Joint - PST* dependencies in Section 7.3.2.

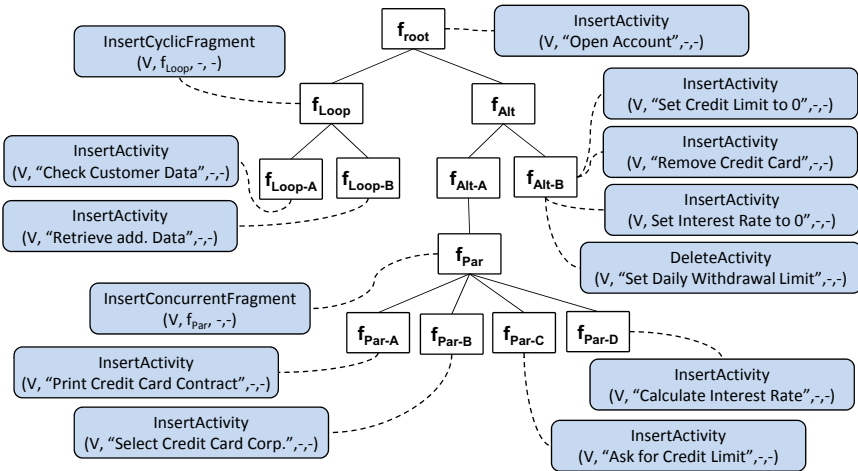


Fig. 7.12 Hierarchical Change Log that represents the Differences between the Process Models V and V_2 (see Figure 1.3)

The idea behind dynamic specification is to compute position parameters only for those change operations that do not depend on other operations (i.e. independent operations). In addition, for the computation of position parameters only corresponding and unchanged model elements are used, i.e. model elements that exist

in both process models and are not affected by a change operation. We refer to these model elements as *fixpoints* in the following. By specifying the position parameters of independent operations, they become applicable. Whenever such an operation is applied, the position parameters of the remaining operations in the change log are reconsidered in two ways: First the position parameters of independent change operations are refined in order to reflect the potentially changed set of fixpoints due to the applied change operation. Second if other operations depend on the recently applied operation, these operations may become independent now and their position parameters need to be computed.

By dynamically specified position parameters of change operations, we aim to avoid unnecessary sequential dependencies and ensure that change operations can be applied in an arbitrary order whenever possible.

In the following, we first introduce *fixpoints* in detail and define how position parameter must be computed to result in correct specifications of compound change operations. Then, we present an algorithm for the computation of position parameters.

Fixpoints and Correct Specification

According to our requirements, differences between two process model versions should be resolvable in an arbitrary way, which depends on the position parameters. To give an example, we consider the insertion of the three activities “*Set Credit Limit to 0*”, “*Remove Credit Card*”, and “*Set Interest Rate to 0*” that have been inserted in process model version V_2 in our running example (see Figure 1.3). For these operations the position parameters can be specified in the order in which the operations have been added to the change log $\Delta(V, V_2)$, resulting in the following change operations with specified position parameters:

- (A) $\text{InsAct}(V, \text{“Set Credit Limit to 0”}, \text{“Prep. Prepaid Bank Card”}, \text{XOR} - \text{Join}_{f_{Alt}}^2)$
- (B) $\text{InsAct}(V, \text{“Remove Credit Card”}, \text{“Set Credit Limit to 0”}, \text{XOR} - \text{Join}_{f_{Alt}}^2)$
- (C) $\text{InsAct}(V, \text{“Set Interest Rate to 0”}, \text{“Remove Credit Card”}, \text{XOR} - \text{Join}_{f_{Alt}}^2)$

As we have seen in the previous section, these operations are transformation dependent since they use newly created model elements as position parameters. Accordingly, the application of the operation is restricted to one particular execution order A, B, and C. Moreover, it is not possible to apply a subset of the operations, e.g. only operation B.

To overcome these issues, we propose to express position parameters in terms of *fixpoints* between two process models. Informally, a *fixpoint* is a node that has a corresponding counterpart in the other process model and is not affected by a change operation. Formally, we define:

Definition 11 (Fixpoint). *Given two process models V, V_i , a mapping $\mathcal{M}(V, V_i)$ between them, and a change log $\Delta(V, V_i)$ representing the differences between V and V_i in terms of compound change operations. We define a pair of nodes (n, n_i) to be a fixpoint pair if $(n, n_i) \in \mathcal{M}(V, V_i)$ and n_i is not affected by a change operation $op \in \Delta(V, V_i)$. To each of the nodes n, n_i we refer as fixpoint.*

Based on the fixpoints, we can define correct specifications of compound change operations that use fixpoints as position parameters:

Definition 12 (Correct Specification). [Küster et al., 2010] *Given an independent compound change operation op with specified position parameters that modifies a model element e , a specification of op is said to be correct if the position parameters (x, y) of op*

- *are chosen inside the parent fragment of e , and*
- *x is the closest preceding fixpoint of e , and*
- *y is the closest succeeding fixpoint of e .*

With regards to the three compound change operations from above, a correct specification of their position parameters is given in the following:

- (A) $\text{InsAct}(V, \text{"Set Credit Limit to 0"}, \text{"Prep. Prepaid Bank Card"}, \text{XOR} - \text{Join}_{fAlt}^2)$
- (B) $\text{InsAct}(V, \text{"Remove Credit Card"}, \text{"Prep. Prepaid Bank Card"}, \text{XOR} - \text{Join}_{fAlt}^2)$
- (C) $\text{InsAct}(V, \text{"Set Interest Rate to 0"}, \text{"Prep. Prepaid Bank Card"}, \text{XOR} - \text{Join}_{fAlt}^2)$

Obviously, the three *InsertActivity* operations are no longer transformation dependent, since their position parameters consist of model elements that already exist in both process models and are not affected by a change operation. Each operation can be applied on its own. If one of the operations is applied the position parameters of the other operations need to be refined. For instance, let us assume we applied the operation B. Thereby the activity “*Remove Credit Card*” is inserted between the nodes “*Prep. Prepaid Bank Card*” and $\text{XOR} - \text{Join}_{fAlt}^2$. The set of fixpoints increases by the activity “*Remove Credit Card*”, which exists now in both process models V, V_2 and is no longer affected by an operation in the change log $\Delta(V, V_2)$. After the application of B, the position parameters of the remaining operations A, B are refined using dynamic specification as follows:

- (A) $\text{InsAct}(V, \text{"Set Credit Limit to 0"}, \text{"Prep. Prepaid Bank Card"}, \text{"Remove Credit Card"})$
- (C) $\text{InsAct}(V, \text{"Set Interest Rate to 0"}, \text{"Remove Credit Card"}, \text{XOR} - \text{Join}_{fAlt}^2)$

In the next subsection, we introduce an algorithm that computes position parameters that result in correct specifications of compound change operations.

Computation of Position Parameters

In the following, we introduce an algorithm to compute position parameters of compound change operations that results in correct specifications according to Definition 12.

The algorithm consists of three methods: the main method `computePositionParameters()` and two helper methods `getPredecessor()` and `getSuccessor()`. As input the algorithm expects a compound change operation op

and two process model versions V and V_i . The algorithm starts at the element which is affected by the change operation and then searches backward and forward until a fixpoint is reached. Depending on the type of the given compound change operation, the algorithm returns the position parameters of the new position and/or the former position. The algorithm is used both for the initial computation of position parameters as well as for their refinement after each application of an operation.

Listing 2. Computation of Position Parameters

```

Input: Compound Change Operation  $op$ , Process Models  $V, V_1$ 
Output: Position Parameters  $a, b, c, d$ 
computePositionParameters( $op, V, V_1$ )
   $x = op.getModelElement()$ ;
  // get old position parameters of  $x$  in model  $V$ 
  if  $op$  is DeleteActivity, MoveActivity, DeleteFragment, ConvertFragment then
    |  $c =$  direct predecessor of  $x \in V$ ;
    |  $d =$  direct successor of  $x \in V$ ;
  end
  // get new position parameters of  $x$  in model  $V_1$ 
  if  $op$  is InsertActivity, MoveActivity, InsertFragment, or MoveFragment then
    |  $a =$  getPredecessor ( $x, V, V_1$ );
    |  $b =$  getSuccessor ( $x, V, V_1$ );
    | if  $a, b \neq null$  then
      | | if  $a$  is not directly connected to  $b$  then
      | | | select an edge  $i$  between  $a$  and  $b$ ;
      | | |  $a = i.getSource()$ ;  $b = i.getTarget()$ ;
      | | | else
      | | | | select an edge  $i$  in  $V$  in the parent fragment of  $op$ ;
      | | | |  $a = i.getSource()$ ;  $b = i.getTarget()$ ;
      | | | end
    | | end
    | end
  end
  return  $a, b, c, d$ ;
end

```

In the next section, we define the notion of *Joint – PST* dependencies and show that it is equivalent to transformation dependencies.

7.3.2 *J-PST Dependencies*

In the following, we introduce the notion of *Joint – PST* dependencies that can be computed between compound change operations whose position parameters have not been specified yet. In addition, we address cyclic dependencies between compound change operations and show that a *Joint – PST* dependency implies a transformation dependency.

Listing 3. Supplying Methods `getPredecessor` and `getSuccessor` for the Computation of Position Parameters

```

Input: Node  $x$ , Process Models  $V, V_1$ 
Output: Predecessor  $p$ , Successor  $s$ 

getPredecessor( $n, V, V_1$ )
  determine predecessor  $p$  of  $x$  in  $V_1$ ;
  if  $p \in V \wedge p$  is not affected by a move operation then
    | return  $p$ ;
  else
    | return getPredecessor( $p, V, V_1$ );
  end
  return null;
end

getSuccessor( $x, V, V_1$ )
  determine successor  $s$  of  $x$  in  $V_1$ ;
  if  $s \in V \wedge s$  is not affected by a move operation then
    | return  $s$ ;
  else
    | return getSuccessor( $s, V, V_1$ );
  end
  return null;
end

```

Joint – PST dependencies are based on the decomposition of process models into a fragment hierarchy and the fact that every model element is enclosed by exactly one fragment, namely its *parent* fragment. Accordingly if a model element is inserted or moved, it is a prerequisite that its parent fragment exists. Analogously if a fragment is deleted, all its contained children must be deleted or moved out of the fragment. These dependencies are irrelevant from the exact position of the model elements in the process models. Based on these findings, we formally define the concept of *Joint – PST* dependencies.

Definition 13 (J-PST Dependencies). (based on [Küster et al., 2010]) Let two process model versions V, V_i and a hierarchical change log $\Delta(V, V_i)$ consisting of compound change operation be given that represents the differences between the process models. For each $op \in \Delta(V, V_i)$, we denote with $depops(op)$ all operations that are dependent on op . We define dependencies on the change operations as follows:

- Let a change operation op be given with $type(op) = InsertFragment$ and let OP_f be the set of all operations associated to a child of the newly inserted fragment $f = fragment(op)$. Then every $op_i \in OP_f$ is dependent on op and therefore $depops(op) = \{op_i \in OP_f\}$.

- Let a change operation op be given with $type(op) = DeleteFragment$ and let OP_f be the set of all operations associated to a child of the deleted fragment $f = fragment(op)$. Then every $op_i \in OP_f$ is a prerequisite of op and therefore $op \in depops(op_i)$.
- Let a change operation op be given with $type(op) = ConvertFragment$ and let OP_f be the set of all operations associated to a child of the converted fragment $f = fragment(op)$. Depending on the type of the operation $op_i \in OP_f$, we distinguish three different cases:
 - If op_i inserts or moves model elements into the converted fragment f , i.e. $type(op_i) = InsertActivity, InsertFragment, MoveActivity, or MoveFragment$, then op_i depends on the conversion of f and $op_i \in depops(op)$.
 - If op_i deletes from or moves model elements out of the converted fragment f , i.e. $type(op_i) = DeleteActivity, DeleteFragment, MoveActivity, or MoveFragment$, then the conversion of f depends on op_i and $op \in depops(op_i)$.
 - If op_i moves models elements within the converted fragments f , there may exist a cyclic dependency between op and op_i . Accordingly, $op \in depops(op_i)$ and $op_i \in depops(op)$.

We call a compound change operation op **independent** if $depops(op) = \emptyset$.

Joint – PST dependencies can be easily computed by traversing the hierarchical change log. For each fragment, dependencies are computed between all operations associated to the fragment and operations associated to the children of the fragment.

Figure 7.13 shows the hierarchical change log with *Joint – PST* dependencies between compound change operations that represent the differences between process models V and V_2 (see Figure 1.3). Dependent operations are marked by squared brackets [\rightarrow *OperationNumber*] meaning that the execution of this operation depends on \rightarrow the operation *OperationNumber*. Again, we have numbered the compound change operation to make them conveniently referenceable. However, in contrast to the transformation dependencies, the numbers do not imply any execution order. Generally, all operations whose position parameters are computed can be applied directly.

In the following subsection, we consider cyclic dependencies between compound change operations.

Cyclic *Joint – PST* Dependencies

For an automatic application of compound change operations it is important to know whether *Joint – PST* dependencies between the operations are acyclic. Compound change operations with acyclic dependencies can be applied in isolation in accordance with their dependencies. However, change operations with cyclic dependencies have to be applied together.

Figure 7.14 provides an example of cyclic dependencies. There, the alternative fragments f_{a-v} and f_{a-v_1} in the process models V, V_1 correspond to each other. V_1 was created out of V by adding a new *XOR-Split* that converts the structure of fragment f_{a-v_1} from a structured fragment to an unstructured fragment. Additionally,

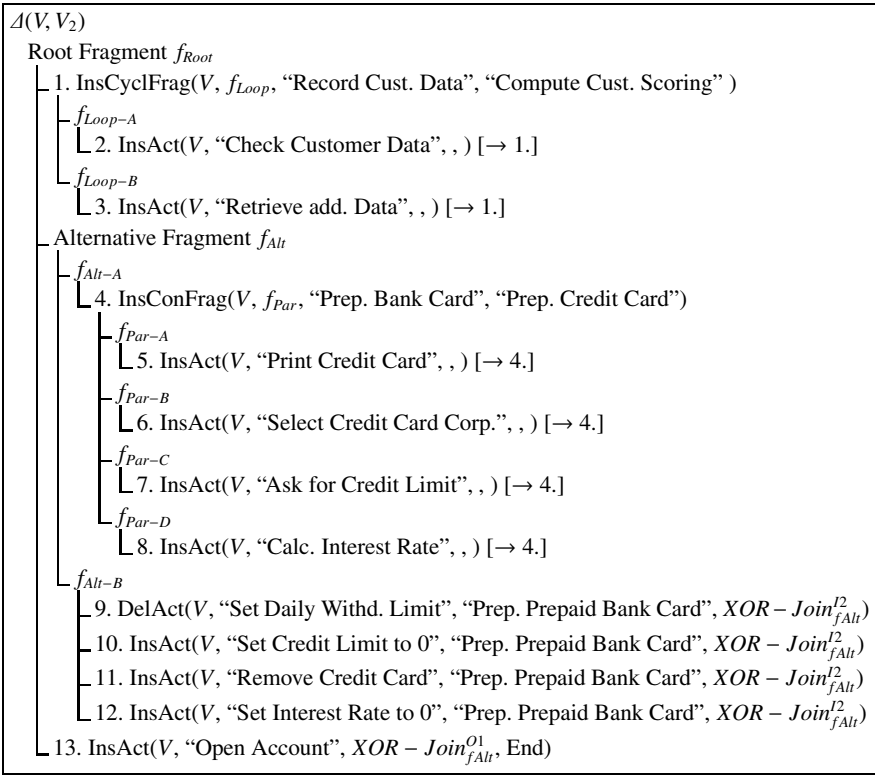


Fig. 7.13 Reconstructed Change Log $\Delta(V, V_2)$ of our running Example with Joint - PST Dependencies

the activity “B” was moved to another fragment. After difference detection, differences between V and V_1 are represented by a *ConvertFragment* and a *MoveActivity* operation.

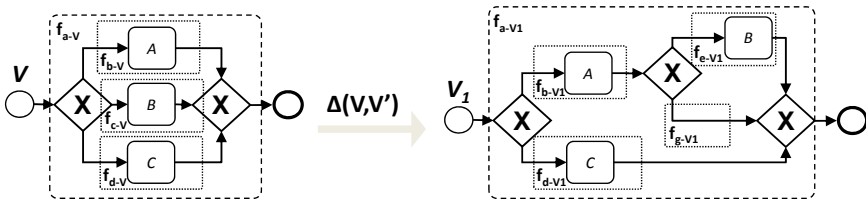


Fig. 7.14 Example of Cyclic Dependencies

If the *ConvertFragment* that transforms the structured fragment f_{a-v} into an unstructured fragment, is applied without the *MoveActivity* operation of the activity “B”, B will be unconnected in the resulting process model, since its

surrounding fragment (i.e. f_{c-v}) is removed by the *ConvertFragment* operation. However, *MoveActivity* cannot be applied before the *ConvertFragment* operation, since it requires that the fragment f_{e-v_1} to which the activity “B” is moved, exists. Hence, both operations must be applied together to obtain a connected process model.

In the following, we show that *Joint – PST* dependencies between compound change operations in a change log that does not contain the operation type *ConvertFragment* are acyclic.

Theorem 3 (Acyclic Joint – PST dependencies). *Let two process model versions V, V_i and a hierarchical change log $\Delta(V, V_i)$ be given. If $\Delta(V, V_i)$ consists only of compound change operations of the types *InsertActivity*, *InsertFragment*, *DeleteActivity*, *DeleteFragment*, *MoveActivity*, and *MoveFragment*, then the Joint – PST dependencies between the compound change operations in $\Delta(V, V_i)$ are acyclic.*

Proof Sketch: (Theorem 3) *Proof by contradiction. In the following, we consider a dependency as a directed edge connecting an operation type (source) that depends on another operation type (target). A cycle in the dependencies can be described by $\langle op_1, \dots, op_k \rangle$ such that $op_{j+1} \in depops(op_j)$ for $j = 1, \dots, k - 1$ and $op_1 \in depops(op_k)$.*

According to the Definition 13, we can derive the following dependency graph (shown in Figure 7.15) for the operation types *InsertActivity*, *InsertFragment*, *DeleteActivity*, *DeleteFragment*, *MoveActivity*, and *MoveFragment*. We divide the edges of the dependency graph into two distinct groups by labeling the edges with *InsertFragment* or *DeleteFragment* edges if their source or target is one of these types.

Based on this dependency graph, a cycle between dependencies can only be closed by edges that connect *DeleteFragment* and *InsertFragment* compound change operations. A cycle cannot consist of *DeleteFragment* or *InsertFragment* edges only because these edges either go downward in the J-PST or upward.

In the former case that means, the application of a *DeleteFragment* operation assigned to a fragment f can only depend on a *DeleteFragment* operation that is assigned to a child of fragment f , but is always independent of the parent fragment of f . In the latter case, an *InsertFragment* operation can only depend on an *InsertFragment* operation assigned to its parent fragment.

Therefore there must be one op_i in the cycle that has an incoming *DeleteFragment* and an outgoing *InsertFragment* edge those target and source refer to

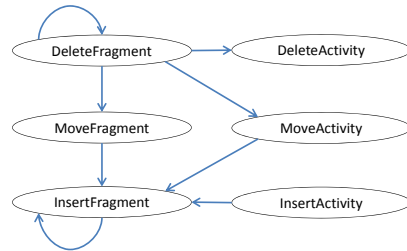


Fig. 7.15 Dependency Graph for Compound Change Operation Types

the same operation or vice versa. In both cases this cannot occur because this implies that op_i has both types (*DeleteFragment* and *InsertFragment*) which is a contradiction.

An important finding of Theorem 3 is that a check for cyclic dependencies only has to be applied for dependencies of *ConvertFragment* operations. This check is straight-forward and consists of a depth-first search over the dependencies in a hierarchical change log starting at the dependencies of a *ConvertFragment* operation. In the case that a cycle is closed, i.e. a strongly connected component is found, the operations in this cycle must be applied together.

In the next subsection, we related *Joint-PST* dependencies to the existing theory of transformation dependencies.

Transformation Independence

Finally, we establish in the following theorem a connection between *Joint-PST* dependencies and transformation dependencies that we have introduced in Section 7.2. The theorem shows that it is sufficient to compute *Joint-PST* dependencies even if operations are associated to different fragments in the *Joint-PST*:

Theorem 4 (TR-independence). ([Küster et al., 2010]) *Let two process model versions V, V_i and a hierarchical change log $\Delta(V, V_i)$ be given. Further, let op_i and op_j be two operations in $\Delta(V, V_i)$ that are attached to different fragments. If op_i and op_j are not *Joint-PST* dependent then op_i and op_j are not transformation dependent on each other.*

Proof Sketch: (Theorem 4) *Proof by Contradiction. Assume that two operations in different fragments exist and that no *Joint-PST* dependency exists between them. Let us now assume that they are transformation dependent on each other when their position parameters are fixed. We consider the dependency matrix given in Appendix B, which specifies transformation dependencies of two operations op_i and op_j .*

*The entries of the matrix specify when two operations are transformation dependent. Each entry requires that the two operations have at least one common parameter. This ensures for all combinations where op_i and op_j are *InsertActivity*, *DeleteActivity*, and *MoveActivity*³ operations that the operations are associated to the same fragment node in the *Joint-PST*, which is a contradiction.*

*For all other combinations involving *InsertFragment*, *DeleteFragment*, *MoveFragment*, or *ConvertFragment*, the common position parameter or the fragment hierarchy (parent-child relationship) ensures that the two operations are associated to the same fragment node or it is the case that *entry(f)* or *exit(f)* occur in the position parameters where f is the fragment manipulated by *InsertFragment*,*

³ Please note that *MoveActivity* and *MoveFragment* operations that move model elements between fragments, appear twice in the hierarchical change log $\Delta(V, V_i)$. Once in the source fragment and again in the target fragment.

DeleteFragment, *MoveFragment*, or *ConvertFragment*. In these cases, by Definition 13, a *Joint – PST* dependency must exist between the two operations which is again a contradiction.

The previous theorem shows that it is sufficient to compute *Joint – PST* dependencies between operations contained in the same parent fragment. Next, we briefly evaluate the notion of *Joint – PST* dependent compound change operations according to our requirements for dependency analysis.

7.3.3 Discussion

In this section, we evaluate whether the presented approach for the computation of dependencies based on the *Joint – PST* and the hierarchical change log fulfills our requirements introduced in Section 7.1.

Analogously to the former approach, the presented approach is capable to identify dependencies between compound change operations. However, in contrast to transformation dependencies, *Joint – PST* dependencies can be computed based on change operations, whose position parameters have not been specified yet. Position parameters are computed for independent compound change operations and are refined dynamically after the application of a change operation.

Thereby, our approach results in fewer dependencies between change operations (six *Joint – PST* dependencies instead of nine transformation dependencies) and ensures that all operations that potentially can be applied in isolations, are also independently applicable, regardless their position parameters. To give an example, let us consider the operations 11, 12, and 13 from Figure 7.13. These operations are transformation dependent if dependencies are computed based on compound change operations, whose position parameter have been specified. However, using our notion of *Joint – PST* dependencies and the dynamic specification of position parameters, the operations can be applied independently in any execution order, since no operation uses modified model elements as position parameters. Accordingly, Requirement 2 is fulfilled.

Moreover, the third requirement is fulfilled, since the application order of change operations is not unnecessarily restricted. For instance, in the example from above, both operations 11 and 12 can be applied in any order. Whenever one of the operations is applied first, the position parameters of the other operations are refined dynamically to reflect the new situation.

Table 7.2 summarizes which requirements are fulfilled by the presented approach to compute *Joint – PST* dependent compound change operations.

In the next section, we summarize the dependency analysis between compound change operations and give an outlook on the next chapter.

7.4 Summary and Discussion

In this chapter, we considered the analysis of dependencies between change operations. For this purpose, we started with a reconstructed change log that describes

Table 7.2 Evaluation of the Dependency Analysis based on Dynamic Specification according to the Requirements for Dependencies (Section 7.1)

Requirements for Dependency Analysis	Approach based on Dynamic Specification
[R1] <i>Dependency Detection</i>	✓
[R2] <i>Application of a Subset of Change Operations</i>	✓
[R3] <i>Arbitrary Execution Order</i>	✓

differences between two process model versions in terms of compound change operations. We first established requirements such an approach to dependency analysis between compound change operations has to fulfill. Then, we introduced two different approaches for the computation of dependencies: transformation dependencies and *Joint – PST* dependencies.

The former approach, computes dependencies between compound change operations, whose position parameter have been specified before. The approach is based on the existing notion of dependencies between graph transformations of typed attributed graphs. We first formalized compound change operation types in terms of graph transformations and then applied a critical pair analysis to identify situations that result in dependencies. Then, we captured the situations that result in dependencies in a dependency matrix. This dependency matrix enables fast checks for dependencies between compound change operations with specified position parameters. However, considering our requirements, the notion of transformation dependencies between compound change operations turned out to be too restrictive and resulted in unnecessary dependencies.

The latter approach, based on the notion of *Joint – PST* dependencies, overcomes the shortcomings of the former approach and is able to identify dependencies even between compound change operations, whose position parameters have not been specified yet. As a consequence, *Joint – PST* dependencies fulfill our requirements for dependency analysis in process model change management.

The compound change operations and dependencies that we have computed in the previous two chapters represent differences between two process model versions, e.g. a source process model V and a descendant version V_1 or V_2 . In a two-way merge scenario, the compound change operations contained in the change log $\Delta(V, V_1)$ can be applied in the order determined by the dependencies to transform the source process model V into version V_1 . Analogously, V is transformed into V_2 by applying the compound change operations contained in the change log $\Delta(V, V_2)$. These two examples represent classical two-way merge scenarios, where one process model is transformed into the other.

In contrast to classical two-way merge scenarios, in a three-way merge scenario, we are interested in a merged process model version V_M , which considers both the compound changes applied to obtain version V_1 as well as the changes applied to obtain V_2 . As a consequence, we have to identify change operations in the change

logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$ that are equivalent and change operations that exclude each other, i.e. are conflicting. These are the topics of the next two chapters.

We consider the identification of changes that result in equivalent process models in the next chapter and compute conflicts of change operations that exclude each other in Chapter 9.

Equivalence Analysis

In this chapter, we propose an approach for deciding equivalence of business process models and individual parts of them based on a normalization of process model fragments. The presented approach is in particular useful in distributed process modeling scenarios, to answer the question whether independently applied changes result in semantically equivalent structures in process models or mutually exclude each other and hence give rise to conflicts. In addition, normalized fragments can directly be adopted in the merged version of process models to obtain integrated process model that are easier to understand, since unstructured fragments may be normalized to structured fragments.

In the next section, we discuss existing approaches to decide equivalence of process models and give an overview of our approach. Then, we introduce process model terms in Section 8.2 and their normalization using a term rewriting system in Section 8.3. In Section 8.4, we demonstrate how equivalence can be decided based on normalized process model terms and conclude with a summary and discussion.

8.1 The Notion of Equivalence

When process models are developed in team environments, it might happen that semantically equivalent concepts are modeled by different developers using different syntactical model elements of a modeling language. Figure 8.1 gives an example. There, a source process model V and two version V_1 and V_2 are shown that describe the claim handling in an insurance company.

Although the different process model versions (V_1 and V_2) look similar, a purely syntax-based comparison of these models results in several conflicts, among them many false positives. We consider changes applied to process models to be conflicting if the application of both change operation mutually excludes each other, e.g. different model elements are inserted at the same position in a process model. A conflict between two change operations constitutes a false-positive conflict if the application of both operations results in syntactically different but semantically equivalent structures. For instance, the highlighted fragments in Figure 8.1 are semantically equivalent, i.e. the same set of activities can be applied in the same

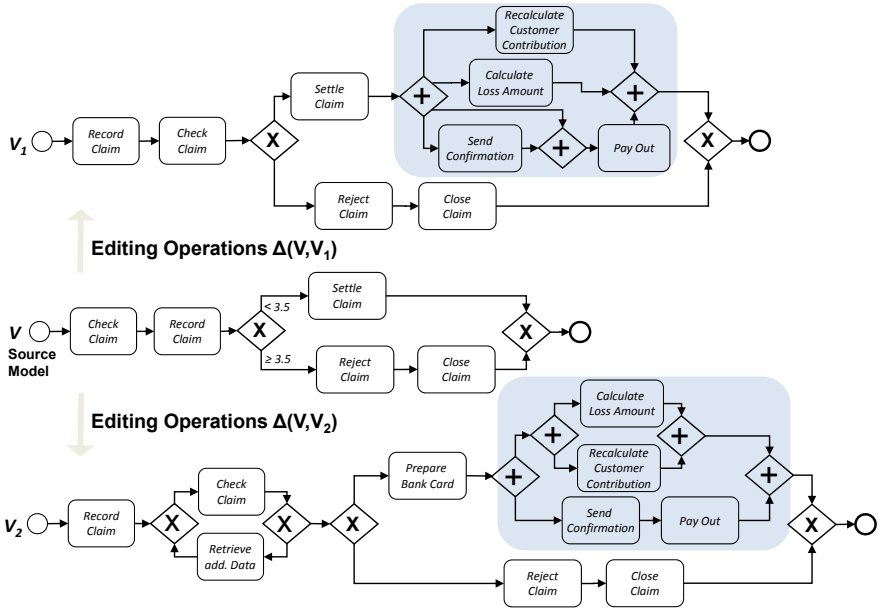


Fig. 8.1 Syntactically different Process Models that share semantically equivalent Fragments

order. However, since their syntactical representation is different, a syntax-based comparison applied to V_1 and V_2 results in conflicts, which are false-positive.

This problem results from the fact that well-established modeling languages such as the Business Process Model and Notation (BPMN) [OMG, 2011a] or Activity Diagrams (UML-AD) [OMG, 2010a] generally allow a user to connect elements such as activities and gateways in an arbitrary way. This favors the construction of syntactically very different process models, which might be semantically equivalent regarding their execution logic and execution order.

To merge process models effectively, the comparison of business process models must consider the semantics of the models and equivalences between different versions of process models must be identified to obtain precise conflicts. In the following, we first consider existing approaches to equivalence analysis of process models and afterwards, we give an overview of our approach.

8.1.1 Existing Approaches to Equivalence Analysis of Process Models

In general, there are two different ways to decide equivalence of business process models: that is syntactic or semantic comparison. According to this distinction, we introduce existing approaches to equivalence analysis of process models.

In a syntactic comparison of two process models, contained nodes and edges are compared. If each contained node and edge in one process model has a

corresponding counterpart in the other model, the two models are considered to be syntactically equivalent. Moreover, the models are also considered to be semantically equivalent. If only some of the nodes and edges have a corresponding counterpart, the models are considered to be similar to some degree. Syntactic comparison has the benefit of being hardly time-consuming. However, it is most unlikely that two process models are completely syntactically equal, especially since process modeling languages allow to express the same semantics with different syntactic constructs. As a consequence, it is rather the case that syntactically different process models are created that may be semantically equivalent.

The following works compare process models syntactically. Ehrig et al. [Ehrig et al., 2007] compute a combined similarity value consisting of syntactic, linguistic, and structural similarity of elements in process models. The execution semantics of process models and the execution order of contained elements, such as activities, is not considered. In [van Dongen et al., 2008], van Dongen et al. relate process elements with their directly preceding and succeeding elements which they call footprints to measure the similarity between EPC processes. In [Li et al., 2008], Li et al. measure distance and similarity of process models based on change operations. Bae et al. [Bae et al., 2006] measure the similarity between process models using a tree representation and compare its block similarity.

To identify semantic equivalences in process models, a semantic comparison of process models usually relies on a notion of equivalence such as trace equivalence or bisimulation [v. Glabbeek, 1988]. Trace equivalence compares the execution traces of processes. In a trace the execution of activities in a process model is logged in a chronological order. Computing trace equivalence can be complex, in particular for concurrent structures or cyclic structures in process models and has exponential complexity in the general case. Even if traces are computed only for parts of a process model the number of traces that need to be compared can be high. To give an example, in the small example in Figure 8.1 the four activities in the highlighted parts of the process models result in 12 different traces. These sets of traces need to be compared to decide the equivalence of the highlighted parts. Trace equivalence does not consider the moment of choice when the control-flow in a process model is splitted or joined. For that purpose, a stronger notion such as bisimulation [v. Glabbeek, 1988] is needed.

Equivalence notions have in common that their result is binary. That means, two process models are either equivalent or not. In the case that two process models have different traces, they are not trace equivalent. Moreover, from different traces it is difficult to identify the actual reasons, i.e. the change operations, which are responsible for the different traces between the two models. Accordingly, traces need to be analyzed further.

An approach that tries to overcome the problem of a binary equivalence result can be found in [van der Aalst et al., 2006]. There, the authors compute a quantified equivalence based on observable behavior given in execution logs of process models. A further approach that is based on the analysis of execution traces is [Weidlich et al., 2009, Weidlich et al., 2011]. Weidlich et al. compare process models based on so called behavior profiles, which reflect different relations between

nodes (strict order, exclusiveness and concurrency). Both approaches are performed on the whole process model and are not applicable on parts of it. Further, the approaches rely on the existence of execution traces of a process model, which may be difficult to handle in the case of large models or contained cyclic structures. In [Wombacher and Li, 2010], Wombacher et al. evaluate different similarity measures for workflows that are based on n-grams.

Eder et al. [Eder et al., 2005] provide an equivalence definition for workflow graphs and describe a set of structural modifications to workflow graphs that are semantic preserving. In contrast to our work, they focus on well-structured models and do not support unstructured fragments like the highlighted fragment in process model V_1 in Figure 8.1.

In contrast to existing works, our approach to equivalence analysis of process models enables a semantic comparison of individual parts of processes. In addition, the result of our equivalence analysis is directly related to the actual change operations that are responsible for the different traces between process models. We give an overview of our approach in the next section.

8.1.2 Overview of Our Approach

Based on process models in the intermediate representation, we propose a more efficient way to decide equivalence between process models that overcomes the shortcomings of trace equivalence. Our approach combines the benefits from both the syntactic and semantic comparison. Figure 8.2 gives an overview. To decide equivalence, business processes (or individual fragments of them) are transformed into a term representation (Section 8.2) by iterating over the process structure tree.

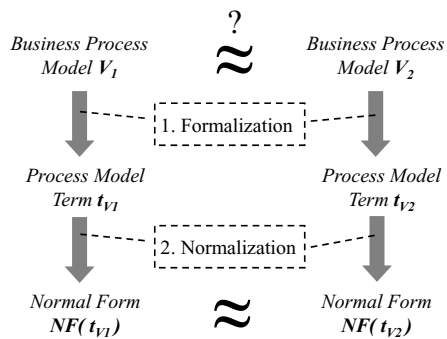


Fig. 8.2 Approach Overview

The resulting process model terms capture semantic information concerning the execution order and the execution logic (such as AND, OR, XOR) of the business process models.

In a second step, the process model terms are normalized using a term rewriting system (Section 8.3). The rules of the term rewriting system reduce syntactically different but semantically equivalent terms of two process models into their normal form by preserving their behavior. Based on the normal forms, we can decide whether the two parts of a process models are semantically equivalent by comparing their syntactic representation (Section 8.4).

In addition, the normal form can directly be used to adopt changes in a merged process model. This potentially results in fewer changes that need to be applied

to merge two process models and contributes to a better understandability of the merged model. A detailed example can be found in Section 8.4.

We introduce the term notation for business process models in the next section, followed by a description of the term rewriting system.

8.2 Process Model Terms

In this section, we develop a process model term notation and show how process models in the intermediate representation are transformed into terms that can be compared using the term rewriting system from Section 8.3.

For the following discussions, we assume a business process model V to be expressed using the intermediate representation as introduced in Chapter 3. A term representation of process models needs to capture precise information about the contained model elements, their hierarchical structure in terms of nested fragments, as well as information about the execution order of the elements.

IR Model Element	Term
Activity, Event η	η
Sequential Fragment σ	$\sigma(\dots)$
Parallel Fragment π	$\pi(\dots)$
Alternative Fragment α	$\alpha(\dots)$
Alternative Loop Fragment λ	$\lambda(\dots)$
Complex Fragment ι	$\iota(\dots)$

Fig. 8.3 Transformation of Process Models into Terms

Figure 8.3 summarizes the translation of model elements of IR process models to their corresponding term representation. η represents the name of an *Activity* or an *Event* in an IR process model. Gateways are not added to process model terms, since they are already represented by their surrounding fragments. Figure 8.4 shows the grammar for valid terms.

$Term ::= Frag \ O$
$Frag ::= \pi(Seqs) \mid \alpha(Seqs) \mid \lambda(Seqs) \mid \iota(Seqs) \mid Seq$
$Frag s ::= Frag \ , \ Frag s \mid Frag$
$Seq ::= \sigma(Frag s) \mid \sigma(Nodes)$
$Seq s ::= Seq \ , \ Seq s \mid Seq$
$Node ::= \eta \mid Frag \mid \epsilon$
$Nodes ::= Node \ , \ Nodes \mid Node$
$O ::= Seq \times Seq$

Fig. 8.4 Grammar for Process Model Terms

The transformation of a process model into terms is straight-forward by traversing its PST using the infix approach. We define O to be the partial order set over the carrier set Seq , i.e. the set of sequences. O specifies the execution order of branches within fragments that is necessary to decide equivalence of unstructured parallel and alternative fragments¹, like the highlighted fragment in process model V_1 in

¹ A fragment is unstructured if it consist of pairs of gateways whose number of outgoing edges differs from the number of incoming edges.

Figure 8.1. For instance, within the highlighted, parallel fragment in process model V_1 (Figure 8.1), the sequence containing the activity "Send Confirmation" is executed before the sequence enclosing the activity "Pay Out". We do not explicitly specify the execution order of elements within sequences, since it is given implicitly. The partial order within a fragment can be obtained easily by traversing all branches of each fragment using the depth first approach.

Let $s \in \mathcal{F}(V)$ be a sequence of the process model V and $\sigma \in Seq$ be its corresponding sequence in the process model term t_V . We define $O_{Pre}(\sigma) = \{(\sigma_i, \sigma) \in O\}$ to be the preset of σ containing tuples $\sigma_i < \sigma$, i.e., the sequences σ_i that are executed directly before σ , and $O_{Pre}^*(\sigma)$ contain all preceding sequences reachable from σ in its parent fragment. Analogously, we define $O_{Post}(\sigma) = \{(\sigma, \sigma_j) \in O\}$ to be the postset of σ containing tuples $\sigma < \sigma_j$, i.e., the sequences σ_j that are executed directly after σ , and $O_{Post}^*(\sigma)$ contain all succeeding sequences reachable from σ in its parent fragment. We denote the union of both sets as $O(\sigma) = O_{Pre}(\sigma) \cup O_{Post}(\sigma)$.

The business process model V_1 introduced in Figure 8.1 results in the process model term t_{V_1} and execution order O_{V_1} shown in Figure 8.5. We use indices for sequences for short. For instance, we use $\sigma_7('Pay Out')$ in the process model term and refer to this particular sequence using σ_7 in the partial order. However, the sequence indices are not part of the original grammar but are only used for the sake of brevity. An empty fragment is represented by dots enclosed by the fragments term representation, e.g. the empty sequential fragment $\sigma_5(\dots)$. The variable η ranges over the activities and events in the process models.

$$\begin{aligned}
 t_{V_1} = & \sigma_{root}('Start', 'Record Claim', 'Record Customer Data', \\
 & \alpha(\sigma_1('Settle Claim', \\
 & \quad \pi(\sigma_3('Recalc. Cust. Contribution'), \sigma_4('Calculate Loss Amount'), \\
 & \quad \sigma_5(\dots), \sigma_6('Send Confirmation'), \sigma_7('Pay Out')) \\
 &), \\
 & \sigma_2('Reject Claim', 'Close Claim'), \\
 &), 'Stop') \\
 O_{V_1} = & \{\sigma_5 < \sigma_7, \sigma_6 < \sigma_7\}
 \end{aligned}$$

Fig. 8.5 Process Model Term t_{V_1} of the Process Model V_1 in Figure 8.1

Process model terms can be syntactically compared very efficiently. However, to compare the semantic equivalence of syntactically different models, their corresponding terms have to be transformed into a normal form to be considered equivalent. Otherwise, syntactically different models result in different terms regardless their semantic meaning. The term rewriting system for this transformation is introduced in the next section.

8.3 Term Rewriting System for Process Model Terms

In general, a term rewriting system reduces terms by applying rules to the terms [Baader and Nipkow, 1998]. In the domain of process modeling reduction rules are used, e.g. for the purpose of process model verification. In [Sadiq and Orłowska, 2000], Sadiq et al. check soundness properties of process models (such as deadlock and lack of synchronization) by iteratively removing sound structures until the model is completely reduced. In [van Dongen et al., 2005, Mendling and van der Aalst, 2007, Dijkman, 2008], reduction rules are applied to EPCs that remove sound functions, events, and connectors in order to reduce the state space and speed up the verification process. However, in our scenario, sound structures cannot be removed, since they are essential to decide equivalence.

In this section, we introduce a term rewriting system [Baader and Nipkow, 1998] for process model terms to enable semantic comparison of business process models. The system consists of a set of rules, which reduce process model terms to a normal form. Then, we consider the correct functional behavior of the rewriting system. Finally, we define equivalence of process models based on the normal form of process model terms.

8.3.1 Term Rewriting System

Our term rewriting system consists of rules for the reduction of sequences σ , parallel fragments π , and alternative fragments α contained in process models. The fragments can be in structured and unstructured form. Overall our rule system consists of 16 reduction rules. Some of the rules are inspired by the rules presented in [van Dongen et al., 2005, Mendling and van der Aalst, 2007, Dijkman, 2008, Eder et al., 2005]. We do not intend the set of reduction rules to be complete, in the sense that by using the rules, equivalence can be decided for all fragments of process model. However, fragments whose equivalence cannot be decided using our approach are known in advance. For these cases, trace equivalence in combination with an analysis of the obtained sets of traces is leveraged. Due to the fragment hierarchy of the intermediate representation, trace equivalence is additionally speeded up, since traces only need to be computed for fragments, which are significantly smaller compared to the whole process model.

In the following, we present the rules of the term rewriting system and give graphical examples for clarification. Further, we briefly consider their correctness.

Rule Par 1. (*Elimination of Empty Sequences*) *Given a parallel fragment π containing at least two sequences. If one of the contained sequences is empty σ_ϵ it is removed and the partial execution order is aligned in such a way that all $\sigma_i < \sigma_\epsilon$ and $\sigma_\epsilon < \sigma_j$ are replaced by new restrictions $\sigma_i < \sigma_j$.*

$$(par1) \frac{\pi(\sigma_1, \dots, \sigma_\epsilon, \dots, \sigma_n) \quad O}{\pi(\sigma_1, \dots, \sigma_n) \quad ((O \setminus \mathcal{P}) \setminus \mathcal{S}) \cup \mathcal{N}}$$

$$\begin{aligned}
\text{where } \mathcal{P} &= \{(\sigma_i, \sigma_\epsilon) \in \mathcal{O} \mid \sigma_i < \sigma_\epsilon\} \\
\mathcal{S} &= \{(\sigma_\epsilon, \sigma_j) \in \mathcal{O} \mid \sigma_\epsilon < \sigma_j\} \\
\mathcal{N} &= \{(\sigma_i, \sigma_j) \mid (\sigma_i, -) \in \mathcal{S} \wedge (-, \sigma_j) \in \mathcal{P}\}
\end{aligned}$$

Rule Par 1 removes one empty sequence of a parallel fragment at a time and is applied until all empty sequences are eliminated. Figure 8.6 gives an example, where the empty sequence σ_3 is removed by applying Rule Par 1. The removal of an empty sequence in a parallel fragment is semantic preserving, since traces are not changed and empty sequences can be neglected in process models.

Rule Par 2. (*Concatenation of Sequences*) Given a parallel fragment π containing two sequences $\sigma_1(a, \dots, n)$ and $\sigma_2(m, \dots, z)$ with the execution order $\sigma_1 < \sigma_2$ and no other restriction of the form $\sigma_1 < \sigma_i$ and $\sigma_i < \sigma_2$. Then $\sigma_1(a, \dots, n)$ and $\sigma_2(m, \dots, z)$ are concatenated into $\sigma_\star(a, \dots, n, m, \dots, z)$ and the partial execution order is aligned in such a way that all $\sigma_i < \sigma_1$ and $\sigma_2 < \sigma_j$ are replaced by new restrictions $\sigma_i < \sigma_\star$ and $\sigma_\star < \sigma_j$.

$$(\text{par2}) \frac{\pi(x, \sigma_1(a, \dots, n), \sigma_2(m, \dots, z), y) \quad \mathcal{O}}{\pi(x, \sigma_\star(a, \dots, n, m, \dots, z), y) \quad \mathcal{O}'}$$

$$\begin{aligned}
\text{where } \mathcal{O}' &= \mathcal{O} \setminus \{(\sigma_1, \sigma_2)\} \cup \mathcal{O}_{\text{Pre}}(\sigma_1) \cup \mathcal{O}_{\text{Post}}(\sigma_2) \cup \mathcal{P} \cup \mathcal{S} \\
\mathcal{P} &= \{(\sigma_i, \sigma_\star) \mid (\sigma_i, \sigma_1) \in \mathcal{O}_{\text{Pre}}(\sigma_1)\} \\
\mathcal{S} &= \{(\sigma_\star, \sigma_j) \mid (\sigma_2, \sigma_j) \in \mathcal{O}_{\text{Post}}(\sigma_2)\}
\end{aligned}$$

Figure 8.6 gives an example. The unstructured parallel fragment π contains four sequences $\sigma_1 \dots \sigma_4$. After the deletion of sequence σ_3 (by the application of Rule Par 1), Rule Par 2 becomes applicable, which concatenates the sequences σ_1 and σ_2 into σ_\star . Rule Par 2 preserves the behavior of the process model since all activities are obviously executed in the same order.

Rule Par 3. (*Resolution of Empty Parallel Fragments*) Given a parallel fragment π that contains one single sequence σ . Then the parallel fragment can be dropped regardless of any given partial order.

$$(\text{par3}) \frac{\pi(\sigma) \quad \mathcal{O}}{\sigma \quad \mathcal{O}}$$

Figure 8.7 gives an example. Similar to the former rule, after the removal of the empty sequence σ_2 by Rule Par 1, Rule Par 3 becomes applicable that removes the parallel fragment π and integrates σ_1 into the enclosing sequence σ . Also Rule Par 1 is behavior preserving since the contained sequence is still executed at the same position.

Rule Seq 1. (*Resolution of Nested Sequences*) Given a sequence that contains another sequence. Then the inner sequence may be dropped and its components are inserted into the outer sequence.

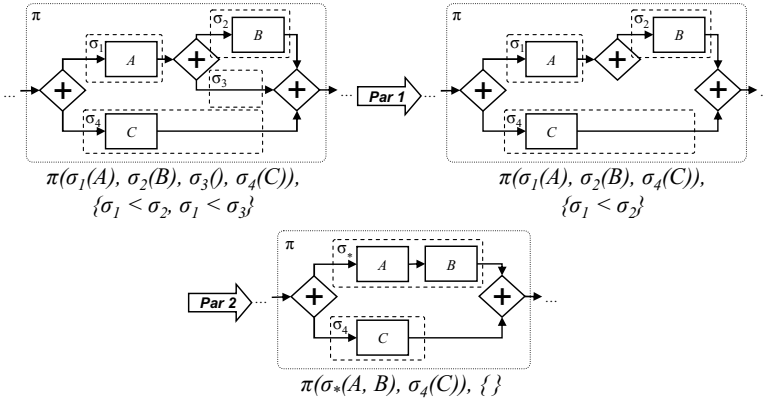


Fig. 8.6 Example for the Application of Rule Par 1 and Par 2

$$(seq1) \frac{\sigma(x, \sigma(a \dots n), y) \quad O}{\sigma(x, a, \dots, n, y) \quad O}$$

The application of Rule Seq 1 is shown in Figure 8.7. Here, the inner sequence σ_1 is removed and its contained elements are integrated into the enclosing sequence σ . Since Rule Seq 1 changes only the fragment hierarchy of the model and not its execution order, it is semantic preserving.

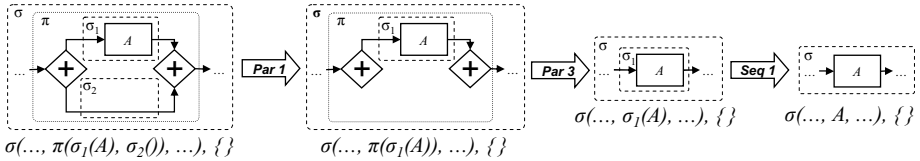


Fig. 8.7 Example for the Application of Rule Par 1, Par 3, and Seq 1

Rule Seq 2. (*Extraction of Sequences from parallel Fragments*) Given a parallel fragment π and a set S comprising all sequences σ directly contained in π . We assume that a non empty sequence $\sigma_i \in S$ exists that is executed **after** all other sequences $\sigma_j \in S$, i.e. $\forall \sigma_j \in S \setminus \{\sigma_i\} : \exists(\sigma_j, \sigma_i) \in O$. We denote this set with \mathcal{P} . Then σ_i is extracted from π and inserted directly after π in the surrounding parent fragment σ .

Analogously, Rule Seq 2(b) is applicable in cases, where σ_i is executed **before** all other sequences $\sigma_j \in S$, i.e., $\forall \sigma_j \in S \setminus \{\sigma_i\} : \exists(\sigma_i, \sigma_j) \in O$. Again, we denote this set with \mathcal{P} .

$$(seq2a) \frac{\sigma(x, \pi(\sigma_1, \dots, \sigma_i, \dots, \sigma_n), y) \quad O}{\sigma(x, \pi(\sigma_1, \dots, \sigma_n), \sigma_i, y) \quad O \setminus \mathcal{P}}$$

$$(seq2b) \frac{\sigma(x, \pi(\sigma_1, \dots, \sigma_i, \dots, \sigma_n), y)}{\sigma(x, \sigma_i, \pi(\sigma_1, \dots, \sigma_n), y)} \frac{O}{O \setminus \mathcal{P}}$$

Figure 8.8 gives an example. The sequence σ_4 is removed by Rule Par 1. Then Rule Seq 2(b) becomes applicable, since sequence σ_1 is executed before all other sequences in π . The Rules Seq 2(a) and (b) are semantic preserving since the set of obtainable traces before and after extracting the sequential fragment are identical.

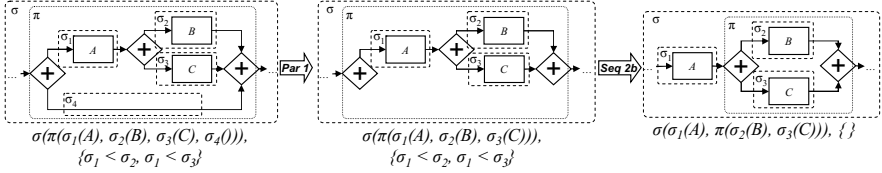


Fig. 8.8 Example for the Application of Rule Par 1 and Seq 2(b)

Rule Par 4. (Resolution of Nested Parallel Fragments) Given a sequence σ in a parallel fragment π_1 . If σ contains only a structured² parallel fragment π_2 then the sequence σ and π_2 are dropped and the contained sequences of π_2 are inserted into the outer parallel fragment π_1 .

Rule Alt 1. (Resolution of Nested Alternative Fragments) Analogously, Rule Alt 1 aligns nested alternative fragments.

$$(par4) \frac{\pi_1(x, \sigma(\pi_2(z)), y)}{\pi_1(x, z, y)} \frac{O}{O}$$

$$(alt1) \frac{\alpha_1(x, \sigma(\alpha_2(z)), y)}{\alpha_1(x, z, y)} \frac{O}{O}$$

where $\forall \sigma \in \pi_2 : O(\sigma) = \emptyset$

where $\forall \sigma \in \alpha_2 : O(\sigma) = \emptyset$

An example for Rule Par 4 can be found in Figure 8.9. There, a structured parallel fragment π_2 is enclosed by a sequence σ_1 , which is otherwise empty. Since, σ_1 is in turn located in a parallel fragment, Rule Par 4 can be applied. The application removes π_2 and replaces σ_1 with the contained sequences σ_2 and σ_3 of π_2 . Nested parallel and alternative fragments that are structured are resolved by Rule Par 4 and Rule Alt 1 in a semantic preserving way, since the process model is not changed at all, but only its representation in the PST.

Rule Alt 2. (Elimination of Doubled Sequences) Given an alternative fragment α that contains two sequences $\sigma_1(z)$ and $\sigma_2(z)$ that equal each other (e.g. they are empty). Furthermore, they need to be in the exact same ordering relation, that is if

² Note that structured (or well-formed) fragments f are indicated by empty partial order set, i.e., $O(f) = \emptyset$.

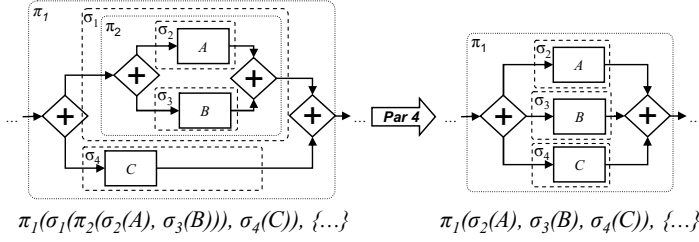


Fig. 8.9 Example for the Application of Rule Par 4

σ_1 is executed before some σ_s and after some σ_p , then σ_2 is executed before σ_s and after σ_p , too. Then one of them may be dropped.

$$(alt2) \frac{\alpha(x, \sigma_1(z), \sigma_2(z), y)}{\alpha(x, \sigma_1(z), y)} \frac{O}{O \setminus O(\sigma_2)} \quad \text{where } O(\sigma_1) = O(\sigma_2)$$

Rule Alt 3. (Elimination of Empty Sequences in Alternative Fragments) Let an alternative fragment α containing an empty sequences σ_ϵ be given. If either the preset $O_{Pre}(\sigma_\epsilon)$ or the postset $PO_{Post}(\sigma_\epsilon)$ of σ_ϵ are not empty. Then, σ_ϵ can be removed and the partial order relation O is aligned as follows:

$$(alt3) \frac{\alpha(x, \sigma_\epsilon, y)}{\alpha(x, y)} \frac{O}{O'}$$

where $O' = O \setminus O_{Pre}(\sigma_\epsilon)$, if $O_{Post}(\sigma_\epsilon) = \emptyset$
 $O' = O \setminus O_{Post}(\sigma_\epsilon)$, if $O_{Pre}(\sigma_\epsilon) = \emptyset$
 $O' = (O \setminus O(\sigma_\epsilon)) \cup S$, otherwise
 $S = \{(\sigma_i, \sigma_j) \mid (\sigma_i, \sigma_\epsilon) \in O_{Pre}(\sigma_\epsilon) \wedge (\sigma_\epsilon, \sigma_j) \in O_{Post}(\sigma_\epsilon)\}$

Figure 8.10 shows two examples for the application of Rule Alt 3. In both cases, sequence σ_4 is removed.

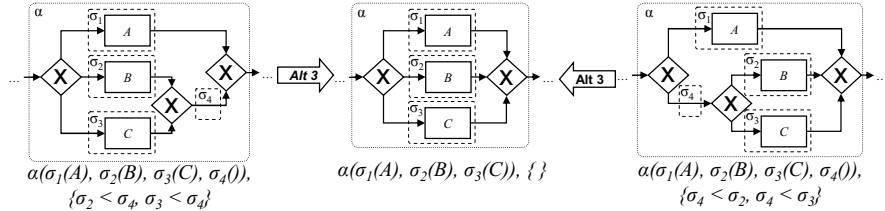


Fig. 8.10 Two Examples for the Application of Rule Alt 3

Rule Alt 4. (Extraction of Activities out of Alternative Fragments) Let an alternative fragment α containing sequences σ_1 to σ_i be given. If all of the sequences start with the same activity A and their presets are equal ($O_{Pre}(\sigma_1) = \dots = O_{Pre}(\sigma_i)$). Then, the activity A can be extracted from the sequences σ_1 to σ_i and is inserted in the preceding sequence σ .

$$(alt4a) \frac{\sigma(\alpha(\sigma_1(A, \dots), \dots, \sigma_i(A, \dots)))}{\sigma(A, \alpha(\sigma_1(\dots), \dots, \sigma_i(\dots)))} \frac{O}{O}$$

where $O_{Pre}(\sigma_1) = O_{Pre}(\sigma_2) = \dots = O_{Pre}(\sigma_i)$

In the top part of Figure 8.11 an examples for the application of Rule Alt 4 is shown. There, the Activity A is extracted from the sequences σ_1 to σ_i that succeed the entry XOR -Split of the alternative fragment α . Afterwards, A is inserted in the preceding sequence σ .

In a similar way, variants of this rule extract activities at the end of alternative fragments (**Rule Alt 4b**) and from several sequences within an alternative fragment into their preceding sequence (**Rule Alt 5a/b**) as shown in the bottom of Figure 8.11.

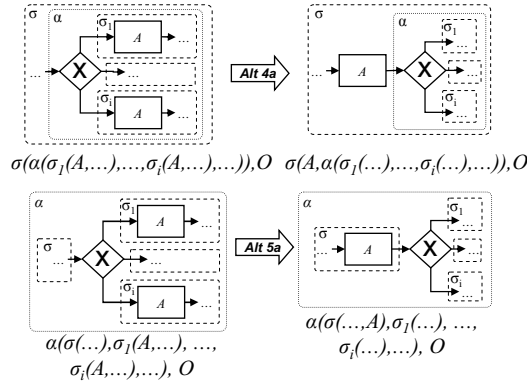


Fig. 8.11 Two Examples for the Extraction of an Activity by Rule Alt 4 and Rule Alt 5

The following commutativity rules reorder sequences within concurrent and alternative fragments.

Rule Com 1. (Reordering of Sequences) Given a parallel fragment π and two contained sequences σ_1 and σ_2 . Further, let σ_1 and σ_2 have the same set of preceding and succeeding sequences in the partial order relation, i.e., $\forall(\sigma_i, \sigma_1) \in O : \exists(\sigma_i, \sigma_2) \in O$ and $\forall(\sigma_1, \sigma_j) \in O : \exists(\sigma_2, \sigma_j) \in O$ and vice versa. Then, the two sequences can swap their positions within their parent fragment π .

Analogously, Rule Com 1b reorders sequences contained in alternative fragments.

$$(com1a) \frac{\pi(x, \sigma_1(u), \sigma_2(v), y)}{\pi(x, \sigma_2(v), \sigma_1(u), y)} \frac{O}{O} \quad (com1b) \frac{\alpha(x, \sigma_1(u), \sigma_2(v), y)}{\alpha(x, \sigma_2(v), \sigma_1(u), y)} \frac{O}{O}$$

Rules Par, Alt, and Seq constitute the rule system which is used to transform process model terms into a normal form. Rules Com 1a and 1b are applied after the normalization to align process model terms for a syntactical comparison. In the next section, we consider the correct functional behavior of the term rewriting system.

8.3.2 *Functional Behavior*

The term rewriting system can be considered as an algorithm that reduces a given process model term into its normal form. This algorithm has a correct functional behavior if it terminates (Termination) and results in a unique normal form (Confluence) for a process model. Functional behavior can be achieved by ensuring a set of criteria, well-known from the theory of abstract reduction systems [Baader and Nipkow, 1998, Küster, 2004]. In the following, we examine termination and confluence for our rewriting system for process model terms.

Termination

Concerning termination, we have to guarantee that no rule is applied infinitely often. One way to show termination is by giving a so-called monotone measure function [Baader and Nipkow, 1998]. This function shows that the application of the rules reduces a certain value, which is limited from below.

In the case of our term rewriting system, a potential candidate for the monotone reduction function is the number of fragments in a process model term, which is limited by the number of fragments contained in a process model. Rules Par, Alt, and Seq 1 reduce a process model term t by exactly one fragment, thus the maximum number of applicable rules is limited by the number of fragments within a process model term t . Rules Seq 2(a) and (b) do not reduce the number of fragments. However, the application of these rules is also limited by the number of fragments, since each application moves a sequence from a parallel fragment into the surrounding sequence.

Rules Com 1(a) and (b) are applied after the normalization to reorder sequences within fragments and can theoretically be applied infinitely often. However, since these commutativity rules are applied after the normalization of the process model terms, we can take care that each sequence is reordered only once, e.g. by recording already reordered sequences.

Confluence

Confluence ensures that in cases where multiple rules are applicable the choice of the rule does not matter. For terminating rewriting systems confluence follows from the weaker local confluence³. This requires if there are two direct rules $t_1 \xleftarrow{r_1} t \xrightarrow{r_2} t_2$, t_1 and t_2 can be joined again, i.e., they have a common successor. In such scenarios, where multiple rules are applicable on a term t , it can happen that

³ This result is usually known as Newman's Lemma [Baader and Nipkow, 1998].

the application of rules overlap and the application of one rule turns the other one in-applicable. All of these so-called critical pairs need to be considered for confluence by analyzing whether they have a common successor, i.e. they are harmless.

In the case of our term rewriting system for process models, we first overlap each pair of the left-hand sides of the rules to identify critical pairs. Then, for each critical pair we show that it is harmless.

Figure 8.12 provides an example for a critical pair. The fragment is transformed into the initial term on the right-hand side. First, the empty sequence σ_2 is removed by applying Rule Par 1. Then, two rules are applicable, either Rule Par 1 on the empty sequence σ_3 or Rule Par 2 to concatenate the sequences σ_1 and σ_3 . If one rule is applied the other one is no longer applicable. However, since the resulting terms are equal ($\sigma_1 = \sigma_{13^*}$) the critical pair is harmless. Further harmless critical pairs can be obtained by overlapping Rule Par 1 and Rule Seq 2.

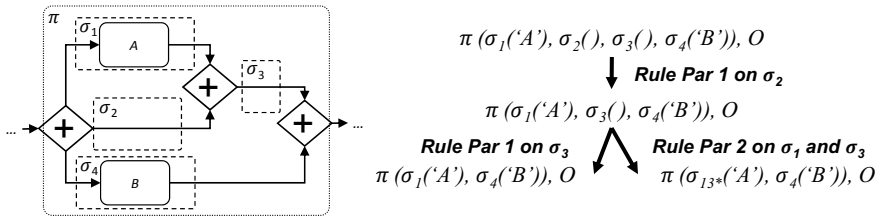


Fig. 8.12 Example for a Critical Pair obtained by overlapping Rule Par 1 and Rule Par 2

In this section, we have examined the correct functional behavior of our term rewriting system for process model terms using the existing theory for abstract reduction systems.

8.3.3 Equivalence of Process Models and Fragments

Based on the normalized process model terms, we first define equivalence of fragments contained in process models as follows:

Definition 14. (Fragment Equivalence) Two fragments f_1 and f_2 in process models V_1 and V_2 are considered to be equivalent if the following properties hold:

1. f_1 and f_2 are of the same type, i.e. $type(f_1) = type(f_2)$, such as parallel, alternative, etc.,
2. model elements contained in f_1 and f_2 correspond to each other, and
3. the process model terms t_{f_1} and t_{f_2} have the same execution order specified in their partial order relations ($O(f_1) = O(f_2)$).

Based on the equivalence of fragments, we now can define equivalence of entire process models:

Definition 15. (Process Model Equivalence) Given two process models V_1 and V_2 and their representation in process model terms t_{V_1} and t_{V_2} . V_1 and V_2 are considered to be equivalent if each fragment f_i in the normalized term t_{V_1} has an equivalent fragment f_2 in the normalized term t_{V_2} and vice versa.

This definition of equivalence relies on a matching of the process models to identify corresponding model elements. We have introduced matching strategies in Chapter 4. For convenience, corresponding model elements in our example share the same name and corresponding fragments are determined based on their type (i.e. alternative, parallel, ...) and their contained model elements as well as sub-fragments.

In the next section, we will apply our term rewriting system to our example introduced in Figure 8.1 to decide equivalence.

8.4 Detection of Semantically Equivalent Fragments

The top of Figure 8.13 shows the highlighted structures of the process model in Figure 8.1. With a purely syntax-based comparison, the insertion of those fragments would be considered as being conflicting. Our approach allows the efficient comparison of these two model fragments while considering their semantics.

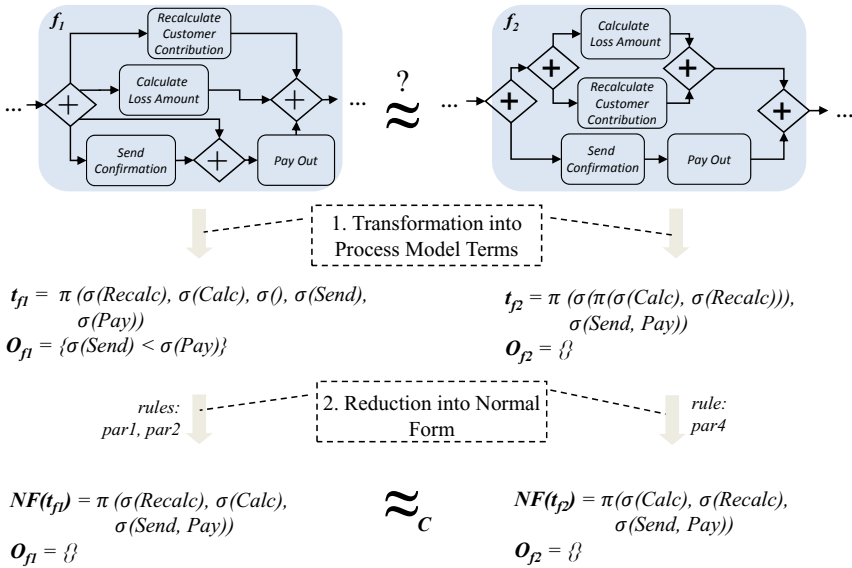


Fig. 8.13 Deciding Equivalence of Process Models

Using a simple traversal algorithm, the two models V_1 and V_2 are transformed into their corresponding term representation t_{V_1} and t_{V_2} . The complexity of this step

in our approach is linear to the size of the process model.⁴ The resulting process model terms are exact representations of the corresponding process models regarding their syntax. Applying our rule system to both terms results in their corresponding normalizations, i.e. a canonical version of the original term that has not been changed regarding its semantics. The term normalization is linear to the length of the term, and thus, linear to the size of the corresponding process model, since every application of a rule decreases the length of the term.

The last step in our approach is the comparison of two normal forms (see bottom of Figure 8.13). According to Definition 15, we decide equivalence of the process model terms based on the equivalence of their contained fragments. The comparison of sequences is straight-forward. The comparison of parallel and alternative fragments has to be performed under the consideration of the commutativity Rule COM 1 that may be used to reorder sequential fragments (branches) in alternative or parallel fragments in order to establish syntactically equal process model terms. In our example, the sequences $\sigma(\text{Calc})$ and $\sigma(\text{Recalc})$ contained in the parallel fragment π of $NF(t_{f2})$ are reordered.

In the case of our example, the parallel fragments in Figure 8.13, turned out to be semantically equivalent, since they have equivalent normal forms. Figure 8.14 shows the visual representation of the normalized terms of the fragments. The normalized fragments can directly be adopted in a consolidated version V_M of the process model. This has the benefit that it requires less changes compared to the highlighted fragments in Figure 8.13 and is more readable. Whether the normal form is always more understandable and can be adopted with fewer (or at least equal) changes than the non-reduced fragment is part of future work.

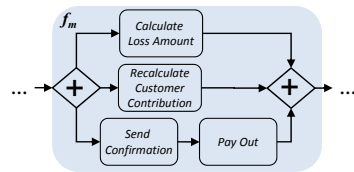


Fig. 8.14 Visual Representation of the Normal Form

8.5 Summary and Discussion

In this chapter, we presented a formalism to detect equivalent business process models based on the detection of equivalent fragments contained in the models. First, we transformed business process models into a process model term. We presented a term rewriting system consisting of several rules that transform process model terms into a normal form. We examined the correct functional behavior of the term rewriting system for process model terms using the existing theory for abstract reduction systems. Finally, we compared the normalized terms to identify equivalent fragments and process models.

The approach combines the benefits from both the syntactic and semantic comparison to decide equivalences between process models and contained fragments.

⁴ Cf. the complexity of an infix tree (PST) traversal and a depth first graph (PM) search.

Thereby, we overcome the shortcomings of approaches based on trace equivalence, e.g. the computational complexity or the need to analyze different sets of traces to identify the actual difference between traces. Based on our initial results, we can conclude that a semantic comparison of business process models in their normal form allows an efficient and effective equivalence analysis.

We leverage our approach to equivalence analysis of process models in our method for a precise detection of conflicts between independently applied change operations on process models, which is considered in the next chapter.

Conflict Analysis

This chapter is concerned with the identification of conflicts between independently applied compound change operations. Informally, two compound change operations are in conflict if the application of one operation turns the other one inapplicable. We begin by giving a brief introduction to conflict analysis in Section 9.1 and point out the challenges that need to be addressed. We then consider different types of conflicts between compound change operations in Section 9.2. In Section 9.3, we propose our method for the detection of conflicts that avoids false-positive conflicts by taking into account semantic equivalences of business process models. At the end of the chapter, we summarize and discuss our solution for conflict analysis in Section 9.4. The content of this chapter is partially based on our earlier publications [Gerth et al., 2010a, Gerth et al., 2011a].

9.1 Conflicts between Change Operations

In this section, we provide a scenario of conflicting compound change operations in change management of business process models in distributed environments and we show why conflict detection needs to take semantics into account.

For the following discussion, we assume that the source process model V and two descendant versions V_1 and V_2 as introduced in Chapter 1 are given. Further, we assume that mappings $\mathcal{M}(V, V_1)$, $\mathcal{M}(V, V_2)$, and $\mathcal{M}(V_1, V_2)$ between the process models have been computed and differences between them are contained in two hierarchical change logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$. An overview of this scenario is given in Figure 9.1.

In order to merge the process model versions V_1 and V_2 into V_M , we have to consider the applied change operations between the source process model V and the

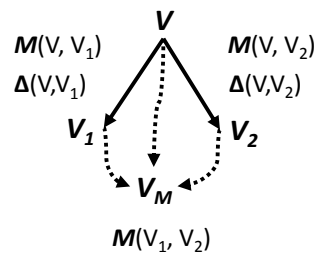


Fig. 9.1 Scenario Overview

two versions V_1 and V_2 . V_M is then created by applying a subset of the changes that were applied to achieve V_1 and V_2 .

Whenever changes are applied individually on different versions of a process model, some changes might be conflicting. An example for a conflicting pair of change operations is given by the following two operations (A) and (B) that represent and resolve the differences raised by the newly inserted corresponding activities “*Open Account*” in the process models V_1 and V_2 .

(A) $InsAct_{\Delta(V,V_1)}(V, \text{“Open Account”}, \text{“Check Cust. Data”}, \text{“Compute Cust. Scoring”})$

(B) $InsAct_{\Delta(V,V_2)}(V, \text{“Open Account”}, XOR - Join_{f_{Alt}}^{O1}, \text{“End”})$

Since the corresponding activities “*Open Account*” are inserted at different positions in the process models, only one of the operations can be applied in the merged version V_M . Otherwise, the same activity would exist twice in V_M and in this case, the banking account would be opened twice.

Informally, two change operations $op_1 \in \Delta(V, V_1)$ and $op_2 \in \Delta(V, V_2)$ are conflicting if the application of op_1 on the consolidated version V_M turns operation op_2 inapplicable. Conflicts between change operations have to be detected before a consolidated version can be created.

Existing, syntax-based approaches to conflict detection (e.g. [Alanen and Porres, 2003, Pottinger and Bernstein, 2003, Schneider et al., 2004, Schneider and Zündorf, 2007, Westfechtel, 2010]) compare models and/or change operations, which modified the models, syntactically to identify conflicting pairs of operations. Conflicts can then be captured using, e.g. conflict sets [Edwards, 1997, Altmanninger, 2007] or conflict matrices [Mens, 2002, Lippe and van Oosterom, 1992, Kögel et al., 2010, Küster et al., 2009], which specify conditions under which two change operations are conflicting. For a comprehensive evaluation of the state of the art in model versioning including conflict detection, we refer to Section 2.4 in Chapter 2.

Applying a syntax-based conflict detection approach on the compound change operations of our example (see Figure 1.3) results in several conflicting change operations in the hierarchical change logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$. Figure 9.2 shows the conflicting change operations, which are indicated by arrows. The curled brackets are added for readability reasons and indicate that every operation within the brackets is in conflict.

Overall, 21 conflicts are detected, among them several conflicts between equivalent change operations. Two operations are equivalent if their applications have identical effects on the process model. For instance, the operations (l) and (v) insert the corresponding activities “*Set Credit Limit to 0*” in process model V_1 and V_2 at the same position, despite their different position parameters. Thus, their effects on the process model are equivalent and shall not give rise to a conflict. We refer to conflicts between equivalent operations as *false-positive conflicts* in the remainder.

Approaches to conflict detection based on syntactic features result potentially in false-positive conflicts because they cannot identify equivalent change operations in every case. For instance, a syntactic comparison of the aforementioned change operations (l) and (v) that insert the activities “*Set Credit Limit to 0*” results in a



Fig. 9.2 Change Logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$ of our Example in Figure 1.3 with Conflicts

false-positive conflict, since the position parameters of the operations differ and it seems that the activities are inserted at different positions in V_1 and V_2 .

A further syntax-based approach would be a comparison of the direct neighbors of the activities “Set Credit Limit to 0” in V_1 and V_2 . In the concrete example, the false-positive conflict could be prevented since in both process models the preceding and succeeding activities correspond to each other. However, in general false-positive conflicts cannot be eliminated based solely on syntactic features. For instance, consider the case where an additional activity exists in V_2 between the activities “Set Credit Limit to 0” and “Remove Credit Card”.

An approach that addresses the semantics of a modeling language for conflict analysis is presented in [Altmanninger, 2007]. *The presented Semantically enhanced Version Control System (SMoVer)* uses semantic views to make semantic aspects of modeling languages explicit. Based on these views, semantic conflicts can be reported. This work can be considered complementary to our work which aims at making the conflict detection more precise by taking into account the execution semantics of models. The approach eliminates syntactic redundancies between model elements in modeling languages, but cannot identify equivalences between more complex structures, such as the unstructured fragments parallel fragments f_{Par-V1} and f_{Par-V2} from our example.

The identification of equivalences in cases where model elements are modified in fragments that are syntactically different but semantically equivalent, is particular

important for conflict analysis between process models. To give an example, let us stick to the above mentioned, newly inserted parallel fragments f_{Par-V1} and f_{Par-V2} from our example, which are shown in Figure 9.3. A syntactic conflict detection between change operations that insert these fragments and their contained activities results in several conflicts between the operations ($e-i$) and ($q-t$) as indicated in Figure 9.2.

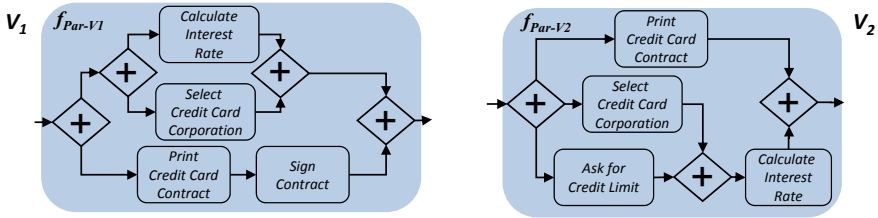


Fig. 9.3 Newly inserted Fragments in our Example in Figure 1.3

For these change operations, it is not straight-forward to decide whether they result in equivalent fragments. As a consequence, a syntactic comparison of the change operations and the fragments results in false-positive conflicts. To give an example, the operations (f) and (q) insert the activities “*Print Credit Card Contract*” into the structures f_{Par-V1} and f_{Par-V2} . By considering the syntax of the operations in terms of their position parameters, the operations seem to insert the corresponding activities “*Print Credit Card Contract*” at different positions and hence result in a conflict. However, considering the behavior of the structures in terms of the execution traces of contained corresponding activities reveals that most of the corresponding activities are also executed in corresponding orders in the structures, e.g. “*Select Credit Card Cooperation*” and “*Print Credit Card Contract*”. Accordingly, these activities result in equivalent execution traces and their change operations should not give rise to conflicts.

To prevent false-positive conflicts and to obtain a precise set of conflicts, syntax-based approaches to conflict detection are not sufficient. In addition, the semantics of process models must be taken into account. For that purpose, we leverage the proposed formalism to detect equivalent business process models that we have introduced in the previous chapter. In Section 9.3, we introduce a method for conflict detection that prevents false-positive conflicts by identifying equivalences between fragments. Before, we define different types of conflicts between compound change operations.

9.2 Types of Conflicts

In this section, we distinguish and define two notions of conflicts between change operations. Conflicts between change operations can be classified into

syntactic or semantic conflicts, which are defined in the following two subsections. Note that the content of this section is partially based on our earlier publications [Gerth et al., 2011a].

9.2.1 Syntactic Conflicts

Informally, two changes are syntactically in conflict if the application of one change operation turns the other one inapplicable. For the definition of syntactic conflicts, we rely on the formalization of compound change operation types in terms of typed attributed graph transformations, which we have introduced in Section 7.2.2 in Chapter 7.

Similarly, to the transformation dependency analysis, we employ an existing conflict notion for graph transformations. Here, we use the concept of *weak parallel independence* for independently applied compound change operations in the two change logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$.

For graph transformations, conflicts have been defined already in several existing works [Corradini et al., 1997, Hausmann et al., 2002, Mens et al., 2007]. Formally, let two graph transformations $G \xRightarrow{p_1(o_1)} H_1$ and $G \xRightarrow{p_2(o_2)} H_2$ be given that transform the graph G into H_1 using a transformation rule $p_1(o_1)$ and the graph G into H_2 using a transformation rule $p_2(o_2)$. The graph transformation $G \xRightarrow{p_1(o_1)} H_1$ is (*weakly parallel independent*) of $G \xRightarrow{p_2(o_2)} H_2$ if the occurrence $o_1(L_1)$ of the left-hand side of p_1 is preserved by the application of p_2 . This is the case if $o_1(L_1)$ does not overlap with objects that are deleted by p_2 .

If the two transformations are mutually independent, they can be applied in any order yielding the same result. In this case we speak of *parallel independence*. Otherwise if one of two alternative transformations is not independent of the second, the second will disable the first. In this case, the two steps are *in conflict*. According to the Local Church Rosser Theorem [Corradini et al., 1997]¹, parallel independence of two transformation steps induces their sequential independence and vice versa (with adapted occurrences).

Formally, we define syntactic conflicts of compound change operations as follows:

Definition 16 (Syntactically Conflicting Change Operations). [Gerth et al., 2011a] Let two compound change operations $op_1 \in \Delta(V, V_1)$ and $op_2 \in \Delta(V, V_2)$ be given such that $V \xRightarrow{op_1} V'$ and $V \xRightarrow{op_2} V''$. We call op_1 and op_2 syntactically conflicting if op_2 is not applicable on V' or op_1 is not applicable on V'' .

In our example, the change operations a) and m) (Figure 9.2) are syntactically conflicting. Both operations insert different elements at the same position in the process models and only one of them can be applied. To obtain the merged process

¹ The Local Church Rosser Theorem has been proven for typed attributed graph transformation in [Ehrig et al., 2004].

model version V_M , the syntactic conflict between the operations must be resolved. Table 9.1 lists possible combinations of compound change operations that result in syntactic conflicts. An operation in the left-hand column of Table 9.1 is syntactically in conflict with an operation in the right-hand column and vice versa, since their applications exclude each other.

Table 9.1 Combinations of Operations that result in Syntactic Conflicts

Syntactic Conflicts	
$InsertActivity(V, a, x, y)$ $MoveActivity(V, a, \rightarrow, x, y)$ $InsertFragment(V, f_a, x, y)$ $MoveFragment(V, f_a, \rightarrow, x, y)^1$ $DeleteFragment(V, f, \rightarrow)^2$ $ConvertFragment(V, f, f_c, \rightarrow, \rightarrow)^{3,4}$	$InsertActivity(V, b, x, y)$ $MoveActivity(V, b, \rightarrow, x, y)$ $InsertFragment(V, f_b, x, y)$ $MoveFragment(V, f_b, \rightarrow, x, y)^1$ $ConvertFragment(V, f, f_d, \rightarrow, \rightarrow)^3$
¹ conflicting if f_a is moved into f_b and f_b into f_a . ² conflicting if x and y are contained in fragment f	³ conflicting if x and y are contained in fragment f but not in f_c ⁴ conflicting if f_c and f_d are syntactically different

Syntactic conflicts can be computed using existing theory by overlapping compound change operation types formulated as graph transformation rules. Given two compound change operations op_1 and op_2 , we compute the critical pairs for all combinations of change operations. Critical pairs obtained, are then encoded by specifying conditions on the parameters of op_1 and op_2 . These conditions are partially shown in the conflict matrix for *InsertActivity* operations in Figure 9.4.

Syntactic Conflict Matrix	InsertActivity (B,V,W)	MoveActivity (B,oP,oS,nP,nS)	DeleteActivity (B,V,W)
InsertActivity (A,X,Y)	$(B \neq A \wedge V = X \wedge W = Y)$ <i>Different element inserted at same position</i>	$(nP = X \wedge nS = Y)$ <i>A inserted and B moved to same position</i>	$B = X \vee B = Y$ <i>Predecessor or successor of A is deleted</i>

Syntactic Conflict Matrix	InsertFragment (F2,V,W)	MoveFragment (F2,oP,oS,nP,nS)	DeleteFragment (F2,V,W)	ConvertFragment (F2,F2c,V,W)
InsertActivity (X,X,Y)	$(V = X \wedge W = Y)$ <i>A and F2 inserted at same position</i>	$(nP = X \wedge nS = Y)$ <i>A inserted and F2 moved to same position</i>	$F2 = parent(A)$ <i>X inserted into deleted fragment F2</i>	$F2 = parent(X) = parent(Y) \wedge (F2 \neq parent(X) \neq parent(Y))$ <i>X and/or Y are deleted during the conversion of fragment F2</i>

Fig. 9.4 Excerpt of our Syntactic Conflict Matrix for the Comparison of Change Operations

In the next section, we consider semantically conflicting change operations.

9.2.2 Semantic Conflicts

In the case of semantic conflicts, we first have to define when two process models are considered to be behavioral equivalent. For the following discussion, we use trace equivalence [v. Glabbeek, 1988] as equivalence relation that has been discussed for process models, e.g. in [Kiepuszewski, 2002, Rinderle et al., 2004]. We consider two process models V and V_i to be trace equivalent ($V \equiv_{trace} V_i$) if their sets of traces are equal. That means, the behavior of V defined by the order of its executed activities and events can also be obtained by executing V_i and vice versa.

Informally, two change operations are semantically conflicting if they modify corresponding model elements and after their application the underlying elements are in different positions in the merged process model resulting in different traces. We define semantically conflicting operations as follows:

Definition 17 (Semantically Conflicting Change Operations). [Gerth et al., 2011a] Let two compound change operations $op_1 \in \Delta(V, V_1)$ and $op_2 \in \Delta(V, V_2)$ be given that modify the elements (activities, events, or fragments) x_1 and x_2 . Further, let x_1 correspond to x_2 , i.e. $(x_1, x_2) \in \mathcal{M}(V_1, V_2)$. Then we call op_1 and op_2 semantically conflicting if $V \xrightarrow{op_1} V'$, $V \xrightarrow{op_2} V''$, and not $V' \equiv_{trace} V''$.

An example for a semantic conflict according to Definition 17 is represented by the operations c) and y) that insert the activities “Open Account” at different positions in the process models V_1 and V_2 in Figure 1.3. To integrate the different versions into the merged process model V_M , this semantic conflict must be resolved, e.g. by selecting a unique position for the activity “Open Account”.

Table 9.2 lists six pairs of compound change operations that result in semantic conflicts, since after their application corresponding model elements would be at different positions in the merged process model.

Table 9.2 Pairs of Operations that result in Semantic Conflicts

Semantic Conflicts
<i>InsertActivity</i> (V, a, x, y) - <i>InsertActivity</i> (V, a, v, w)
<i>MoveActivity</i> (V, a, v, w, x, y) - <i>MoveActivity</i> (V, a, v, w, s, t)
<i>MoveActivity</i> (V, a, v, w, x, y) - <i>DeleteActivity</i> (V, a, v, w)
<i>InsertFragment</i> (V, f, x, y) - <i>InsertFragment</i> (V, f, v, w)
<i>MoveFragment</i> (V, f, v, w, x, y) - <i>MoveFragment</i> (V, f, v, w, s, t)
<i>ConvertFragment</i> (V, f, f_c, x, y) - <i>ConvertFragment</i> (V, f, f_d, x, y)

Semantic conflicts of compound change operations that modify activities can be identified based on a syntactic comparison of change operations and the underlying process models. For instance, the semantic conflict between two *Insert-Activity* operations that insert corresponding activities at different positions in the merged process models (*InsertActivity*(V, a, x, y) - *InsertActivity*(V, a, v, w)), can be

identified by comparing the change operations syntax. Analogously to the syntactic conflicts, we formalize these conditions in a conflict matrix shown in Figure 9.5. In our method for conflict detection, we will later use the union of both conflict matrices shown in Figures 9.4 and 9.5.

Semantic Conflict Matrix	InsertActivity (V,b,v,w)	MoveActivity (V,b,ov,ow,nv,nw)	DeleteActivity (V,b,v,w)
InsertActivity (V,a,x,y)	(b = a & v ≠ x & w ≠ y) <i>Same element inserted at different positions</i>		
MoveActivity (V,a,ox,oy,nx,ny)		(b = a) & (nv ≠ nx & nw ≠ ny) <i>Same element is moved to different positions</i>	b = a <i>Same element is moved and deleted</i>

Fig. 9.5 Excerpt of our Semantic Conflict Matrix for the Comparison of Change Operations

However, in the case of operations that modify fragments, conflicts cannot be identified based on a syntactic comparison, since fragments may be syntactically different but semantically equivalent. A naive solution to identify such semantically conflicting change operations would be to apply Definition 17 directly. That would require that all changes need to be applied individually on V (with respect to dependencies between the changes) and their traces need to be computed to verify their trace equivalence. This approach suffers from several drawbacks: First of all, the application of the individual operations represents a significant overhead, since it requires in the worst case the application of all subsets of change operations, which is not always possible. Second, for the evaluation of trace equivalence all possible execution traces need to be computed that may result in exponential complexity.

To overcome these shortcomings, we identify semantic equivalences between process models using the process model terms for equivalence analysis as presented in the previous chapter. We integrate this approach in our method for precise conflict detection, which is introduced in the next section.

9.3 Method for Precise Conflict Detection

In this section, we present a method to compute conflicts between given compound change operations. It avoids false-positive conflicts by taking into account semantic equivalences between business process models. The method presented in this section has also been described in one of our earlier publications [Gerth et al., 2011a].

In the following, we classify change operations into independent and dependent operations, since the approaches of conflict detection differ for both categories of operations. In Chapter 7, we have shown how dependencies of change operations can be computed efficiently. For example, a change operation is dependent if it inserts or

moves an element into a fragment that was newly inserted itself. Based on this classification, our approach consists of two main steps (Figures 9.6 and 9.9): In the first step, we compute conflicts between independent change operations (Section 9.3.1) and in the second step, we determine conflicts between dependent operations (Section 9.3.2).

9.3.1 Conflict Detection of Independent Change Operations

In the first step, we compute conflicts between independent change operations by comparing the change operations syntactically using the aforementioned conflict matrix (see Figure 9.4). In addition, we compare the operations in a specific order and use dynamic computation of position parameters to determine the position parameters of change operations. Thereby, equivalent operations are identified.

Step 1	Conflict Detection of Independent Change Operations
1	Specify position parameters of change operations using fixpoints as introduced in Chapter 7.
1a	Compute syntactic conflicts of operations modifying corresponding model elements using the syntactic conflict matrix and fixpoints . → If no conflict, increase set of fixpoints and recompute position parameters.
1b	Compute conflicts of operations modifying non-corresponding model elements using the syntactic conflict matrix and fixpoints .

Fig. 9.6 Conflict Detection of Independent Operations

First, position parameters for all independent change operations are specified using fixpoints (Definition 11), i.e. position parameters only consist of corresponding model elements that are not modified by a change operation in the process models V_1 and V_2 (Step 1a). For instance, the activities “Record Customer Data” in the models V_1 and V_2 constitute a pair of fixpoint nodes, since they correspond to each other and are not modified.

In Step 1b, we iterate over the independent change operations whose position parameters have been specified using fixpoints and syntactically compare pairs of change operations $op_1 \in \mathcal{A}(V, V_1)$ and $op_2 \in \mathcal{A}(V, V_2)$ that modify corresponding model elements. In the case that only one change operation of such a pair is independent, a syntactic conflict between the operations is identified, since op_1 and op_2 modify corresponding elements differently. Otherwise, we identify syntactic conflicts between pairs of independent change operations using our conflict matrix. Figure 9.4 shows an excerpt of this conflict matrix for change operations that specifies condition in which change operations are conflicting. For instance, two

InsertActivity operations are in conflict if they insert corresponding model elements at different positions in the merged process model.

In the case, that operations are not in conflict, the underlying corresponding model elements will be at the same position after the execution of the operations, resulting in equal traces. The corresponding model elements modified by op_1 and op_2 are added to the set of fixpoints. Before the next comparison of change operations, position parameters of the remaining change operations are recomputed using dynamic specification to reflect the increased set of fixpoints. In the case that the operations are in conflict according to the conflict matrix, op_1 and op_2 are marked (semantically) conflicting, since their application results in corresponding model elements at different positions.

Figure 9.7 provides an example using the operations j, k, l and v, w, x from our example change logs shown in Figure 9.2. However in contrast to the operations shown in the change logs in Figure 9.2, here we use the concept of dynamic specification of position parameter in terms of fixpoints, resulting in the change operations shown in Figure 9.7 (a). We start the comparison with the operations j and x , which are not in conflict. Accordingly, their underlying model elements “Set Interest Rate to 0” are added to the set of fixpoints and the position parameters are recomputed, reflecting the new fixpoint. Next in (b), the operations k and w are compared, with the result that “Remove Credit Card” is added to the set of fixpoints entailing again a re-computation of the position parameter of the remaining operations. Finally in (c), the remaining operations l and v are compared and the activities “Set Credit Limit to 0” are added to the set of fixpoints.

<i>a)</i> $\Delta(V, V_1)$:		$\Delta(V, V_2)$:
...		...
j) InsertAct(V, "Set Interest ...", "Prepare Prepaid ...", XOR-Join ² _(A,V1))		v) InsertAct(V, "Set Credit ...", "Prepare Prepaid ...", XOR-Join ² _(A,V2))
k) InsertAct(V, "Remove ...", "Prepare Prepaid ...", XOR-Join ² _(A,V1))		w) InsertAct(V, "Remove ...", "Prepare Prepaid ...", XOR-Join ² _(A,V2))
l) InsertAct(V, "Set Credit ...", "Prepare Prepaid ...", XOR-Join ² _(A,V1))		x) InsertAct(V, "Set Interest ...", "Prepare Prepaid ...", XOR-Join ² _(A,V2))
<hr/>		
j) InsertAct(V, "Set Interest ...", "Prepare Prepaid ...", XOR-Join ² _(A,V1))	✓	v) InsertAct("Set Credit ...", "Set Interest ...", XOR-Join ² _(A,V2))
k) InsertAct(V, "Remove ...", "Set Interest ...", XOR-Join ² _(A,V1))	✓	w) InsertAct("Remove ...", "Set Interest ...", XOR-Join ² _(A,V2))
l) InsertAct(V, "Set Credit ...", "Set Interest ...", XOR-Join ² _(A,V1))		x) InsertAct("Set Interest ...", "Prepare Prepaid ...", XOR-Join ² _(A,V2))
<hr/>		
j) InsertAct(V, "Set Interest ...", "Prepare Prepaid ...", XOR-Join ² _(A,V1))	✓	v) InsertAct("Set Credit ...", "Remove ...", XOR-Join ² _(A,V2))
k) InsertAct(V, "Remove ...", "Set Interest ...", XOR-Join ² _(A,V1))	✓	w) InsertAct("Remove ...", "Set Interest ...", XOR-Join ² _(A,V2))
l) InsertAct(V, "Set Credit ...", "Remove ...", XOR-Join ² _(A,V1))		x) InsertAct("Set Interest ...", "Prepare Prepaid ...", XOR-Join ² _(A,V2))

Fig. 9.7 Conflict Computation between independent Change Operations modifying corresponding Model Elements

Note that by specifying the position parameters of the operations j, k, l and v, w, x in terms of fixpoints and a dynamic computation of change operation parameters, no false-positive conflicts are detected between the equivalent operations. As an outcome of Step 1b, all conflicts between independent change operations modifying corresponding model elements have been computed.

In the case that a pair of change operations modifying corresponding model elements exists, where one change operation is independent and the other one is dependent, the two change operations are marked as conflicting. Operation a and n , which

both modify the corresponding activities “*Check Customer Data*”, provide an example of this scenario. Operation a is independent but the Operation n depends on the execution of Operation m in the change log $\Delta(V, V_2)$. The operations are in conflict, since they insert corresponding activities at different positions in the merged process model.

In Step 1c, we compare the remaining independent change operations that modify non-corresponding model elements. According to the conflict matrix, a syntactic conflict between these operations is detected if non-corresponding elements are located at the same position after the application of the operations. An example for such a conflict is the conflict between the operations a and m in Figure 9.8, which insert the activity “*Check Customer Data*” and the fragment f_{Loop} at the same position.

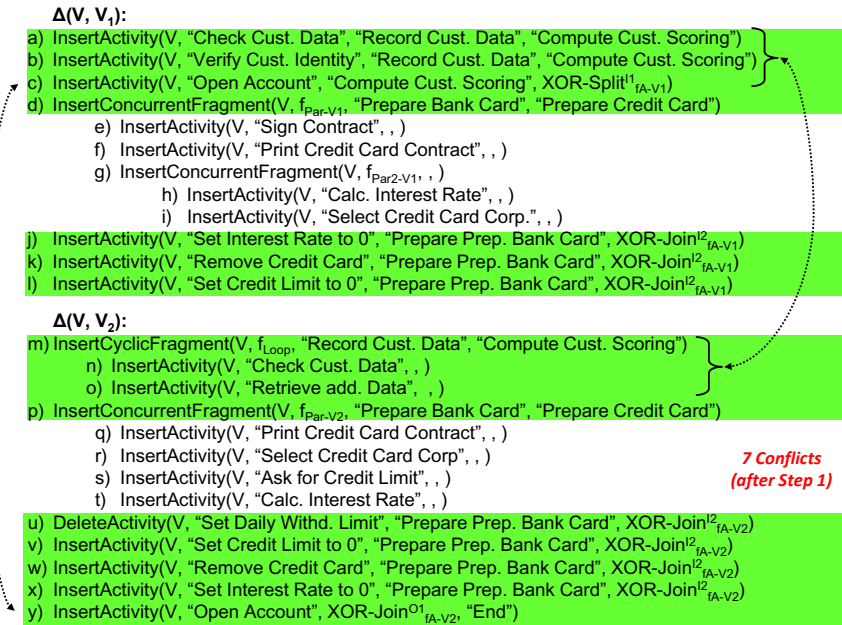


Fig. 9.8 Detected Conflicts after Step 1

Figure 9.8 shows the conflicts between the change operations in $\Delta(V, V_1)$ and $\Delta(V, V_2)$ that have been computed after Step 1. Conflicts of the highlighted operations have been computed in this step and are indicated by dotted arrows. In the following, we compute conflicts of the remaining dependent operations ($e-i$ and $q-t$) within the fragments f_{Par-V1} and f_{Par-V2} . Since the application of these change operations depends on the application of other operations, the conflict detection approach differs from the one described above.

9.3.2 Conflict Detection of Dependent Change Operations

For conflict analysis, position parameters of dependent change operations within modified fragments are difficult to compare because syntactically different fragments may have the same behavior in terms of their execution traces. As a consequence, beside the actual position of an element within a fragment, also the execution logic of the fragment and the execution order of contained model elements must be considered. To give an example, in the top of Figure 9.10 the highlighted fragments of our example (Figure 1.3) are shown. These fragments are syntactically different. However, considering the behavior of the fragments in terms of the execution traces of contained activities reveals that most of the corresponding activities are also executed in corresponding orders in the fragments, e.g. “*Select Credit Card Cooperation*” and “*Print Credit Card Contract*”.

Step 2	Conflict Detection of Dependent Change Operations
2a	Compute semantic conflicts of operations modifying corresponding model elements within fragments using Process Model Terms .
2b	Compute conflicts of operations modifying non-corresponding model elements using the syntactic conflict matrix and fixpoints . → If position parameters cannot be specified using fixpoints, assign conflict to the operations.

Fig. 9.9 Conflict Detection of Dependent Operations

Existing, syntax-based approaches to conflict detection (e.g. [Westfechtel, 2010, Kögel et al., 2010, Taentzer et al., 2010]) would mark the dependent operations contained in modified fragments as conflicting, since the activities are inserted into syntactically different fragments. Whether two corresponding activities are also at the same position with respect to their execution order cannot be decided based on the syntax of the fragments alone. However, in the case of the fragments f_{Par-V1} and f_{Par-V2} , most of the conflicts between the contained change operations constitute false-positive conflicts.

To avoid these false-positive conflicts, we check whether the corresponding elements within the two fragments lead to equivalent traces. For that purpose, we iterate in Step 2a (Figure 9.9) over corresponding fragments that are modified by change operations. For each pair of these fragments, we then leverage the equivalence analysis based on process model terms as introduced in the previous Chapter 8 to identify conflicts of dependent change operations contained in the fragments. Process model terms enable us to compare two fragments for semantic equivalence by detecting differences in the terms. In the following, we first define differences of process model terms, which we then use to identify conflicting change operations.

Definition 18 (Term Difference). [Gerth et al., 2011a] Let two process models V_1, V_2 and two corresponding fragments $f_1 \in V_1$ and $f_2 \in V_2$ together with a mapping $\mathcal{M}(V_1, V_2)$ of V_1 and V_2 be given. Let further the normalized process model terms t_{f_1}, t_{f_2} of the fragments be given that are reduced to their corresponding model elements $(e_1, e_2) \in \mathcal{M}(V_1, V_2)$. We define a term difference as a difference of the two terms t_{f_1}, t_{f_2} or a difference of their partial orders.

Given a term difference, we now define the operations that yield the term difference, as *term-conflicting operations*. Figure 9.10 shows the fragments f_{Par-V_1} and f_{Par-V_2} of our example. We first reduce the fragments to their corresponding model elements (by removing the activities “Sign Contract” and “Ask for Credit Limit”) and transform them into their process model terms. These terms are normalized using our term rewriting system introduced in Section 8.3 of Chapter 8. The normal forms of the terms together with their graphical representation are shown in the bottom of Figure 9.10. Finally, we compare the normalized terms under consideration of commutativity in order to identify term differences. Since the terms are not equal, a term difference is obtained: The sequence $s(Calc)$ in the normal form $NF(t_{Par-V_1})$ cannot be mapped to a sequence in $NF(t_{Par-V_2})$. The reason for this is that in our example, the activities “Calculate Interest Rate” and “Select Credit Card Operation” are executed in parallel in f_{Par-V_1} , however they are executed sequentially in f_{Par-V_2} . Thus, the operations h and t that insert the activities “Calculate Interest Rate” are term-conflicting operations.

The following theorem shows the equivalence of term differences in process model terms and differences in the execution traces of process models.

Theorem 5 (Equivalence of Term Difference and Trace Difference). [Gerth et al., 2011a] Let two process models V_1, V_2 and two corresponding fragments $f_1 \in V_1$ and $f_2 \in V_2$ together with a mapping $\mathcal{M}(V_1, V_2)$ of V_1 and V_2 be given. f_1 and f_2 are reduced to their corresponding elements $(e_1, e_2) \in \mathcal{M}(V_1, V_2)$. Let further the normalized process model terms t_{f_1}, t_{f_2} be given. Each difference between the terms t_{f_1}, t_{f_2} induces a trace difference in the execution traces of f_1 and f_2 and equal terms induce equal traces.

Proof Sketch: (Theorem 5) To prove Theorem 5, we have to show that each term difference induces a trace difference and no term difference induces no trace difference.

Case 1 (Term Difference \rightarrow Trace Difference):

We assume that the terms t_{f_1}, t_{f_2} contain at least one difference. A difference can have two reasons. Either the term representations itself differ, or there is a difference in the partial order of the branches of the fragments. A difference in the former case occurs if corresponding elements are in different orders what obviously results in different traces. In the latter case, there is no difference in the term representation, since all contained sequences can be matched. However, the partial orders of the terms are different. That means, at least one branch is executed in a different order resulting in different execution traces.

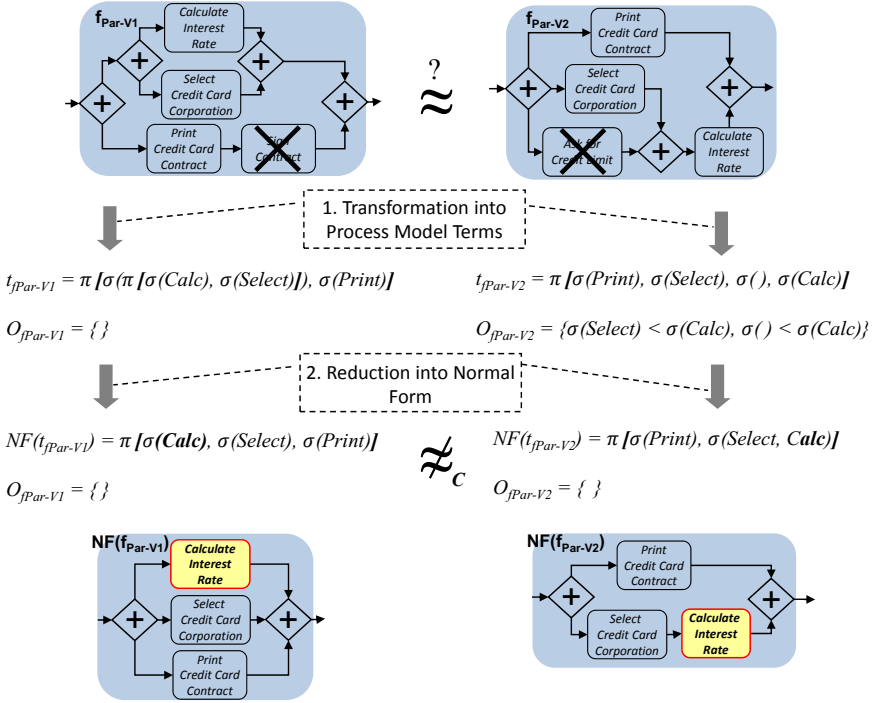


Fig. 9.10 Term-Conflicting Operations

Case 2 (No Term Difference \rightarrow No Trace Difference):

We assume that in the terms t_{f1} , t_{f2} no term difference exists. That means, the corresponding elements in the terms itself are in identical orders. In addition, since the partial orders of the terms are identical, the sequences within the terms are executed in the same order. Thus, an execution of the fragments results in equal traces.

We have shown that for each pair of term-conflicting change operations that modify corresponding model elements, a term difference in the process model terms exists, which induces a trace difference (Theorem 5). Hence, the term-conflicting operations constitute semantically conflicting change operations according to Definition 17. This shows that we have found a way to efficiently compute semantically conflicting operations.

In Step 2a, we have computed conflicts between change operations modifying corresponding model elements within fragments. What remains, is the computation of conflicts between dependent operations that modify non-corresponding elements that were ignored in the previous step. Similar to Step 1c, this can be done, using corresponding elements, whose change operations are not conflicting as fixpoints. Therefore, we compute position parameters of dependent change operations within the fragment in terms of fixpoint with respect to the semantically equivalent parts of

the fragments (e.g. operation (e) *InsertActivity*("Sign Contract", "Print Credit...", *Join*_{p1-v1})). Then the operations are compared using the conflict matrix to identify conflicts. In some cases, position parameters of dependent change operations cannot be specified using fixpoints only. These operations are marked as conflicting and require user intervention. Figure 9.11 shows the syntactic and semantic conflicts of our example that were computed using our method.

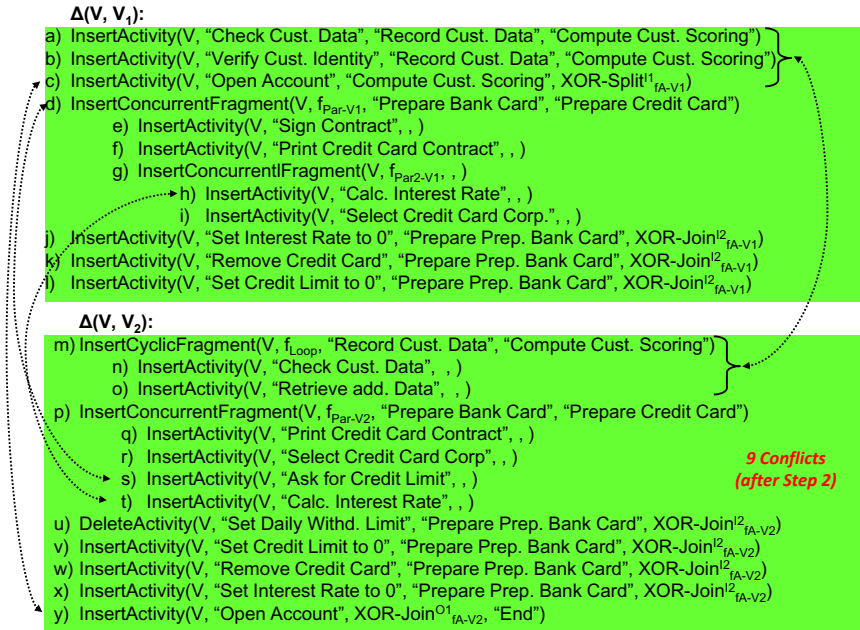


Fig. 9.11 Detected Conflicts after Step 2

Our work shows that conflict detection can be performed on a semantic level using a term formalization of process models and their hierarchical structure. Thereby, we have significantly reduced the overall number of conflicts (from 21 to 9 in the example) between change operations and in particular the number of false-positive conflicts.

As already introduced in Chapter 8, based on process model terms equivalent operations contained in complex fragments cannot be identified. Instead, for those fragments, we leverage trace equivalence. This still is way faster than a pure trace equivalence approach, since traces only need to be computed for fragments, which are significantly smaller compared to the whole process model.

9.4 Summary and Discussion

In this chapter, we have introduced a method for the precise detection of conflicting compound change operations in version management of business process models.

First, we have identified shortcomings of existing approaches for conflict detection that rely on a purely syntactic comparison and potentially result in false-positive conflicts. Then, we have distinguished conflicts between change operations into the notion of syntactic and semantic conflicts.

Based on these conflict notions, we have introduced a method for conflict detection between compound change operations given in two change logs. As an input, the method expects change operations, whose position parameters have been specified in terms of fixpoints. By evaluating the change operations in a certain order, the number of detected conflicts is independent of the actual order in which the change operations have been applied.

Moreover, our method avoids false-positive conflicts between change operations modifying syntactically different fragments that are semantically equivalent. To that extent, we applied our approach to equivalence analysis for process model fragments. In this approach, we compared the process model terms of fragments with each other in order to identify *term differences* and showed that a term difference implies a trace difference.

Our results have shown that taking the semantics of process modeling languages into account, helps to compute precise conflicts and avoids false-positive conflicts.

Having introduced a detection approach of conflicting compound change operation, the analysis of the hierarchical change logs is completed and we can merge different process model versions, which is the topic of the next chapter.

Process Model Merging

In this chapter, we consider the merging of different process model versions into an integrated business process model. For that purpose, we will resolve differences between the process model versions by applying change operations contained in the hierarchical change logs, which we have reconstructed in the previous chapters.

We begin by giving an overview of the merging process in Section 10.1. In Section 10.2, we translate generic compound change operations that we have computed based on abstracted models in the intermediate representation, into language-specific change operations to make them applicable on process models in a concrete modeling language. Based on such language-specific compound change operations, we then introduce different ways to apply non-conflicting change operations in Section 10.3. Afterwards, we point out resolution strategies for conflicting change operations in Section 10.4.

10.1 Merging Overview

In this section, we give a brief overview how different process model versions are merged by applying compound change operations. Figure 10.1 sketches our approach. Beginning with a source process model V , two different versions V_1 and V_2 have been independently created. These versions shall be merged by applying a subset of the change operations applied on version V_1 and V_2 on the source process model V to obtain V_M .

To be independent of a concrete process modeling language, we have abstracted the different process model versions from their concrete modeling language, e.g. BPMN, into the intermediate representation (IR) as introduced in Chapter 3. Based on the process models in the IR, we have then reconstructed IR hierarchical change logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$ in the previous chapters that represent differences between the process model versions in terms of compound change operations.

To merge the process models, the generic compound change operations contained in these IR hierarchical change log have to be translated back into language-specific compound change operations, which can be applied on the source process model V

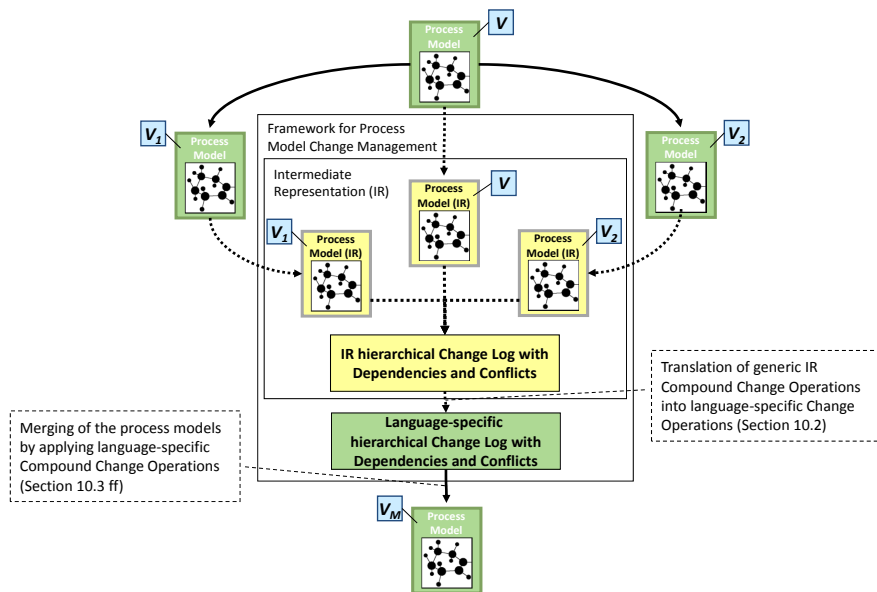


Fig. 10.1 Merging of Process Model Versions

specified in its underlying modeling language, e.g. BPMN. The translation of the generic compound change operations is described in the next section.

Finally, in Sections 10.3 and 10.4 we show how language-specific compound change operations can be applied by considering dependencies and conflicts between them.

10.2 Translation of IR Compound Change Operations into Language-Specific Compound Change Operations

In this section, we translate generic compound change operations that we have computed based on process models in the intermediate representation (IR) to language-specific change operations. Thereby, we make the change operations applicable on process models in their concrete modeling language to resolve differences between different versions of process models. This section is partially based on our earlier publication [Gerth et al., 2009]. As an example, we consider the translation of IR change operations into BPMN change operations in the following.

In general, the abstraction of a concrete language such as the BPMN to the IR is a trade-off between changes that can be detected on the level of the IR and changes that need further interpretation on the level of the concrete modeling language. For instance, we mapped both BPMN event types *Start* and *End* to the generic IR element *Event*. That means, on the level of the IR, we are able to detect differences (insertions, deletions, or movements) of the IR element *Event*. However, we have to

identify on the level of the BPMN modeling language whether a BPMN *Start* event or *End* event is affected by this difference.

Accordingly, for the translation of generic compound change operations into BPMN change operations, underlying elements of generic operations need to be evaluated. Underlying elements are given by the *node* attribute of operations (respectively *fragment* attribute in the case of compound fragment operations) and provide a link to their corresponding concrete model element that was established during the abstraction from BPMN to IR. For clarification, our difference meta-model is shown in Figure 10.2

In the case of a compound node operation op_n , the type of a concrete BPMN change operation is determined based on the type of the corresponding BPMN model element of op_n . For instance, a generic *InsertActivity* operation inserting an activity in an IR process model is translated into a concrete *InsertTask* operation that inserts the corresponding BPMN *Task*, as shown in Figure 10.3.

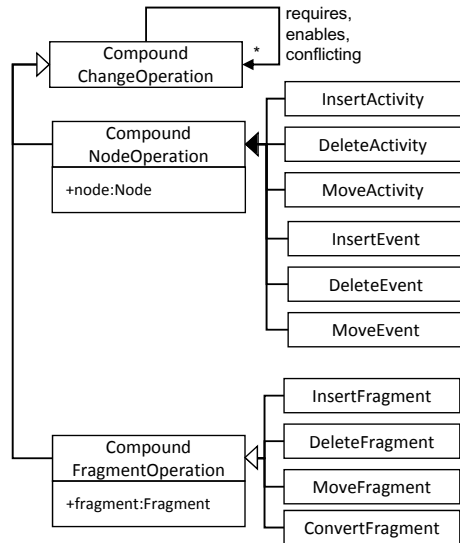


Fig. 10.2 Meta-Model of the Difference Model based on Compound Change Operations as introduced in Chapter 3

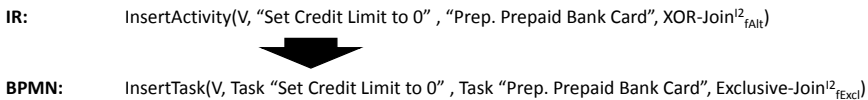


Fig. 10.3 Translation of a generic Compound Change Operation based on the IR into a concrete BPMN Change Operation

In the case of a compound fragment operation op_f , the type of the underlying fragment determines the type of the concrete BPMN change operation, e.g. a generic *InsertConcurrentFragment* operation op_{Par} with an *AND-Split* as entry, *AND-Join* as exit, and no further child-gateways is translated into a BPMN *InsertParallelFragment* operation that inserts a structured fragment with BPMN *ParallelGateways*. Please note that a concrete change operation for fragments must take care that the compound change operation is applied completely. That means, in the case of the *InsertConcurrentFragment* operation op_{Par} , the insertions of the fragments

entry node and exit node are also executed by the BPMN *InsertParallelFragment* operation.

Finally, position parameters of generic insert and move operations that specify former and/or new predecessor and successor of modified model elements are translated by substituting generic *Node* elements with their corresponding concrete BPMN element.

By applying language-specific compound change operations, we will merge different versions of a process model in the next sections.

10.3 Applying Non-conflicting Compound Change Operations

As introduced earlier, the merging of different process model versions requires the resolution of differences between the versions by applying compound change operations that represent and resolve the differences. For the application of change operations, we divide the set of compound change operations into subsets of conflicting and non-conflicting operations. In this section, we consider the application of non-conflicting change operations.

In general, the application of non-conflicting compound change operations is relevant for both two-way and three-way merging scenarios, as introduced in Chapter 2. In a two-way merging scenario, differences are computed between two versions of a process model, e.g. versions V and V_i . In this scenario, conflicts between change operations cannot be obtained, since the change log describes how process model V can be transformed into process model V_i . As a consequence, in two-way merge scenarios only non-conflicting change operations are applied. However, in three-way merge scenarios non-conflicting as well as conflicting change operations are applied. In the following two subsections, we introduce two methods to apply non-conflicting change operations.

10.3.1 Iterative Application of Change Operations

As a first method to merge different process model versions, we consider the manual and iterative application of non-conflicting compound change operations that resolve differences between process models. To that extent, a hierarchical change log is presented to a user, who then iteratively selects and applies change operations. For clarification, the hierarchical change log $\mathcal{A}(V, V_2)$ from our example (see Figure 1.3) is given in Figure 10.4.

Based on such a hierarchical change log, a user can select iteratively a change operation that shall be applied next until the desired merged process model is obtained. Please note that in case of a three-way merge scenario, two such hierarchical change logs must be shown to a user: one representing the differences between the Versions V and V_1 and the other representing the differences between Versions V and V_2 .

The selection of the compound change operation that shall be applied next has to consider dependencies between change operations. That means, it must be ensured

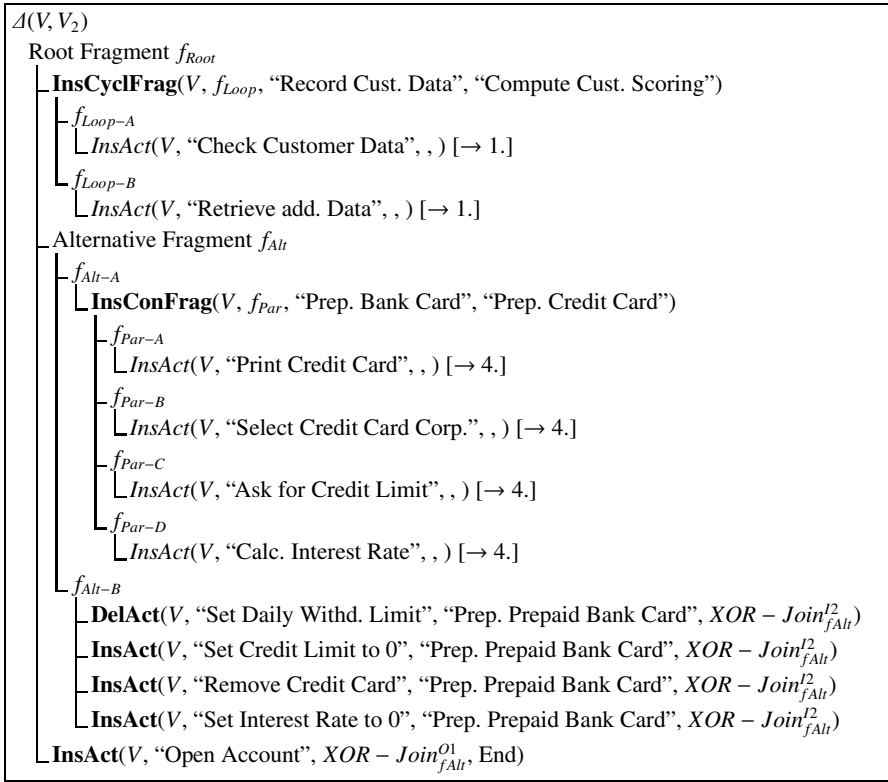


Fig. 10.4 Hierarchical Change Log $\Delta(V, V_2)$ of our running Example with *Joint – PST* Dependencies

that a user does not apply a change operation that is dependent on the application of another change operation that is not applied yet. Otherwise, a potentially unconnected process model is obtained, as discussed in Chapter 7. This can be achieved by disabling the application of dependent compound change operations in a hierarchical change log until they become applicable. In Figure 10.4, we have visualized dependent change operations using an italic font style and directly applicable change operations are highlighted in a bold font style.

Change operations are applied on the source Version V of the process models. After each application of a change operation, the position parameters of the remaining operations are recomputed based on the concept of dynamic specification as introduced in Section 7.3.1 in Chapter 7. For instance, let us assume a user first applies the independent change operation $InsCyclFrag(V, f_{Loop}, \text{“Record Cust. Data”}, \text{“Compute Cust. Scoring”})$ from Figure 10.4 that inserts a cyclic fragment in process model V .

After the application, the hierarchical change log $\Delta(V, V_2)$ is updated by dynamic computation as shown in Figure 10.5.

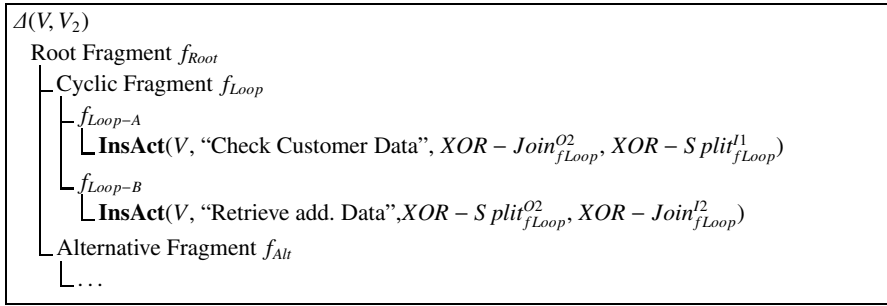


Fig. 10.5 Excerpt of the hierarchical Change Log $\Delta(V, V_2)$ of our running Example after the Insertion of the Cyclic Fragment f_{Loop}

In particular, the two change operations contained in the newly inserted cyclic fragment become applicable and their position parameter have been specified. Analogously, further operations are applied until a merged version is obtained. In the next subsection, we consider the automatic application of non-conflicting compound change operations.

10.3.2 Automatic Application of Change Operations

Analogously to the conventional procedure of well-known concurrent versioning systems for textual documents, such as concurrent versions systems (CVS) [CVS, 2011] or Subversion (SVN) [Subversion, 2011], all non-conflicting change operations may also be applied automatically without the need of further user intervention. This requires that a valid resolution order of all non-conflicting compound change operations contained in a hierarchical change log is computed with respect to the dependencies between change operations. After the application of these operations, only conflicting compound change operations remain in the change logs.

The computation of an execution order is straight-forward by iterating over all compound change operations in a hierarchical change log. If an independent change operation is identified it is numbered and marked as applied. In the case of a dependent operation, we check if all of its required operations have been marked as applied. If this is the case, the dependent operation is also numbered and marked as applied. This procedure is repeated until all non-conflicting operations are applied.

Utilizing this algorithm on the change log $\Delta(V, V_2)$ of our running example results in the execution order for the contained compound change operations shown in Figure 10.6. We indicated the order of the change operations execution by numbering the change operations in their execution order.

Further variants of an automatic application of non-conflicting change operations include, e.g. the automatic application of a subset of the change operations contained in a hierarchical change log in a specific (user-defined) order. For instance, the application of all operations from the beginning of a process model to its end by iterating

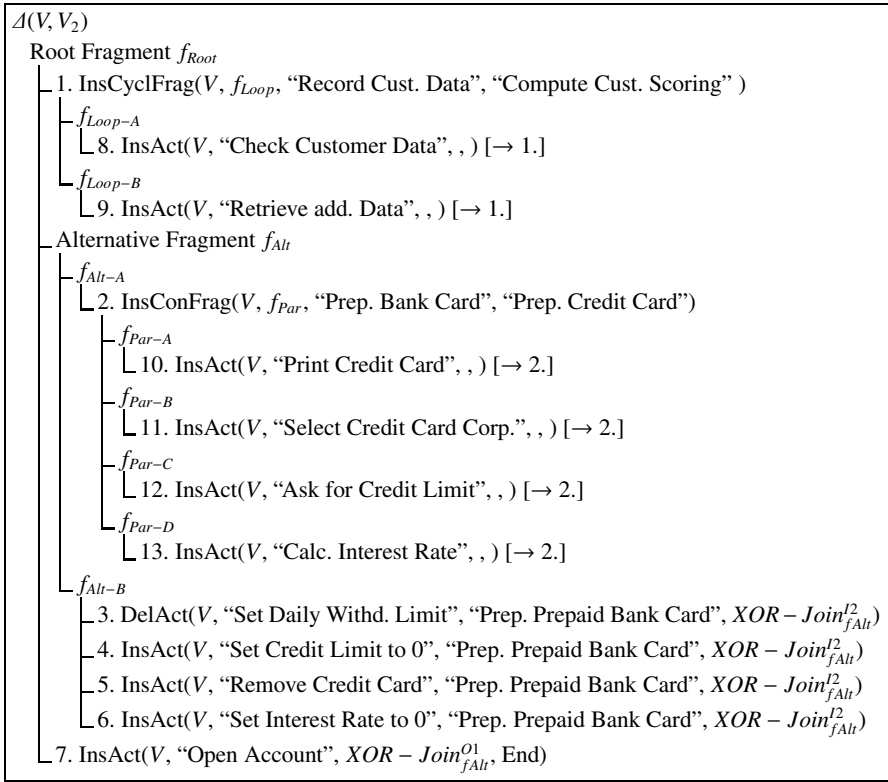


Fig. 10.6 Reconstructed Change Log $\Delta(V, V_2)$ of our running Example with an Execution Order for an automated Application

the process structure tree (PST) in an prefix manner or the application of all changes within a certain subtree of the PST of a process model.

10.4 Applying Conflicting Compound Change Operations

Having introduced different ways to apply non-conflicting compound change operations, we consider the application of conflicting change operations in this section. In the following, we present an approach that has been published in one of our earlier publication [Gerth et al., 2011a].

In contrast to non-conflicting change operations that can be applied automatically, conflicting change operations require user interaction, since their application mutually excludes each other. To that extent, we first introduce different resolution strategies for conflicts between change operations. Based on the strategies, we present a method for conflict resolution. For clarification, we apply the method on our example and come up with a merged process model V_M .

10.4.1 Strategies for Conflict Resolution

In general, a conflict between change operations can be resolved by applying one of the following strategies:

- (Strategy S_1) Given two conflicting change operations op_1 and op_2 . Trivially, the conflict is resolved by applying none of the conflicting operations in the merged process model V_M .
- (Strategy S_2) Given two conflicting change operations op_1 and op_2 . The conflict is resolved by applying one of the change operations, e.g. op_1 , to obtain the merged process model V_M . The other change operation op_2 is discarded.
- (Strategy S_3) Given two syntactically conflicting change operations op_1 and op_2 that modify non corresponding model elements x and y . To resolve the conflict, both change operations are applied iteratively in such a way that the model elements x, y (or y, x) directly succeed each other in the merged process model V_M .

Strategies S_1 and S_2 are straight-forward and can be applied to resolve semantic and syntactic conflicts between change operations. To give an example for Strategy S_2 , we consider the change logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$ given in the top of Figure 10.7. There, the conflict between the operations (c) and (y) that insert the node “*Open Account*” at different positions can be resolved by applying only one of the operations in the merged process model.

In contrast to the first two strategies, Strategy S_3 can only be used for syntactically conflicting change operations that modify non-corresponding model elements. Such operations are in conflict if after the application of the conflicting operations the non-corresponding model elements would be located at the same position in the merged process model. To resolve the conflict, both operations could be applied in such a way that the underlying model elements directly succeed each other after the application. To that extent, a user has to specify, which operation shall be applied first. The second operation is then adapted, i.e. its position parameters are aligned in such a way that after the application of the second operation the underlying model element is located directly after the model element of the operation that was applied first. In our example, the conflict between the operations (b) and (m) (see top of Figure 10.7) can be resolved using Strategy S_3 . The operations insert different model elements (“*Verify Customer Identity*” and the fragment f_{Loop} to complete the customer’s data) at the same position resulting in a syntactic conflict. To resolve the conflict, Strategy S_3 can be adopted that applies the operations by applying operation (m) first and (b) afterwards.

10.4.2 Method for Conflict Resolution

In the following, we present a method for the resolution of conflicts between change operations in order to merge different versions of process models into an integrated version V_M . The method guides a user through the process of conflict resolution

by providing an order in which conflicts should be resolved and suggesting appropriate strategies for the resolution of individual conflicts. Based on the suggestion for an individual conflict, a user selects a strategy to resolve a conflict between two change operations. This decision is usually based on the user's domain knowledge and cannot be automated.

In general, we can distinguish two situations for conflict resolution: The resolution of a single conflict between two change operations that are not conflicting to other change operations and the resolution of a conflict between change operations that are in conflict with other change operations.

In the former situation, a conflict c between two operations op_1 and op_2 can be considered independently of any other conflict. If c is a syntactic conflict between op_1 and op_2 , it can be resolved by applying one of the strategies S_1, S_2 , or S_3 . If c is a semantic conflict the resolution is limited to strategies S_1 or S_2 . For instance, in the merged process model V_M in Figure 10.7, we resolved the semantic conflict between the operations (h) and (t) that insert the activity “*Calculate Interest Rate*” to different positions, by adopting strategy S_2 , i.e. we applied operation (h) ¹ and discarded operation (t) .

In the latter situation, a conflict c between two change operation op_1 and op_2 cannot be resolved in isolation, since the resolution of c potentially impacts the resolution of other conflicts of op_1 and op_2 . As a consequence, in such multi-conflict situations, the resolution of an individual conflict must consider all conflicts of op_1 and op_2 .

In our method, we propose to resolve semantic conflicts between change operations first for two reasons: First, the resolution of semantic conflicts is limited to the adoption of two strategies (S_1 and S_2). Second, change operations that are semantically conflicting modify a merged process model in different parts that are often completely unrelated to each other and require a careful investigation. For instance, the semantically conflicting operations (c) and (y) insert the activity “*Open Account*” to different positions that are far away from each other. Whereas, syntactic conflicting change operations modifies model elements in a process model that are located in the same area. Accordingly, syntactic conflicts are resolved in a second step.

Figure 10.7 gives a concrete example, the operation (a) is in conflict with the operations (m) , (n) , and (o) . In addition operations (m) , (n) , and (o) are in conflict with operation (b) . An adoption of Strategy S_2 resolves the semantic conflict between the operations (a) and (n) by applying operation (n) that inserts the activity “*Check Customer Data*” in the fragment and discarding operation (a) . Subsequently, the conflicts between the $(a), (m)$, and (o) are resolved, too. Finally, we resolve the syntactic conflict between (b) and (m) , whereas an adoption of strategy S_1 is no longer available, since the operation (m) , which inserts the alternative loop, must be applied, to enable the application of operation (n) that inserts the activity “*Check Customer Data*” in the loop.

¹ In the merged process model V_M in Figure 10.7, operation (h) was applied using the normal form of its surrounding fragment f_{P1-V1} .

- $\Delta(V, V_1)$:
- a) *InsAct("Check Cust. Data", "Record Cust. Data", "Compute Cust. Scoring")*
 - b) InsAct("Verify Cust. Identity", "Record Cust. Data", "Compute Cust. Scoring")**
 - c) InsAct("Open Account", "Compute Cust. Scoring", "XOR-Split_(a,v1)")*
 - d) InsCon.Fragment(f_{Par-V2} , "Prepare Bank Card", "Prepare Credit Card")**
 - e) *InsAct("Sign Contract", ,)*
 - f) InsAct("Print Credit Card Contract", ,)**
 - g) InsCon.Fragment(f_{Par-V2} , ,)*
 - h) InsAct("Calc. Interest Rate", ,)**
 - i) InsAct("Select Credit Card Corp.", ,)*
 - j) InsAct("Set Credit Limit to 0", "Prepare Prep. Bank Card", "XOR-Join_(a,v1)")**
 - k) InsAct("Remove Credit Card", "Set Credit Limit to 0", "XOR-Join_(a,v1)")*
 - l) InsAct("Set Interest Rate to 0", "Remove Credit Card", "XOR-Join_(a,v1)")**
- $\Delta(V, V_2)$:
- m) InsAlt.Fragment(f_{loop} , "Record Cust. Data", "Compute Cust. Scoring")**
 - n) InsAct("Check Cust. Data", ,)*
 - o) InsAct("Retrieve add. Data", ,)*
 - p) InsParallelFragment(f_{Par-V2} , "Prepare Bank Card", "Prepare Credit Card")**
 - q) InsAct("Print Credit Card Contract", ,)**
 - r) InsAct("Select Credit Card Corp", ,)*
 - s) InsAct("Ask for Credit Limit", ,)*
 - t) InsAct("Calc. Interest Rate", ,)*
 - u) DelAct("Set Daily Withd. Limit", "Prepare Prep. Bank Card", "XOR-Join_(a,v2)")**
 - v) InsAct("Set Interest Rate to 0", "Prepare Prep. Bank Card", "XOR-Join_(a,v2)")**
 - w) InsAct("Remove Credit Card", "Prepare Prep. Bank Card", "XOR-Join_(a,v2)")*
 - x) InsAct("Set Credit Limit to 0", "Prepare Prep. Bank Card", "XOR-Join_(a,v2)")**
 - y) InsAct("Open Account", "XOR-Join_(a,v2)", "End")**

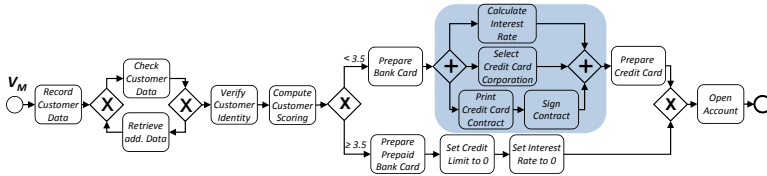


Fig. 10.7 A possible merged Process Model V_M

Figure 10.7 illustrates one possible resulting process model V_M . In order to visualize the conflict resolution process, applied change operations are printed in bold letters and rejected changes in italic letters.

We start the merging of the process models V_1 and V_2 into V_M by resolving the conflicts between the change operations (a), (b) and operations (m), (n), and (o) as described above. Then, the semantic conflict between the operations (c) and (y) that insert the node “Open Account” to different positions is resolved by adopting strategy S_2 and applying operation (y). The highlighted fragment in the merged process model V_M was added by inserting the normal form of the fragment f_{Par-V1} . Finally, the non-conflicting operations (u), (j), (l), (v), and (x) are applied in the merged process model V_M .

This example shows that using our approach conflicts between change operations can be resolved systematically in an iterative way with minimal manual user intervention such that a consolidated process model is constructed.

10.5 Summary and Discussion

In this chapter, we considered the merging of different process models by applying compound change operations. We first showed how generic change operations based on models in the intermediate representation are translated into language-specific change operations, which are applicable on process models in a concrete modeling language. For the application of non-conflicting change operations, we introduced two methods: one for the iterative application of change operations requiring user intervention and one for the automatic application of compound change operations, which first computes an execution order. Finally, we proposed three different strategies for the resolution of conflicts between change operations together with a method that guides a user through conflict resolution when merging process models.

To show the feasibility of our solution for process model change management and to present the parts of our solution, which are released in the IBM WebSphere Business Modeler, we introduce our tool support in the next chapter.

Tool Support

In this chapter, we present tool support for process model change management. Most of the parts of our framework that we have introduced in the previous chapters are implemented in a prototype and have been instantiated for process models in two modeling languages, namely BPMN and BPEL.

The remainder of this chapter is structured as follows: In the next section, we introduce two commercial software products, which serve as our implementation platform. In Section 11.2, we give an overview on our prototypic implementation of our framework for process model change management. In addition, we briefly present the *Compare & Merge Framework* that is contained in a commercial software product and relies on parts of our solution.

11.1 Implementation Platform

As a proof of concept, we realized our framework for process model change management in terms of a prototypic implementation. To speed up the development, we decided to integrate our framework into an existing business process management suite. In particular, we choose the IBM WebSphere software products (Version 6.2) [IBM, 2009a] as our implementation platform. The IBM WebSphere software products support the different phases, such as *Model*, *Develop*, *Deploy*, *Monitor*, and *Analyze & Adapt* of a typical business process management lifecycle as introduced in Section 2.3 in Chapter 2.

In business process management, a business analyst creates high-level business process models in the *Model* phase using the IBM WebSphere Business Modeler (WBM) [IBM, 2009a]. The WBM provides state-of-the-art support for process modeling and simulation. It relies on a proprietary modeling language that can be visualized using the BPMN. The execution semantics of the language is based on token flow and is very similar to UML Activity Diagrams [OMG, 2010b].

Figure 11.1 shows a screenshot of the IBM WBM. On the right hand side, the two process models V and V_2 of our running example are visualized (see ① and ② in Figure 11.1). On the left hand side, a project tree is shown ③ that can be used to

access the individual process models and business objects of the current modeling project.

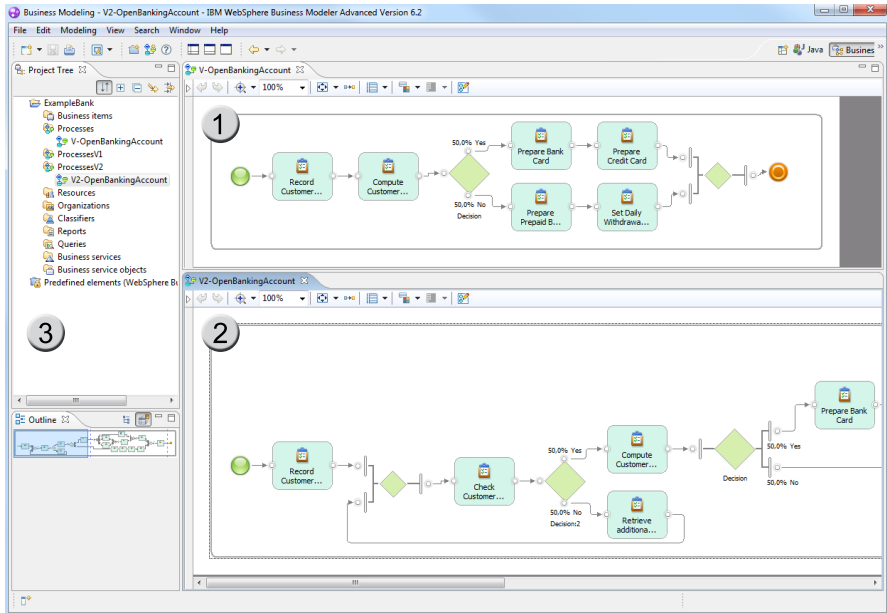


Fig. 11.1 Process Modeling with the IBM WebSphere Business Modeler

Following the business process management lifecycle, high-level process models created with the WBM are further refined in the *Develop* phase to make them executable. For that purpose, the IBM WebSphere Integration Developer (WID)¹ [IBM, 2009a] can be used to transform a given high-level business process model into a BPEL process model that is further enriched with implementation details.

Both software products, IBM WebSphere Business Modeler (WBM) and the IBM WebSphere Integration Developer (WID) are based on the Eclipse platform [Eclipse Foundation, 2011a]. We extended both tools by integrating our prototypic framework for process model change management. In the following section, we give a detailed overview of this implementation.

11.2 Overview of the Process Merging Solution

In this section, we report about our prototypic framework for process model change management, which we have instantiated the framework for the IBM WebSphere Business Modeler and the IBM WebSphere Integration Developer.

¹ Since April 2011, WID is continued in the follow-on product IBM Integration Designer [IBM, 2009a]

Table 11.1 gives an overview of the implemented aspects (denoted by filled circles) of our framework. Only, two aspects have not been implemented, namely the equivalence analysis (see Chapter 8) and the conflict analysis based on the modeling languages semantic as described in Chapter 9. However, these two aspects can be integrated into the framework in the course of a single master thesis.

Table 11.1 Implemented Aspects of our Framework for Process Model Change Management

Framework for Process Model Change Management	Implemented
Abstraction of process models into the intermediate representation	●
Decomposition of process models into fragments	●
Matching of process model versions	●
Difference detection between process model versions	●
Dependency analysis between compound change operations	●
Equivalence analysis of process models and fragments	○
Syntax-based conflict detection between compound change operations as described in [Küster et al., 2009]	●
Semantic-based conflict detection between compound change operations as described in [Gerth et al., 2010a]	○
Merging of process model versions	●*

* The graph transformation rules that realize our compound change operations are not implemented in our prototypic framework. However, they are supported in the Compare & Merge Framework of the IBM WebSphere Business Modeler Version V7.0.

In addition to the prototypic implementation of the framework, certain aspects of our solution are also used in the *Compare & Merge Framework* of the commercial software product IBM WebSphere Business Modeler (Version 7) [IBM, 2009a]. We report about this framework in Section 11.2.4.

In the next section, we give a brief architectural overview of our implementation. Afterwards, we consider the reconstruction of a hierarchical change log and the merging of process models using our framework in the Sections 11.2.2 and 11.2.3. Finally, we conclude with a summary and discussion in Section 11.3.

11.2.1 Architectural Overview

Our framework for process model change management consists of several components, which are shown in Figure 11.2.

Technically, the components are realized by several plug-ins using the plug-in mechanism of the underlying Eclipse development platform. We distinguish between *language-independent components* that solely work on the intermediate representation (see Chapter 3) and *language-specific components* that provide necessary support for process models in a concrete modeling language. In the following, we first consider language-independent components of our framework and afterwards language-specific components.

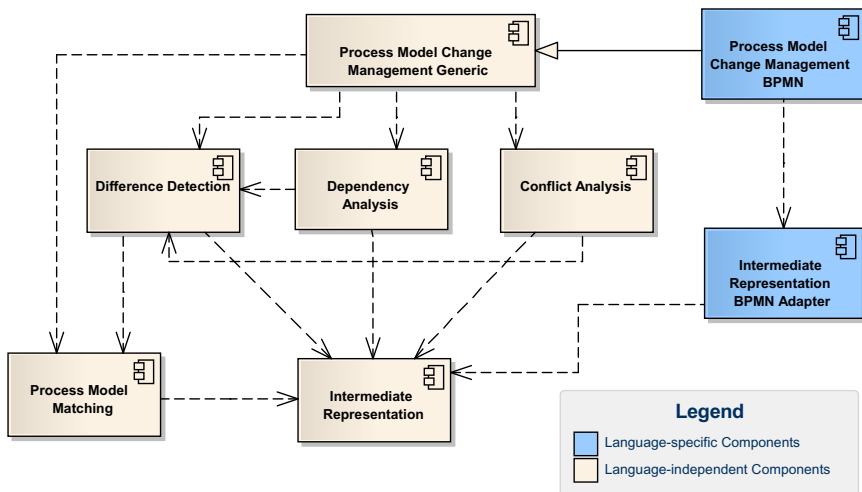


Fig. 11.2 Architecture of our Framework for Process Model Change Management

Language-Independent Components

In Figure 11.2, components with a light shaded background represent generic components of our framework, which are independent of the process modeling language. These components on its own constitute a solution for process model change management and can be used to merge process models.

The *Intermediate Representation* component serves as an abstract representation of process models in a concrete modeling language, such as BPMN [OMG, 2011a] or BPEL [OASIS, 2007]. In addition, this component is used to decompose process models into fragments as described in Chapter 3.

The *Process Model Matching* component is capable to match two given versions of a process model in the intermediate representation and results in a mapping containing correspondences between related model elements. In this component, we have implemented the basic functionality of the matching approach (i.e. the identity-based matching) presented in Chapter 4. An elaborated matching component for process models has been described and implemented in [Fazal-Baqai, 2009].

Based on a mapping between process models, the *Difference Detection* component identifies differences between two process models and captures these differences in terms of compound change operations (cf. Chapter 6). Thereby, a change log is reconstructed. The *Dependency Analysis* component provides functionality to identify dependencies between change operations in such a reconstructed change log. Finally, in cases where a process model is individually refined by several users and multiple change logs exist, the *Conflict Analysis* component is used to identify pairs of change operations in these change logs whose application mutually exclude each other (cf. Chapter 9).

The *Process Model Change Management Generic* component coordinates and composes the previous components.

Language-Specific Components

The language-specific components of our framework are shown with a blue background in Figure 11.2 and are necessary to obtain an instantiation of our framework for process models in a concrete modeling language - here for process models in the BPMN [OMG, 2011a].

The *Process Model Change Management BPMN* component is a BPMN-specific instantiation of our framework. It adapts the order of component invocations of the *Process Model Change Management Generic* component to BPMN-specific needs.

An example for such an adaptation is the invocation of the *Intermediate Representation BPMN Adapter* component, which is responsible of transforming BPMN process models into our language-independent intermediated representation (IR). For that purpose, the component comprises a mapping between BPMN model elements and IR model elements. To enable the traceability from IR model elements back to their underlying BPMN model elements, the component establishes links during the transformation of BPMN models into IR models.

In addition to the BPMN-specific instantiation shown in Figure 11.2, we have instantiated our prototypic framework also for change management of BPEL process models [OASIS, 2007] in the IBM WebSphere Integration Developer [IBM, 2009a]. To that extend, we substituted the BPMN-specific components in Figure 11.2 by BPEL-specific components. Language-independent components are reused without modification.

11.2.2 Reconstruction of a Hierarchical Change Log

For the reconstruction of a change log between two process model versions all components introduced in the architectural overview (cf. Figure 11.2) are used.

First, the *Process Model Matching* component computes a mapping between two process model versions relying on the matching strategies described in Chapter 4. Based on this mapping, an initial change log is created by overlapping the fragment hierarchies of the two process models. Differences that are computed by the *Difference Detection* component are added to this change log in such a way that each change operation is assigned to the fragment, which is affected by the application of the operation (Chapter 6). Finally, the reconstruction of an hierarchical change log is completed by identifying dependencies between contained change operations as described in Chapter 7.

To visualize a reconstructed hierarchical change log to a business user in the IBM WebSphere Business Modeler, we have developed a merge view that is shown in Figure 11.3.

This two-way merge view shows the differences between the process model versions V and V_2 of our example introduced in Figure 1.3 and consists of three parts: On the left hand side the elements contained in process model version V are shown

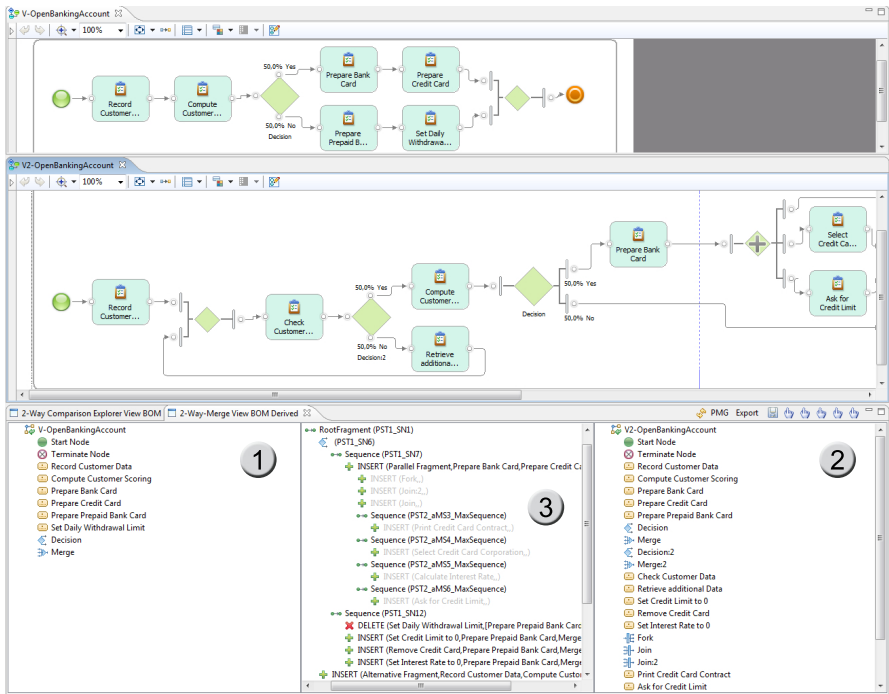


Fig. 11.3 Iterative Change Application using our prototypic Two-Way Merge View in the IBM WebSphere Business Modeler

(see ① in Figure 11.3). Analogously, on the right hand side the model elements contained in process model V_2 are listed (see ② in Figure 11.3). The reconstructed change log $\Delta(V, V_2)$ representing the differences between the two process model versions is shown in the middle ③.

How process model versions can be merged using this view is addressed in the next section.

11.2.3 Merging of Process Models

For the merging of process models, we provide two merge views² in our prototypic framework, which we briefly introduce in the following. We begin with a two-way merge view for iterative and automatic merging of process models, followed by a three-way merge view for the merging of process models in distributed modeling scenarios.

² Please note that our prototypic implementation currently only supports the visualization of the differences between process model versions, as well as dependencies and conflicts between them. Full merging supported is provided in the Compare & Merge Framework of the IBM WebSphere Business Modeler Version V7.0.

Two-Way Merge

Based on the view visualized in Figure 11.3, two process models can be merged by applying change operations contained in the hierarchical change log ③. The change log contains compound change operations that are arranged according to the hierarchical structure of the underlying process models. These change operations represent the differences between the two process models V and V_2 , whose model elements are shown in ① and ② of Figure 11.3. By applying all change operations contained in the change log on the process model V , V is transformed into V_2 .

As described in Chapter 7, change operations may dependent on the application of other change operations or they are independent. Dependent change operations are grayed out in the view (see ③) and cannot be applied until all required change operations are applied before.

In order to merge two process models, a user can select and apply change operations in the hierarchical change log ③ in an iterative way until all desired change operations are applied.

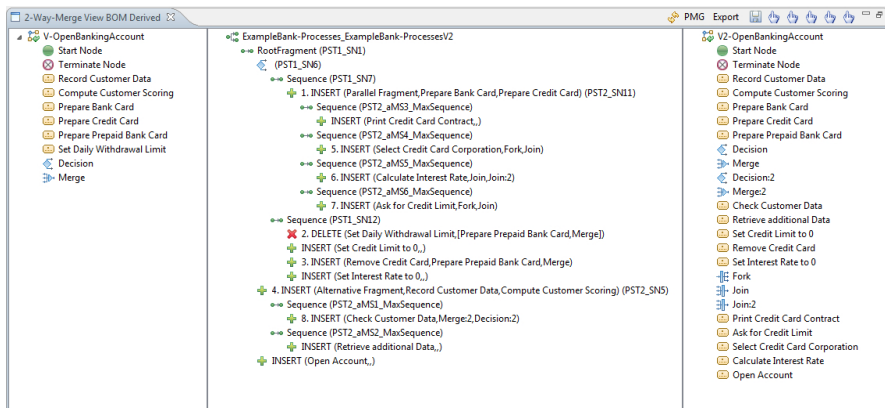


Fig. 11.4 Automatic Change Application using our prototypic Two-Way Merge View in the IBM WebSphere Business Modeler

To speed up the merging of process models, change operations can also be applied automatically using our view (see Figure 11.4). Here, a user can either decide to apply all compound change operations or a valid subset of change operations. In the former case, a possible application order for all compound change operation in the hierarchical change log is computed, that respects the dependencies among the change operations. In the latter case, a user first selects a subset of change operations that shall be applied. For this subset, an algorithm evaluates the validity of the selection of change operations and then suggests a possible application order of the operations in this subset. A subset of change operations is valid if all operations that are required by a dependent operation in the subset are also contained in the subset. In the case that a required change operation is not selected, the required change operation is added to the subset of selected operations and the user is

informed. Figure 11.4 shows a possible application order of a subset of compound change operations contained in the hierarchical change log $\Delta(V, V_2)$.

Three-Way Merge

To support scenarios, where multiple users individually modify process models and different versions are created, we developed a three-way merge view. This view can be used to merge two different process model versions while considering their common ancestor version. Figure 11.5 shows a screenshot of a three-way merge view of our example process model V and its descendant versions V_1 and V_2 introduced in Figure 1.3.

The three-way merge view consists of several parts indicated in Figure 11.5: The tree views of the process model versions V_1 and V_2 (① and ②) and two hierarchical change logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$ (③ and ④).

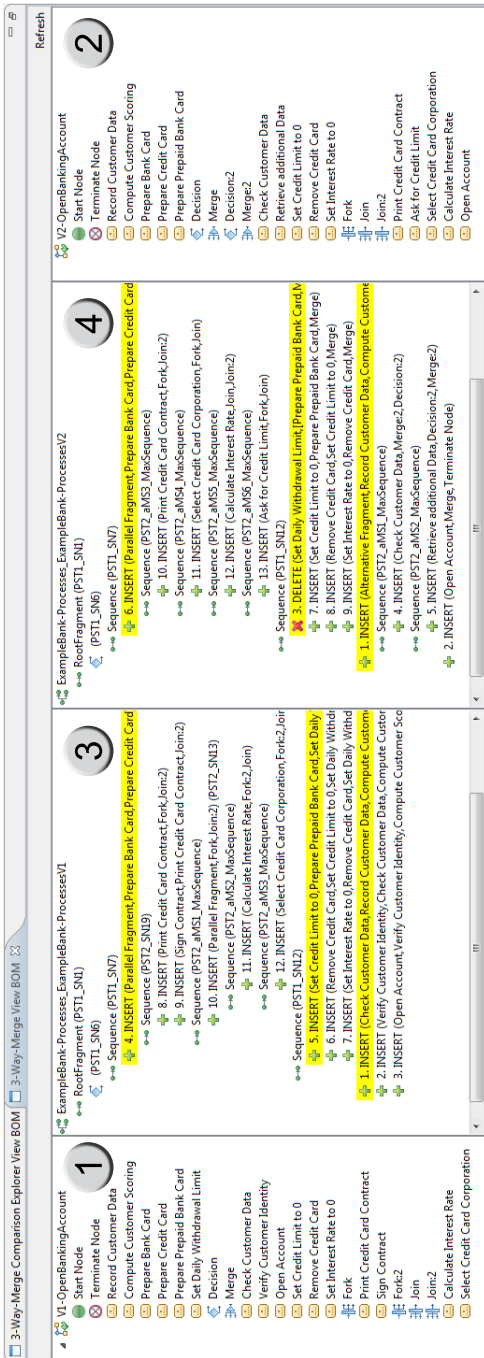


Fig. 11.5 Merging and Conflict Resolution using our prototypic Three-Way Merge View in the IBM WebSphere Business Modeler

In three-way merge scenarios, we additionally have to identify and visualize conflicts between change operations contained in the change logs. In general, two change operations are in conflict if they mutually exclude each other. In our prototypic implementation, we implemented the syntax-based conflict detection approach, which we have presented in our earlier publication [Küster et al., 2009].

Using the three-way merge view, the process models V , V_1 , and V_2 can be consolidated by applying compound change operations contained in the hierarchical change logs $\Delta(V, V_1)$ and $\Delta(V, V_2)$. If a change operation is selected in one of the change log, which is in conflict with another operation from the other change log, this conflict is visualized to the user by highlighting the underlying change operations.

11.2.4 Compare and Merge Framework of the IBM WebSphere Business Modeler

In addition to the prototypic implementation of the framework, certain aspects of our solution for process model change management are also used in the *Compare & Merge Framework* in the commercial IBM WebSphere Business Modeler (Version 7) [IBM, 2009a]. In particular, our techniques for differences detection based on fragments and the dependency analysis are used in the commercial software product.

The *Compare & Merge Framework* is used to merge two process model versions. To give an example, when a newer version of an existing process model (or entire process modeling project) is imported into the local modeling workspace the *Compare & Merge Framework* is used to integrate the different process model versions. For that purpose, differences between the two versions are first computed in terms of change operations in such a way that the application of all change operations transforms the local version of the process model into the imported process model version. Then a subset of the change operations can be selected, which shall be applied on the local version of the process model.

Figure 11.6 shows a screenshot of the *Compare & Merge Framework*. The user interface of the framework consists of three parts: ① A project tree that shows the changed process models of the project. ② For each pair of process model versions, a list of change operation representing the differences between the process models. ③ A visual representation of the local process model in the workspace.

In order to merge the process models, changes that shall be applied on the local version of a process model can be selected in the change list. The impact of the selected changes is immediately visualized in the representation of the local version of the process model (see ② and ③ in Figure 11.6).

11.3 Summary and Discussion

We have presented our prototypic framework for process model change management, which we have instantiated for two commercial software products, namely the IBM WebSphere Business Modeler (WBM) [IBM, 2009a] and the IBM WebSphere

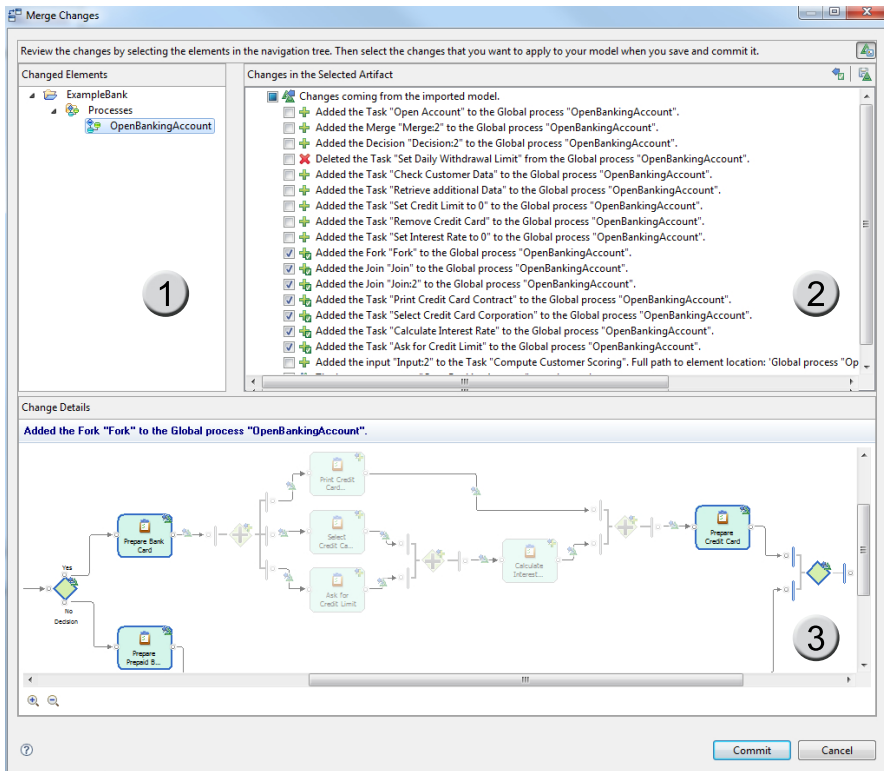


Fig. 11.6 Compare and Merge Framework of the IBM WebSphere Business Modeler Version 7.0 [IBM, 2009a]

Integration Developer (WID) [IBM, 2009a] (both Version 6.2). The framework extends these software products with effective tool support for the merging of different process model versions.

We realized the prototypic framework using several plug-ins in a language-independent way. Overall, the instantiation of the framework for BPMN process models of the WBM consists of more than 20k lines of code. Roughly 80% of the code base are language-independent and can be used without modification also for the merging of BPEL process models in the WID.

Parts of our implementation also contributed to the *Compare & Merge Framework* of the IBM WebSphere Business Modeler Version 7 [IBM, 2009a], which was realized as an IBM product in 2009.

In the next chapter, we conclude this book and give an outlook on future work.

Conclusion

In this book, we have presented our framework for process model change management as a solution for model versioning support in distributed model-driven development approaches of software systems. We presented the prototypic implementation of our framework as well as the parts that found their way into the *Compare & Merge Framework* of the commercial IBM WebSphere Business Modeler (Version 7) [IBM, 2009a].

In this concluding chapter, we first summarize our contributions in Section 12.1. Then, we consider future works in process model change management in Section 12.2 and, finally in Section 12.3, we conclude with final remarks and discuss lessons learned in the course of this work.

12.1 Contribution Summary

The goal of this book was to develop a solution for process model change management that enables the merging of different process model versions into an integrated process model. For that purpose, it is required that differences between different versions are identified in a suitable granularity that supports the merging of the process models. Further, to enable a high degree of automation within merging of different process model versions, it is important to identify dependencies and conflicts of differences. In addition, we required that a solution shall be generically applicable to process models in commonly used modeling languages, such as BPMN [OMG, 2011a], UML Activity Diagrams [OMG, 2010b], and BPEL [OASIS, 2007].

To achieve the goals of this book, we presented a framework for process model change management. Figure 12.1 gives an overview of the framework's components together with the contributing concepts and approaches. In the following, we summarize the contributions along the structure of our framework for process model change management.

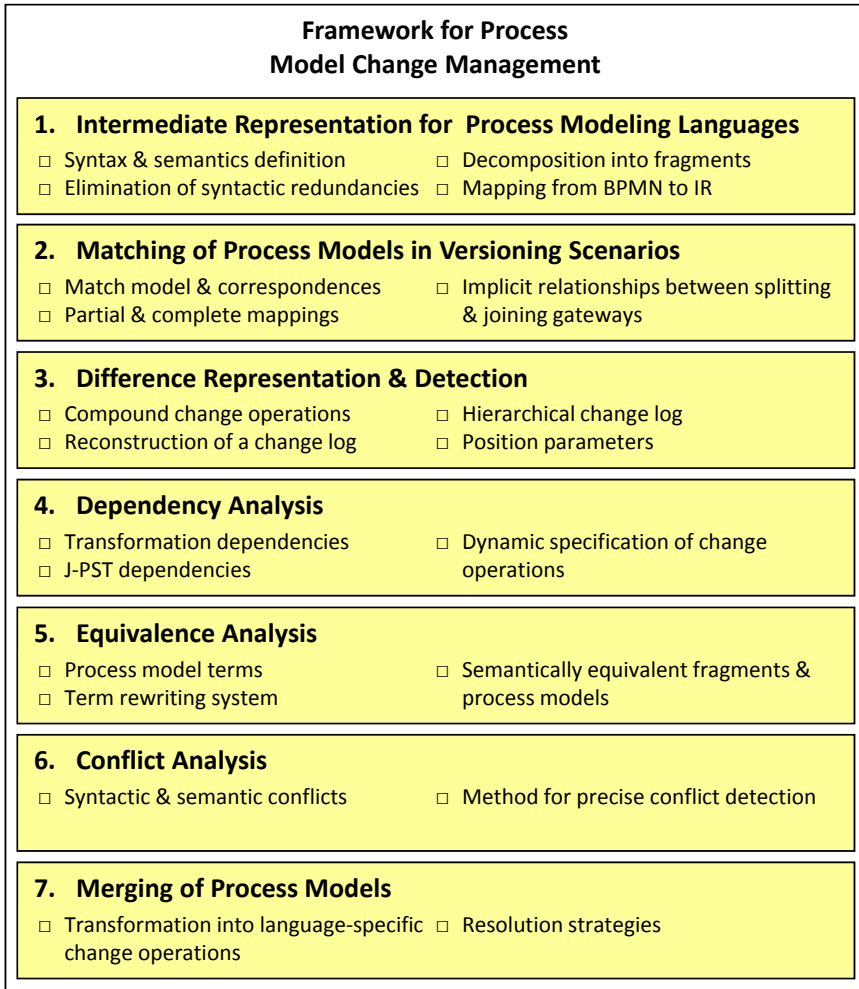


Fig. 12.1 Framework for Process Model Change Management with Contribution Overview

1. Intermediate Representation for Process Modeling Languages

To generalize our framework for process model change management, we introduced the intermediate representation as a common representation of process models in different modeling languages. We focus to support the commonly used modeling languages BPMN [OMG, 2011a], UML Activity Diagrams [OMG, 2010b], and BPEL [OASIS, 2007]. Models in these languages can be abstracted to the IR. This enables us to compare and analyze process models for the purpose of model merging - independent from the concrete modeling languages of the process models.

We defined the syntax of the IR in terms of a meta-model and specified the semantics of IR process models formally using typed graph transformation rules. By focusing on core concepts of process modeling languages, such as activities, events, and gateways, the IR helps to eliminate syntactic redundant model elements of concrete process modeling languages.

Further, we introduced an approach for the decomposition of process models into fragments, which enclose nested subgraphs with distinguished behaviors. Thereby, we made the implicit structure of IR process models explicit and harmonize block-oriented and graph-oriented process modeling languages, like BPEL and BPMN. Finally, we described a mapping of a core subset of the BPMN to the IR.

2. Matching of Process Models

Based on process models in the intermediate representation, we introduced an approach to match process models in versioning scenarios. For that purpose, we proposed a match model consisting of correspondences between related model elements. We introduced the concept of a partial mapping that is based on model elements that are common in all versions. Such a partial mapping can be created and updated automatically in versioning scenarios. Based on the partial mapping, we then described an approach to compute mappings between versions of process models. To that extend, we apply different matching strategies including identity-based and similarity-based matching strategies.

Moreover, our matching approach for process models is able to identify implicit relationships between splitting and joining gateways within a single process model, which constitute a subgraph with a distinguished behavior, such as parallel or alternative structures. The identification of these relationships is based on the decomposition of process models into fragments.

3. Difference Representation and Difference Detection

For the representation of differences between process models, we introduced a difference model based on compound change operations that comprise several related elementary changes. Compound change operations turned out to be more suitable for the representation of differences in change management of process models [Weber et al., 2007, Küster et al., 2008b]. Due to their coarser granularity, compound change operations require far less user interactions to merge different process models than approaches based on elementary changes.

In order to detect differences between different process model versions, we proposed an approach that results in a reconstructed change log consisting of compound change operations. To enable an intuitive and natural understanding of the differences between process models, we further transformed the reconstructed change log into a hierarchical change log. The idea of a hierarchical change log is to arrange compound change operations according to the structure of the underlying process models. Thereby, differences are directly located to the fragment of a process model, which is affected by the difference. Finally, we considered the computation of position parameters of compound change operations that specify the predecessor and the successor of a modified model element in a change operation.

4. *Dependency Analysis*

Compound change operations that represent differences between two process models, may depend on each other. That means, the application of a change operation requires the prior application of another change operations. These dependencies need to be computed before process models can be merged. Otherwise potentially unconnected process models are created. We introduced two different notions of dependencies: transformation dependencies and *Joint – PST* dependencies, and provided approaches to identify both notions of dependencies.

The former approach, computes dependencies between compound change operations, whose position parameter have been fixed. The approach is based on the existing notion of dependencies between graph transformations of typed attribute graphs. In contrast to transformation dependencies, *Joint – PST* dependencies can be computed even between compound change operations, whose position parameters have not been specified yet. The computation of *Joint – PST* dependencies is based on the concept of dynamic specification of change operations that dynamically computes position parameters after each application of a change operation. Using *Joint – PST* dependencies and dynamic specification of change operations, different business process models can be integrated by applying change operations without being unnecessarily restricted to a certain application order.

5. *Equivalence Analysis of Process Models and contained Fragments*

We proposed an approach for deciding equivalence between business process models based on a normalization of syntactically different but semantically equivalent fragments. In our approach, we transform process models into process model terms. These terms are then normalized by a term rewriting system. We have examined the correct functional behavior of the term rewriting system for process model terms using existing theory for abstract reduction systems. Based on process model terms in their normal form, we decide semantic equivalence of process model fragments and entire process models.

The approach combines the benefits of syntactic and semantic comparison approaches to decide equivalences between process models and contained fragments. Thereby, we overcome the shortcomings of approaches based on trace equivalence, such as computational complexity or the need to analyze different sets of traces to identify the actual difference between traces.

6. *Conflict Analysis*

Whenever process models are modified independently by applying change operations, there might be the case that change operations are conflicting. Two change operations are conflicting if the application of one operation turns the other one inapplicable. For conflict analysis, we first distinguished conflicting change operations into syntactic and semantic conflicts. Based on these conflict notions, we then introduced a method for conflict analysis between compound change operations.

Our method avoids false-positive conflicts between change operations that modify syntactically different fragments that are semantically equivalent. To that extent,

we applied our approach to equivalence analysis for process models and fragments. Our initial results have shown that taking the semantics of process modeling languages into account, helps to compute precise conflicts and avoids false-positive conflicts.

7. Merging of Process Models

Finally, we considered the merging of different process models by applying compound change operations. We first showed how generic change operations based on models in the intermediate representation are translated into language-specific change operations, which are applicable on process models in a concrete modeling language. For the application of non-conflicting change operations, we introduced two methods: one for the iterative application of change operations requiring user intervention and one for the automatic application of compound change operations, which first computes an execution order. Finally, we proposed three different strategies for the resolution of conflicts between change operations together with a method that guides a user through conflict resolution when merging process models.

To show the feasibility of our solution for process model change management, we implemented tool support for most of the components in our framework. The tool support is integrated in the IBM WebSphere Business Modeler (WBM) [IBM, 2009a] and the IBM WebSphere Integration Developer (WID) [IBM, 2009a]. Parts of this work contributed also to the Compare & Merge framework of the IBM WebSphere Business Modeler V 7.0 [IBM, 2009a], which was released as an IBM product in fall 2009.

12.2 Outlook on Future Work

There are some issues that are currently not covered by our solution to process model change management, which might be addressed in future work.

Our proposed intermediate representation serves as an abstraction of commonly used concrete process modeling languages, such as BPMN [OMG, 2011a], UML Activity Diagrams [OMG, 2010b], and BPEL [OASIS, 2007]. This abstraction does not consider specialized model elements, such as BPMN Pools that represent participants in BPMN processes and are used to for partitioning of activities. Future work can extend the intermediate representation by such specialized model elements.

Moreover, the flow of business objects in process models, also known as data flow, is not yet addressed in our approach. The support of data flow in the intermediate representation might also result in new dependencies and conflicts between change operations. For instance, the insertion of an activity may require the insertion of another activity to fulfill requirements with regards to input/output data. In this context, the approach to consistency of object life cycles in process models presented in [Wahler, 2009] can serve as a foundation for the integration of data flow support in our approach.

We have introduced an approach to match different process model versions in Chapter 4 that focuses on 1-1 correspondences between model elements. Future

work can extend this approach to support also 1:n, n:1, or n:m correspondences between model elements. These more complex correspondences reflect scenarios in which, e.g. single model elements have been refined into several model elements. A promising step towards the automated identification of such correspondences is described in [Weidlich et al., 2010]. There, the ICOP framework is presented, that can be used to match activities contained in different process models and additionally provides an approach to identify correspondences between a single activity and a group of activities.

Currently, our approach for equivalence analysis identifies equivalences on the level of fragments contained in process models. That means, semantically equivalent substructures in process models, which are not enclosed in matching fragments cannot be identified using our approach. For instance, let us consider two process models V_1 and V_2 . In V_1 a cyclic fragment (e.g. a *BPMN Loop*) exists that executes a sequence of activities iteratively, e.g. three times. In contrast to V_1 , in process model V_2 , this cyclic fragment is rolled out, i.e. the sequence of activities is modeled three times resulting in a larger sequential fragment. Considering trace equivalence, the obtainable traces of activity executions in both process model fragments are equal. However, since the types of the fragments do not match (cyclic fragment vs. sequential fragment), the semantic equivalence is not identified by our approach.

Such equivalences could be identified by establishing a pre-processing step that normalizes process models before they are compared. For that purpose, our term rewriting system (cf. Section 8.3 in Chapter 8) could be extended by further reduction rules that capture syntactic redundant structures.

Finally, our framework does not yet support change management across modeling language boundaries, e.g. the synchronization of BPMN process models with BPEL processes. However, we believe that the use of a common representation of process models, like our intermediate representation, eases the realization of a solution for change management across language boundaries. One reason for this is that in our framework process models can be compared in a common representation, e.g. for difference detection. As a first step towards the extension of our framework for change management across language boundaries, a partial mapping between the meta-models of different modeling languages is required.

12.3 Final Remarks

The contributions achieved in this book support the model-driven development (MDD) of complex software systems, as a promising development methodology that is able to cope with the increasing complexity of today's software systems.

We are convinced that MDD can only deliver its full potential benefits if suitable tools are provided that support the distributed development of models properly. This requires in particular adequate model versioning support that is tailored to meet the specific requirements of different modeling languages.

In the course of our work, we have noticed that generic approaches to model versioning are often not suited when it comes to specific modeling languages. For

instance in the case of process modeling languages, generic approaches do not consider the semantics of concrete modeling languages. As a consequence, the described shortcomings are obtained, such as the limitation on elementary differences or false-positive conflicts, since semantic equivalences between models remain undiscovered. We see this as a hint on limitations of generic approaches to model versioning.

During the abstraction of different concrete process modeling languages to our intermediate representation, we observed that current ways to specify the semantics of modeling languages in natural language hardens their understandability and results in mismatches due to their ambiguity. Precise and formal semantic definitions are urgently necessary, which can be specified, e.g. by applying the Dynamic Meta Modeling approach [Engels et al., 2000, Hausmann, 2005].

To completely support the development cycle of business-driven development as introduced in Section 2.3 in Chapter 2, models used from different development phases need to be synchronized. For instance, *analysis* models used in early development phases to describe what a process is doing on a high-level of abstraction, must be synchronized with *design* models, which have been enriched during development with, e.g. data flow and the underlying decision logic. For that purpose, so far no solution exists. We believe that the development of such a solution may benefit from our framework for process model change management as mentioned above.

Despite these open gaps, we believe that business process modeling and model-driven development are moving in the right direction. We are convinced that the issues described here will be addressed by suitable solutions in the course of the maturing of the areas.

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Evaluation Case Study

As an initial evaluation, we provide a case study that compares an approach to process model change management based on elementary change operations with our approach using compound change operations. In particular, we evaluate the effects of the change operations granularity on the detection of differences and the identification of dependencies and conflicts between change operations.

In the remainder, we first settle the scenario of our case study and introduce a set of elementary change operations together with configurations of the operations that lead to sequential dependencies and conflicts in Section A.1. Then, we use the set of elementary change operations to express the differences of our example. Finally, we compare the required user interventions in terms of work units to resolve selected differences, dependencies, and conflicts in a realistic example using compound change operations and elementary change operations.

A.1 Scenario of the Case Study

In our case study, we evaluate the impact of the change operation granularity on the computation of dependencies and conflicts between change operations and their consequences on the usability of a solution for process model change management. As an example, we use the process model versions presented in Figure A.1. These process model versions describe the handling of a claim in an insurance company. The source process model V was initially created and then stepwise refined by two different users into the versions V_1 and V_2 . These two descendant version shall be merged with respect to their common source version V into an integrated version V_M .

To compare the suitability of different change operation granularities for process model change management, we compute differences between the process model versions shown in Figure A.1 in terms of elementary change operations and in terms of compound change operations.

As introduced in Section 5.3 in Chapter 5, the set of compound change operations consists of the following operations: *InsertActivity*, *DeleteActivity*,

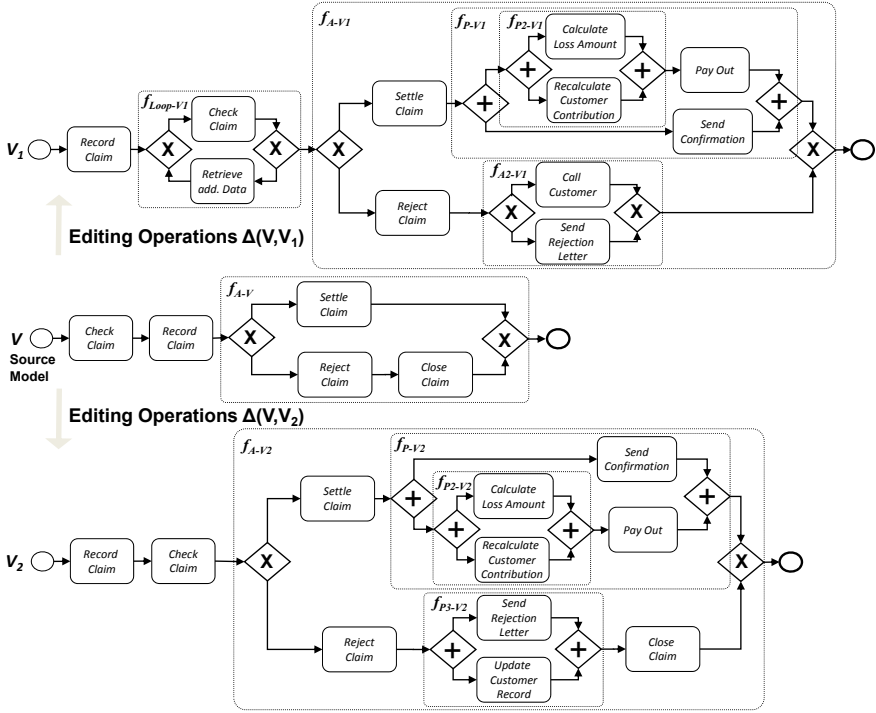


Fig. A.1 Process Model Versions used in the Case Study

MoveActivity, *InsertFragment*, *DeleteFragment*, *MoveFragment*, and *Convert-Fragment*. Figure A.2 shows the change logs $\Delta_{Compound}(V, V_1)$ and $\Delta_{Compound}(V, V_2)$ that represent the difference between the process models in Figure A.1 in terms of compound change operations.

- | | |
|--|---|
| <p>$\Delta_{Compound}(V, V_1)$:</p> <ul style="list-style-type: none"> 101.InsertCyclicFragment(V, $f_{Loop-V1}$, "Record Claim", XOR-Split$_{AV1}$) 102.MoveActivity(V, "Check Claim", Start, "Record Claim", XOR-Join$_{Loop}$, XOR-Split$_{Loop}$) 103.InsertActivity(V, "Ret. add. Data", XOR-Split$_{Loop}$, XOR-Join$_{Loop}$) 104.InsertCon.Fragment(V, f_{P-V1}, "Settle Claim", XOR-Join$_{AV1}$) 105.InsertActivity(V, "Send Confirmation", XOR-Split$_{P-V1}$, XOR-Join$_{P-V1}$) 106.InsertActivity(V, "Pay Out", AND-Split$_{P-V1}$, AND-Join$_{P-V1}$) 107.InsertCon.Fragment(V, f_{P2-V1}, AND-Split$_{P-V1}$, "Pay Out") 108.InsertActivity(V, "Calc. Loss Amount", AND-Split$_{P2-V1}$, AND-Join$_{P2-V1}$) 109.InsertActivity(V, "Recalc. Cust. Contrib.", AND-Split$_{P2-V1}$, AND-Join$_{P2-V1}$) 110.InsertAlt.Fragment(V, f_{A2-V1}, "Reject Claim", "Close Claim") 111.DeleteActivity(V, "Close Claim", XOR-Join$_{AV1}$, XOR-Join$_{AV1}$) 112.InsertActivity(V, "Call Customer", XOR-Split$_{A2-V1}$, XOR-Join$_{A2-V1}$) 113.InsertActivity(V, "Send Rej. Letter", XOR-Split$_{A2-V1}$, XOR-Join$_{A2-V1}$) | <p>$\Delta_{Compound}(V, V_2)$:</p> <ul style="list-style-type: none"> 201.MoveActivity(V, "Check Claim", Start, "Record Claim", "Record Claim", XOR-Split$_{AV2}$) 202.InsertCon.Fragment(V, f_{P-V2}, "Settle Claim", XOR-Join$_{AV2}$) 203.InsertActivity(V, "Send Confirmation", AND-Split$_{P-V2}$, AND-Join$_{P-V2}$) 204.InsertCon.Fragment(V, f_{P2-V2}, AND-Split$_{P-V2}$, AND-Join$_{P2-V2}$) 205.InsertActivity(V, "Calc. Loss Amount", AND-Split$_{P2-V2}$, AND-Join$_{P2-V2}$) 206.InsertActivity(V, "Recalc. Cust. Contrib.", AND-Split$_{P2-V2}$, AND-Join$_{P2-V2}$) 207.InsertActivity(V, "Pay Out", AND-Join$_{P2-V2}$, AND-Join$_{P2-V2}$) 208.InsertCon.Fragment(V, f_{P3-V2}, "Reject Claim", "Close Claim") 209.InsertActivity(V, "Update Cust. Record", AND-Split$_{P3-V2}$, AND-Join$_{P3-V2}$) 210.InsertActivity(V, "Send Rej. Letter", AND-Split$_{P3-V2}$, AND-Join$_{P3-V2}$) |
|--|---|

Fig. A.2 Compound Change Operations of our Example

The set of elementary change operations consists of the following four operations, as introduced in Section 5.2 in Chapter 5: *InsertNode*, *DeleteNode*, *InsertEdge*, and *DeleteEdge*. Using elementary change operations to express the

differences between the process models V , V_1 , and V_2 of our example (Figure 1.3) results in the change logs $\Delta_{Elementary}(V, V_1)$ and $\Delta_{Elementary}(V, V_2)$ given in Figure A.3.

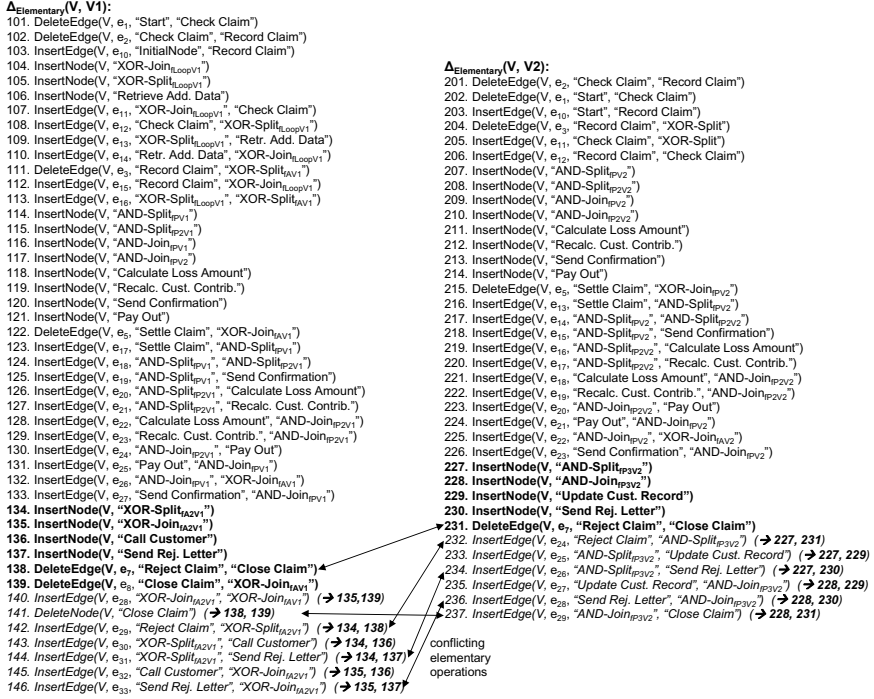


Fig. A.3 Elementary Change Operations of our Example with Dependencies and Conflicts for selected Operations

For each set of change operations, we compute dependencies and conflicts. In the case of compound change operations, we compute dependencies as introduced in Chapter 7 and conflicts by applying the approach presented in Chapter 9. In the case of elementary change operations, we present respective dependency and conflict matrices in the following.

Analogously to our set of compound change operations (see Chapter 7), we have formulated the elementary change operations in terms of graph transformation rules and have computed sequential dependencies and conflicts. Figure A.4 shows all configurations of elementary operations that lead to sequential dependencies. In general, two operations sequentially depend on each other if the application of one operation requires that the other one is applied before. For instance, there is a sequential dependency between $InsertNode(V, n)$ and $InsertEdge(V, e, s, t)$ if either the source s of the edge e is the newly inserted node n ($s = n$) or the target t of the edge e is the newly inserted node ($t = n$). The result of this dependency is that n needs to be inserted before the insertion of the edge e can be applied.

	InsertNode(V,b)	DeleteNode(V,b)	InsertEdge(V,e2,v,w)	DeleteEdge(V,e2,v,w)
Insert Node(V,a)	[IN(a), IN(b)]:	[IN(a), DN(b)]:	[IN(a), IE(e2)]: v = a w = a	[IN(a), DE(e2)]:
Delete Node(V,a)	[DN(a), IN(b)]:	[DN(a), DN(b)]:	[DN(a), IE(e2)]:	[DN(a), DE(e2)]:
InsertEdge(V,e1,x,y)	[IE(e1), IN(b)]:	[IE(e1), DN(b)]:	[IE(e1), IE(e2)]:	[IE(e1), DE(e2)]:
DeleteEdge(V,e1,x,y)	[DE(e1), IN(b)]:	[DE(e1), DN(X2)]: b = x b = y	[DE(e1), IE(e2)]: v = x w = y	[DE(e1), DE(e2)]:

Fig. A.4 Transformation Dependencies of Elementary Change Operations

Conflicts between elementary change operations, which can occur in three-way merge scenarios, are shown in Figure A.5. In general, two elementary change operations are conflicting if the application of one operation turns the other one inapplicable. Analogously to the syntax-based computation of conflicts between compound change operations, we determined critical pairs between two rule sets of elementary change operations and encoded conflicting situations in terms of change operation parameters. To give an example, two independently applied elementary change operations *DeleteNode(V,n)* and *DeleteNode(V,m)* are in conflict if $n = m$. In this case, the application of one of the operation turns the other one inapplicable.

	InsertNode(V,b)	DeleteNode(V,b)	InsertEdge(V,e2,v,w)	DeleteEdge(V,e2,v,w)
Insert Node(V,a)				
Delete Node(V,a)		b = a	v = a w = a	
InsertEdge(V,e1,x,y)		b = x b = y	(v = x & w ≠ y) (v ≠ x & w = y)	
DeleteEdge(V,e1,x,y)				e2 = e1

Fig. A.5 Conflicts between Elementary Change Operations

Dependencies and conflicts for selected change operations are visualized in Figure A.3. Dependencies are indicated directly behind the elementary operations, e.g. the application of Operation 143 requires that Operations 133 and 135 were applied earlier. Conflicts are represented by black arrows connecting operations in the

change logs. For instance, the two *DeleteEdge* Operations 138 and 231 are in conflict, because they delete the same link ($L2 = L1$).

Figure A.6 visualizes a merged process model V_M that can be obtained by applying a combination of operations contained in the change logs $\Delta(V, V1)$ and $\Delta(V, V2)$ on the source process V . Changes to the original source process model V (introduced in Figure 1.3) are highlighted.

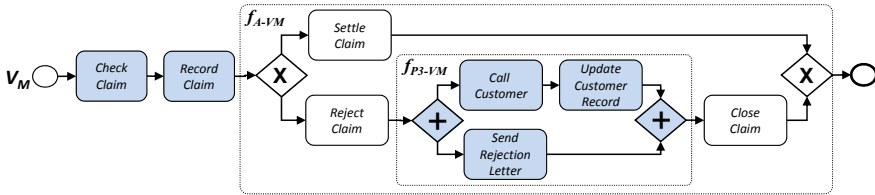


Fig. A.6 Merged Process Model

In the following two subsections, we measure the required user intervention to obtain the merged process model V_M . Along the change application, we measure the required user interventions in terms of work units for the inspection of conflicts and the application of change operations. For simplicity, we assume that each inspection and application of an operation, dependency or conflict requires one work unit. In Section A.2, we merge V_1 and V_2 into V_M using compound change operations. In Section A.3, V_M is created by applying elementary change operations.

A.2 Difference and Conflict Resolution Using Compound Change Operations

The compound change operations, which need to be applied on the source process model V in order to create the merged process model V_M , are represented in Figure A.7.

In *Step 1* the conflict between the insertions of the two fragments f_{A2V1} and f_{P3V2} is inspected (one work unit). We assume that a user decides to resolve the conflict by a unification of the compound change operations and inserts the fragment f_{P3V2} in the source process model V_M and naming it f_{P3V_M} (done in *Step 2*, one work unit). Thereby, the position parameters of the remaining operations 111-113 and 209-210 in the change logs are

Case Study: Difference and Conflict Resolution using Compound Change Operations		Work Units
Step 1	Inspect conflict between the insertions of the fragments f_{A2V1} and f_{P3V2}	1
Step 2	Resolve conflict through unification	1
Step 2	Inspect conflict between "Call Customer" and "Update Customer Record"	1
Step 3	Resolve conflict by applying both operations	2
Step 3	Inspect remaining operations that both insert "Send Rej. Letter"	1
Step 4	Apply only right hand operation	1
		7

Fig. A.8 Required User Intervention using Compound Change Operations

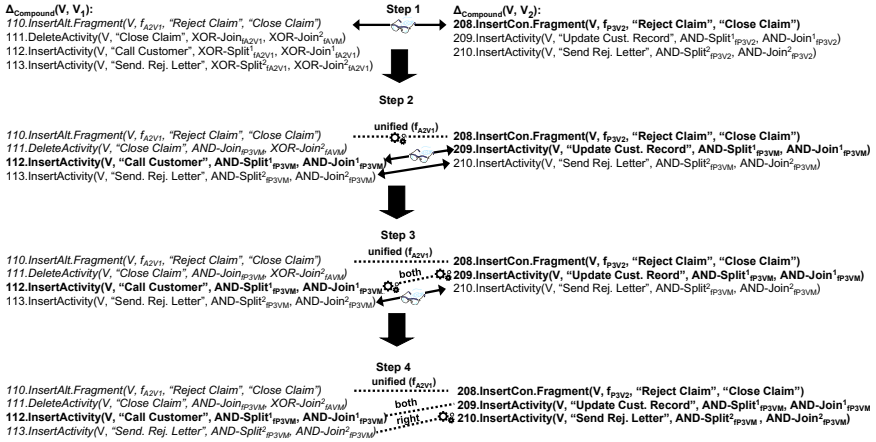


Fig. A.7 Process Merging using Compound Change Operations

adapted to reflect the entry (*AND-Split*) and exit (*AND-Join*) of fragment f_{P3VM} . Further, the conflict between the insertions of "Call Customer" and "Update Customer Record" is inspected and it is decided to apply both operations in *Step 3*. The inspection and the application of both operations increases the work unit counter by three.

Finally, the remaining operations 113 and 210 are inspected that both insert the Activity "Send Rej. Letter" (one work unit) and only the right hand operation 210 is applied (one work unit). In total a user intervention of seven work units were necessary to obtain the merged process model V_M .

A.3 Difference and Conflict Resolution Using Elementary Change Operations

In contrast to compound change operations, a conflict-driven approach for the resolution of differences using elementary change operations is not applicable at once. Since most of the conflicting elementary operations, e.g. all *InsertEdge* operations, require other operations to be applied before. However, we suggest an element-driven approach for elementary change operations that starts with the decision, which elements shall be inserted or deleted.

Figure A.10 visualizes the parts of the elementary change logs that need to be considered in order to create the merged process model V_M . We start with an inspection of all *InsertNode* and *DeleteNode* operations in *Step 1* (resulting in nine work units). Then in *Step 2*, we insert the five required elements (five work units).

Afterwards, the remaining link operations need to be inspected in order to identify the operations that are applicable with respect to the inserted and deleted elements. Since this step is straight-forward computation, we assume that applicable link operations are determined automatically and produces no costs.

In *Step 3*, the applicable link operations are applied. In our example, these are the Operations 138, 232, and 234 - 237, increasing the work unit counter by six. Finally, the process model needs to be connected manually in *Step 4*, since not all elements are connected so far. That means, a user has to insert two edges by hand in order to complete the concurrent structure in the merged process model V_M . Overall, by using elementary change operations a user has to perform 22 work units to merge the process model versions V_1 and V_2 into V_M .

Case Study: Difference and Conflict Resolution using Elementary Change Operations, Insert/DeleteNode-Driven		Work Units
Step 1	Inspect all Insert- and DeleteNode operations	9
Step 2	Apply five InsertNode operations (AND-Split, AND-Join, Call Customer, Send Rej. Letter, Update Cust. Record)	5
	Inspect Insert/DeleteEdge operations (edge operations that become inapplicable due to in Step 2 applied node insertions can be computed – inspections are not counted)	(15)
Step 3	Apply edge operations 138, 232, 234-237	6
Step 4	Manually connect the process model with five edges	2
		22

Fig. A.9 Required User Intervention using Elementary Change Operations

A.4 Summary and Discussion

In our evaluation, we have shown that an approach based on compound change operations leads to less conflicts and dependencies than an approach relying on elementary change operations, illustrated in Table A.11 for our example introduced in Figure A.1.

Another goal was to show that our approach also leads to less required user intervention than an approach based on elementary operations. We can distinguish between the application of operations, conflict examination and conflict resolution. On average, the number of elementary change operations is three times the number of compound change operations, which makes the resolution of differences to merge models more complex. For the application of operations, the user intervention triples (unless further optimizations are implemented for the elementary operations).

The relation of conflicts for the elementary and compound operations cannot be estimated, since it depends completely on the underlying models. In our running example, we obtain the number of conflicts as indicated in the Figure A.11.

In general, the user interventions required for conflict resolution depends on the support given by the modeling tool. However, our example shows that computed dependencies and conflicts between elementary change operations do not really help a user to merge different versions of a process model. Firstly, dependencies between related elementary change operations are not always given. For instance, the information, which pair of gateways form a fragment and need to be inserted or deleted

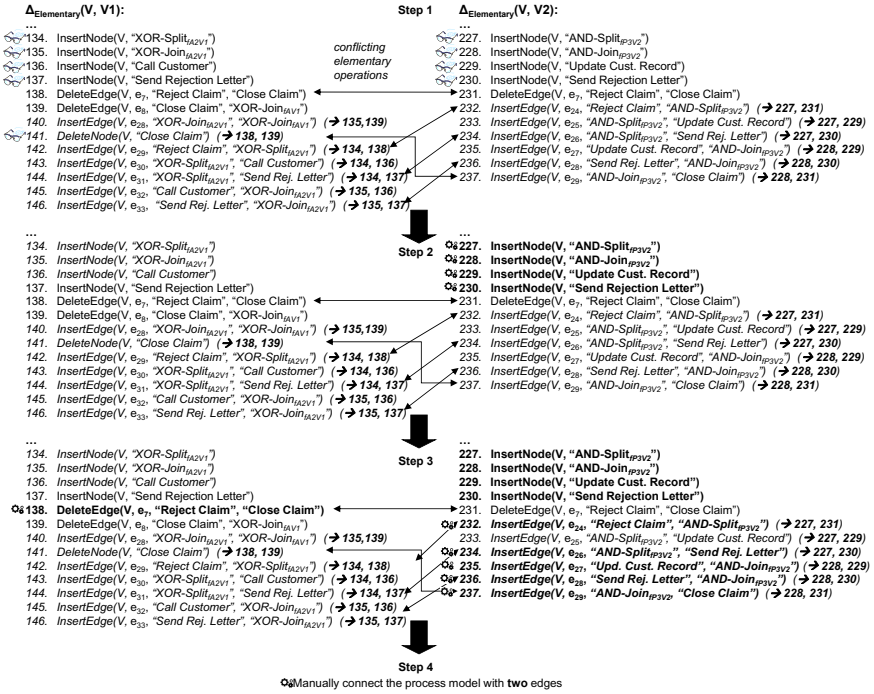


Fig. A.10 Process Merging using Elementary Change Operations

	Elementary Change Operations		Compound Change Operations	
	$\Delta_E(V, V1)$	$\Delta_E(V, V2)$	$\Delta_C(V, V1)$	$\Delta_C(V, V2)$
# of Change Operations	46	37	13	10
# of Dependencies	45	36	10	7
# of Conflicts	23		3	
# of Work Units for Sample Resolution	22		7	

Fig. A.11 Evaluation Results of the Case Study

together is not given and requires further computation on the process models. Secondly, the granularity of elementary change operations is on a too low level resulting in conflicts between operations those intention remains unclear. Most of the conflicts are between operations that modify links and these operations require other operations to be applied before. Overall, it can be concluded that the user intervention required when compound change operations are used is much less than when using elementary change operations.

B

Dependency and Conflict Matrices

B.1 Dependency and Conflict Matrices for Compound Change Operations

Figure B.1 and B.2 show configurations of compound operations that lead to transformation dependencies as introduced in Chapter 7. For a given fragment f , $entry(f)$ and $exit(f)$ are used to denote the entry or exit nodes of a fragment as described in Chapter 3. Further, for a given node n or a fragment f , $parent(n)$ or $parent(f)$ denotes the parent fragment of n or f .

An entry in the transformation dependency matrix is read as follows: The application of an operation in a column is dependent on the prior application of the operation in the row if the conditions specified in the entry are met. For instance, the operations $InsertActivity(V, b, v, w)$ depends on operation $InsertActivity(V, a, x, y)$ if $v = a \ \& \ w = y$ or $v = x \ \& \ w = a$. In other words, $InsertActivity(V, a, x, y)$ either inserts the predecessor ($v = a$) or the successor ($w = a$) of the activity b , which is inserted by the operation $InsertActivity(V, b, v, w)$.

Similarly, configurations of compound operations that lead to syntactic conflicts are given in Figure B.3.

The entries of the matrices in Figure B.1, B.2, and B.3 have been partially computed using the critical pair analysis of the AGG tool [Taentzer, 2003].

Transformation Dependencies (V,a,x,y)	InsertActivity (V,b,v,w)	DeleteActivity (V,b,v,w)	MoveActivity (V,b,ov,ow,nv,nw)	InsertFragment (V,f2,v,w)	DeleteFragment (V,f2,v,w)	MoveFragment (V,f2,ov,ow,nv,nw)	ConvertFragment (V,f2,fc,v,w)
InsertActivity (V,a,x,y)	[I(A), I(A)(b): (v = a & w = y) (v = x & w = a)]	[I(A), DA(b): (b = x & w = a) (v = a & b = y)]	[I(A), MA(b): (nv = x & nw = a) (nv = a & nw = y) (b = x & ow = a)]	[I(A), IF(f2): (v = a & w = y) (v = x & w = a)]	[I(A), DF(f2): (v = a & entry(f2) = y) (exit(f2) = x & w = a)]	[I(A), MF(f2): (nv = x & nw = a) (nv = a & nw = y) (ov = a & entry(f2) = y) (exit(f2) = x & ow = a)]	[I(A), CF(f2): (v = a & entry(f2) = w) (exit(f2) = x & w = a)]
DeleteActivity (V,a,x,y)	[DA(a), DA(b): (v = x & b = y) (b = x & w = y)]	[DA(a), DA(b): (v = x & b = y) (b = x & w = y)]	[DA(a), MA(b): (nv = x & nw = y) (ov = x & b = y) (b = x & ow = y)]	[DA(a), IF(f2): (v = x & w = y)]	[DA(a), DF(f2): (v = x & entry(f2) = y) (exit(f2) = x & w = y) (entry(f2) = y & exit(f2) = y)]	[DA(a), MF(f2): (nv = x & nw = y) (ov = x & entry(f2) = y) (exit(f2) = x & ow = y)]	[DA(a), CF(f2): (v = x & entry(f2) = y) (exit(f2) = x & w = y) (f2 = parent(x) & f2 = parent(y))]
MoveActivity (V,a,ox,oy,nx,ny)	[MA(a), I(A)(b): (v = ox & w = oy) (v = a & w = ny) (v = nx & w = a)]	[MA(a), DA(b): (v = ox & b = oy) (b = ox & w = oy) (v = nx & w = a) (v = a & w = ny)]	[MA(a), MA(b): (nv = ox & nw = oy) (ov = ox & b = oy) (b = ox & ow = oy) (ov = a & b = nx) (b = nx & ow = a) (nv = nx & nw = a) (nv = a & nw = ny)]	[MA(a), IF(f2): (v = ox & w = oy) (v = a & w = ny) (v = nx & w = a)]	[MA(a), DF(f2): (v = ox & entry(f2) = oy) (exit(f2) = ox & w = oy) (v = a & entry(f2) = ny) (exit(f2) = nx & w = a) (entry(f2) = ox & exit(f2) = oy)]	[MA(a), MF(f2): (nv = ox & nw = oy) (ov = ox & entry(f2) = oy) (exit(f2) = ox & ow = oy) (ov = a & entry(f2) = nx) (exit(f2) = nx & ow = a) (nv = nx & nw = a) (nv = a & nw = ny)]	[MA(a), CF(f2): (v = ox & entry(f2) = oy) (exit(f2) = ox & w = oy) (v = a & entry(f2) = ny) (exit(f2) = nx & w = a) (f2 = parent(ox) & f2 = parent(oy))]

Fig. B.1 Transformation Dependencies of Compound Change Operations (Part 1/2)

Transformation Dependencies (V,b,v,w)	InsertActivity (V,b,v,w)	DeleteActivity (V,b,v,w)	MoveActivity (V,b,ov,nv,nw)	InsertFragment (V,z,v,w)	DeleteFragment (V,z,v,w)	MoveFragment (V,z,ov,nv,nw)	ConvertFragment (V,z,fc,ov,nw)
InsertFragment (V,f1,x,y)	[IF(f1), IA(b): (v = x & w = entry(f1)) (v = entry(f1) & w = y) (v = entry(f1) & w = exit(f1))]	[IF(f1), DA(b): (b = x & w = entry(f1)) (v = exit(f1) & b = y)]	[IF(f1), MA(b): ov = exit(f1) ow = entry(f1) nv = entry(f1) nw = exit(f1) nw = entry(f1) nw = exit(f1)]	[IF(f1), IF(2): (v = x & w = entry(f1)) (v = exit(f1) & w = y) (v = entry(f1) & w = exit(f1))]	[IF(f1), DF(2): (v = exit(f1) & entry(2) = y) (exit(2) = x & w = entry(f1))]	[IF(f1), MF(2): (ov = exit(f1) & entry(2) = y) (exit(2) = x & ow = entry(f1)) (nv = x & nw = entry(f1)) (nv = exit(f1) & nw = y)]	[IF(f1), CF(2): (v = exit(f1) & entry(2) = y) (exit(2) = x & w = entry(f1))]
DeleteFragment (V,f1,x,y)	[DF(f1), IA(2): (v = x & w = y)]	[DF(f1), DA(b): (v = x & b = y) (b = x & w = y)]	[DF(f1), MA(b): (ov = x & b = y) (b = x & ow = y) (nv = x & nw = y)]	[DF(f1), IF(2): (v = x & w = y)]	[DF(f1), DF(2): (v = x & entry(2) = y) (exit(2) = x & w = y)]	[DF(f1), MF(2): (ov = x & entry(2) = y) (exit(2) = x & ow = y) (nv = x & nw = y)]	[DF(f1), CF(2): (v = x & entry(2) = y) (exit(2) = x & w = y) (f2 = parent(x) & f2 = parent(y))]
MoveFragment (V,f1,ox,oy,nx,ny)	[MF(f1), IA(b): (v = ox & w = oy) (v = nx & w = entry(f1)) (v = exit(f1) & w = ny)]	[MF(f1), DA(b): (v = ox & b = oy) (b = ox & w = oy) (b = ox & w = entry(f1)) (v = exit(f1) & b = ny)]	[MF(f1), MA(b): (nv = ox & nw = oy) (ov = ox & b = oy) (b = ox & ow = y) (ov = exit(f1) & b = ny) (b = nx & ow = entry(f1)) (nv = nx & nw = entry(f1)) (nv = exit(f1) & nw = ny)]	[MF(f1), IF(2): (v = ox & w = oy) (v = nx & w = entry(f1)) (v = exit(f1) & w = ny)]	[MF(f1), DF(2): (v = ox & entry(2) = oy) (exit(2) = ox & w = oy) (exit(2) = ox & w = entry(f1)) (v = exit(f1) & entry(2) = ny)]	[MF(f1), MF(2): (nv = ox & nw = oy) (ov = ox & entry(2) = oy) (exit(2) = ox & w = oy) (ov = exit(f1) & entry(2) = ny) (exit(2) = nx & ow = entry(f1)) (nv = nx & nw = entry(f1)) (nv = exit(f1) & nw = ny)]	[MF(f1), CF(2): (v = ox & entry(2) = oy) (exit(2) = ox & w = oy) (v = exit(f1) & entry(2) = ny) (exit(2) = nx & ow = entry(f1)) (f2 = parent(ox) & f2 = parent(oy))]
ConvertFragment (V,f1,fc,xy)	[CF(f1), IA(b): (v = x & w = entry(fc)) (v = exit(fc) & w = y) (parent(w) = fc & parent(w) = fc)]	[CF(f1), DA(b): (v = exit(fc) & b = y) (b = x & w = entry(fc))]	[CF(f1), MA(b): (nv = x & nw = entry(fc)) (nv = exit(fc) & nw = y) (b = x & ow = entry(fc)) (parent(nv) = fc & parent(nw) = fc)]	[CF(f1), IF(2): (v = x & w = entry(fc)) (v = exit(fc) & w = y) (parent(w) = fc & parent(w) = fc)]	[CF(f1), DF(2): (v = exit(fc) & entry(2) = y) (exit(2) = x & w = entry(fc))]	[CF(f1), MF(2): (nv = x & nw = entry(fc)) (nv = exit(fc) & nw = y) (ov = exit(fc) & entry(2) = y) (parent(nv) = fc & parent(nw) = fc)]	[CF(f1), CF(2): (v = entry(fc) & entry(2) = y) (exit(2) = x & w = entry(fc))]

Fig. B.2 Transformation Dependencies of Compound Change Operations (Part 2/2)

Syntactic Conflicts	InsertActivity (V,b,v,w)	DeleteActivity (V,b,v,w)	MoveActivity (V,b,ov,ow,nv,nw)	InsertFragment (V,f2,v,w)	DeleteFragment (V,f2,v,w)	MoveFragment (V,f2,ov,ow,nv,nw)	ConvertFragment (V,f2,f2c,v,w)
InsertActivity (V,a,x,y)	(b ≠ a & v = x & w = y) Different elements are inserted at same position		(nv = x & nw = y) a is inserted and b is moved to same position	(v = x & w = y) a and f2 are inserted at same position	f2 = parent(a) a is inserted into deleted fragment f2	(nv = x & nw = y) a is inserted and f2 is moved to same position	f2 = parent(x) & f2 = parent(y) x and y may be deleted during the conversion of fragment f2
DeleteActivity (V,a,x,y)							
MoveActivity (V,a,ox,oy,nx,ny)	(v = nx & w = ny) b is inserted and a is moved to same position		(nv = nx & nw = ny) a and b are moved to same position	(v = nx & w = ny) f2 is inserted and a is moved to same position	f2 = parent(a) a is moved into deleted fragment f2	(nv = nx & nw = ny) a and f2 are moved to same position	f2 = parent(nx) & f2 = parent(ny) nx and ny may be deleted during the conversion of fragment f2
InsertFragment (V,f1,x,y)	(v = x & w = y) Different elements (f1 and b) are inserted at same position		(nv = x & nw = y) f1 is inserted and b is moved to same position	(v = x & w = y) f1 and f2 are inserted at same position	f2 = parent(f1) f1 is inserted into deleted fragment f2	(nv = x & nw = y) f1 is inserted and f2 is moved to same position	f2 = parent(x) & f2 = parent(y) x and y may be deleted during the conversion of fragment f2
DeleteFragment (V,f1,x,y)	parent(b) = f1 b is inserted into deleted fragment f1		parent(b) = f1 b is moved into deleted fragment f1	parent(f2) = f1 f2 is inserted into deleted fragment f1		parent(nv) = f1 & parent(nw) = f1 f2 is moved into deleted fragment f1	
MoveFragment (V,f1,ox,oy,nx,ny)	(v = nx & w = ny) b is inserted and f1 is moved to same position		(nv = nx & nw = ny) b and f1 are moved to same position	(nv = x & nw = y) f2 is inserted and f1 is moved to same position	f2 = parent(f1) f1 is moved into deleted fragment f2	(nv = nx & nw = ny) f1 and f2 are moved to same position	f2 = parent(nx) & f2 = parent(ny) nx and ny may be deleted during the conversion of fragment f2
ConvertFragment (V,f1,f1c,x,y)	parent(v) = f1 & parent(w) = f1 v and w may be deleted during the conversion of fragment f1		parent(nv) = f1 & parent(nw) = f1 nv and nw may be deleted during the conversion of fragment f1	parent(v) = f1 & parent(w) = f1 v and w may be deleted during the conversion of fragment f1		parent(nv) = f1 & parent(nw) = f1 nv and nw may be deleted during the conversion of fragment f1	(f2 = f1 & v = x & w = y) f1 and f2 may be converted into syntactically different fragments

Fig. B.3 Syntactic Conflicts using Dynamic Specification of Compound Change Operations