Towards Vertical Impact Analysis of UML Models

By:

Tao Yue

A thesis submitted to the Faculty of Graduate Studies and Research

In partial fulfillment of the requirements for the degree of

Master of Applied Science

Ottawa-Carleton Institute of Electrical and Computer Engineering

Department of Systems and Computer Engineering

Carleton University

Ottawa, Ontario, Canada

July 2006

Copyright © 2006 by Tao Yue

Library and
Archives Canada

Bibliothèque et
Archives Canada

Published Heritage
Branch

Direction du
Patrimoine de l'édition

395 Wellington Street
Ottawa ON K1A 0N4
Canada

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

ISBN: 978-0-494-18337-3

Our file Notre référence

ISBN: 978-0-494-18337-3

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protègent cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Abstract

During iterative, UML-based software development, various UML diagrams, modeling the same system at different levels of abstractions are developed. These models must remain consistent when changes are performed. In this context, we refine the notion of impact analysis and distinguish horizontal impact analysis—that focuses on changes and impacts at one level of abstraction, and vertical impact analysis—that focuses on changes at one level of abstraction and their impacts on another level. We propose a vertical impact analysis approach for UML 2.0 models which is based on a careful formalization of changes to those models, refinements which are composed of those changes, and traceability links corresponding to refinements. We show how actual refinements and corresponding traceability links are formalized using the Object Constraint Language. Tool support and an initial case study are also described.

Acknowledgments

First, I would like to sincerely express my thanks to Dr. Briand and Dr. Labiche for their help and guidance throughout my research. I have learnt a great deal from them.

I would like to thank Maged Elaasar for his help, encouragement and patience.

I would like to thank everyone at the SQUALL Lab for mutual support, inspiration and encouragement.

I would like my thesis to be acknowledged in memory of my dear father who is always in my deep heart and with warmest thanks to my mother, my brothers and sisters for their unconditional support, encouragement and love.

A special thanks goes to my husband, Wenjun Bian, for his constant support, care and love. Without him, I could not accomplish this thesis.

Last, but not least, I would like to thank all my friends for their support and encouragement.

Table of Contents¹

ABSTRACT.....	3
ACKNOWLEDGMENTS.....	4
TABLE OF CONTENTS.....	5
LIST OF FIGURES	7
LIST OF TABLES	10
1 INTRODUCTION.....	11
2 DEFINITIONS AND CONCEPTS.....	14
2.1 VIEWS.....	14
2.2 IMPACT ANALYSIS.....	14
2.3 ATOMIC CHANGE	15
2.4 REFINEMENT.....	15
2.5 TRACEABILITY AND TRACEABILITY LINK.....	16
3 STATE OF THE ART	17
3.1 CLASSIFYING AND IDENTIFYING REFINEMENT.....	18
3.2 CAPTURING TRACEABILITY INFORMATION.....	23
3.3 PERFORMING IMPACT ANALYSIS	25
3.4 SUMMARY.....	33
4 APPROACH TAKEN.....	34
4.1 METAMODELS.....	35
4.2 TAXONOMY OF ATOMIC CHANGES	44
4.3 TAXONOMY OF REFINEMENTS	45
4.4 REFINEMENT/TRACEABILITY LINK SPECIFICATION	46
5 AUTOMATION	51
5.1 THE ECLIPSE PLATFORM.....	52
5.2 RATIONAL SOFTWARE ARCHITECT	55
5.3 EMF MODELS IN VIATool.....	56
6 CASE STUDY	59
6.1 DETAILASSOFUNCTIONALITY	60
6.2 TURNATTRIINTOCLASS	62
6.3 ASSOENDMULTIPLICITYREF.....	64

¹ A complete table of contents can be found at the very end of the document.

6.4	ASSOENDISNAVIGABLEREF	66
6.5	ASSOENDTYPEREF	67
7	CONCLUSION.....	69
	REFERENCES	72
APPENDIX A	METAMODEL	75
APPENDIX B	DICTIONARY FOR METAMODEL.....	76
APPENDIX C	EXAMPLE ATOMIC CHANGES.....	88
APPENDIX D	TAXONOMY FOR ATOMIC CHANGES	95
APPENDIX E	TAXONOMY AND FORMALIZATION FOR REFINEMENTS.....	101
APPENDIX F	FORMALIZATION OF PATH.....	191

List of Figures

Figure 1 Horizontal vs. vertical impact analysis	15
Figure 2 Example merge conflict (from [26])	18
Figure 3 Transformation rules for creation and deletion	20
Figure 4 Example the approach of Shen et al.	21
Figure 5 Example the possible improvement for the approach proposed in [4]	26
Figure 6 Example dependency analysis – code	27
Figure 7 Example dependency analysis - dependency graph	28
Figure 8 The conceptual metamodel	37
Figure 9 Example composite refinement - original class diagram (from [31])	38
Figure 10 Example composite refinement - refined class diagram (from [31])	38
Figure 11 The metamodel for atomic change	39
Figure 12 The constraints of the metamodel for atomic change	40
Figure 13 The metamodel for traceability link	42
Figure 14 The metamodel for performing vertical impact analysis	44
Figure 15 Taxonomy of Atomic Changes	45
Figure 16 Taxonomy of Refinements	45
Figure 17 Refinement ClassIsAbstractRef	47
Figure 18 Refinement MovedAttributeRef	48
Figure 19 Refinement TopDownGen	50
Figure 20 VIATool Architecture Overview	52
Figure 21 Creating a new refinement repository model	57
Figure 22 Creating a TopDownGen refinement object	57
Figure 23 Creating new objects using the editor	58
Figure 24 Editing Attributes and Associations using the editor	58
Figure 25 Case Study (from [20])	60
Figure 26 Refinement DetailAssoFunctionality	62
Figure 27 Refinement TurnAttriIntoClass	64
Figure 28 Refinement AssoEndMultiplicityRef	65
Figure 29 Refinement AssoEndIsNavigableRef	67
Figure 30 Refinement AssoEndTypeRef	68
Figure 31 The complete metamodel	75
Figure 32 Complete Taxonomy for Atomic Changes – Top Level	98
Figure 33 Taxonomy for Atomic Changes of Type ChangedClass	99
Figure 34 Taxonomy for Atomic Changes of Type ChangedAttribute	99
Figure 35 Taxonomy for Atomic Changes of Type ChangedOperation	99
Figure 36 Taxonomy for Atomic Changes of Type ChangedAssociation	99
Figure 37 Taxonomy for Atomic Changes of Type ChangedGeneralization	99
Figure 38 Taxonomy for Atomic Changes of Type ChangedInterface	100
Figure 39 Taxonomy for Atomic Changes of Type ChangedDependency	100
Figure 40 Taxonomy for Refinements - Top Level	101
Figure 41 Taxonomy for Refinement of Type Class->Classes+Rels	102

Figure 42 TopDownGen - Specification	104
Figure 43 Refinement TopDownGen	105
Figure 44 TopDownGen - Example	106
Figure 45 TopDownCom - Specification	107
Figure 46 Refinement TopDownCom	108
Figure 47 TopDownCom - Example	109
Figure 48 ExtractClass - Specification	110
Figure 49 Refinement ExtractClass	112
Figure 50 ExtractClass - Example	113
Figure 51 ExtractSubclass - Specification	114
Figure 52 Refinement ExtractSubclass	115
Figure 53 ExtractSubclass - Example	116
Figure 54 TurnAttriIntoClass - Specification	117
Figure 55 Refinement TurnAttriIntoClass	118
Figure 56 TurnAttriIntoClass - Example	119
Figure 57 TurnAttriIntoSubclass - Specification	120
Figure 58 Refinement TurnAttriIntoSubclass	121
Figure 59 TurnAttriIntoClass - Example	122
Figure 60 TurnOprIntoRel - Specification	123
Figure 61 Refinement TurnOprIntoRel	124
Figure 62 Taxonomy for Refinements of Type Classes+Rels->Class	125
Figure 63 CollapseHierarchy - Specification	126
Figure 64 Refinement CollapseHierarchy	127
Figure 65 InlineClass - Specification	128
Figure 66 Refinement InlineClass	129
Figure 67 InlineClass - Example	130
Figure 68 CollapseHierarchyIntoAttri - Specification	131
Figure 69 Refinement CollapseHierarchyIntoAttri	132
Figure 70 TurnClasses+AssoIntoAttri - Specification	133
Figure 71 Refinement TurnClasses+AssoIntoAttri	134
Figure 72 TurnClasses+RelsIntoConstructor - Specification	135
Figure 73 Refinement TurnClasses+AssoIntoConstructor	136
Figure 74 Taxonomy for Refinements of Type Classes+Rels->Classes+Rels	137
Figure 75 PullUpAttribute - Specification	138
Figure 76 Refinement PullUpAttribute	140
Figure 77 PullUpOperation - Specification	141
Figure 78 Refinement PullUpOperation	143
Figure 79 PushDownAttribute - Specification	144
Figure 80 Refinement PushDownAttribute	145
Figure 81 PushDownOperation - Specification	146
Figure 82 Refinement PushDownOperation	147
Figure 83 EliminateDupliByInheritance - Specification	148

Figure 84 (a) Refinement EliminateDupliByInheritance (part A)	150
Figure 85 (b) Refinement EliminateDupliByInheritance (part B)	151
Figure 86 EliminateDupliByComposition - Specification.....	152
Figure 87 (a) Refinement EliminateDupliByComposition (part A)	154
Figure 88 (b) Refinement EliminateDupliByComposition (part B).....	155
Figure 89 SplitSubclass – Specification	156
Figure 90 Refinement SplitSubclass.....	158
Figure 91 Taxonomy for Refinements of Type Rel->Classes+Rels.....	159
Figure 92 DetailAssoFunctionality – Specification.....	160
Figure 93 Refinement DetailAssoFunctionality	162
Figure 94 Example DetailAssoFunctionality – the original class diagram.....	163
Figure 95 Example DetailAssoFunctionality – the refined class diagram.....	163
Figure 96 AddBridgeClass - Specification.....	164
Figure 97 Refinement AddBridgeClass.....	166
Figure 98 ByBridgeClass - Specification.....	167
Figure 99 Refinement ByBridgeClass	169
Figure 100 Example ByBridgeClass – the original class diagram	170
Figure 101 Example ByBridgeClass – the refined class diagram.....	170
Figure 102 AssoRefUsingAssociationClass - Specification	171
Figure 103 Refinement AssoRefUsingAssociationClass	172
Figure 104 Taxonomy for Refinements of Type Classes+Rels->Rel.....	173
Figure 105 ReplaceAssociationClassWithAsso - Specification	173
Figure 106 Refinement ReplaceAssociationClassWithAsso	175
Figure 107 Taxonomy for Refinements of Type Rels->Rel.....	176
Figure 108 RefAssoesIntoAssoSuperclassAndClient - Specification	176
Figure 109 Refinement RefAssoesIntoAssoSuperclassAndClient (part A)	178
Figure 110 Refinement RefAssoesIntoAssoSuperclassAndClient (part B).....	179
Figure 111 Taxonomy for Refinements of Type Rel->Rels.....	180
Figure 112 RefAssoIntoAssoesSubclassesAndClient – Specification.....	180
Figure 113 Refinement RefAssoIntoAssoesSubclassesAndClient (part A)	182
Figure 114 Refinement RefAssoIntoAssoesSubclassesAndClient (part B).....	183
Figure 115 Taxonomy for Refinements of Type InterfaceRefinement.....	184
Figure 116 ExtractInterface - Specification.....	185
Figure 117 Refinement ExtractInterface.....	186
Figure 118 ReplaceClassWithInterface - Specification.....	187
Figure 119 Refinement ReplaceClassWithInterface	188
Figure 120 ReplaceInterfaceWithSuperclass - Specification.....	189
Figure 121 Refinement ReplaceInterfaceWithSuperclass	190
Figure 122 The metamodel for Path	191

List of Tables

Table 1 The comparison of existing impact analysis approaches.....32

1 INTRODUCTION

The use of the Unified Model Language (UML) [29] for complex systems leads to a large number of inter-dependent UML diagrams that have to be consistent, e.g., the operations used in sequence diagrams must be defined in class diagrams. Furthermore, recent development methodologies, such as the Rational Unified Process [19], promote successive modeling iterations evolving and refining models until the final product is complete. As a result, for a specific system, different versions of the same UML models are produced at different levels of abstraction at successive points in time. In the simplest case, one can consider two standard analysis and design abstraction levels [5]. An iterative development process should ensure that these two models remain consistent as they are incrementally refined and changed.

Using and updating these different models should be supported by some tool infrastructure, and one way to cope with the maintenance of such models is to comply with the Model Driven Architecture (MDA) Framework [18]. According to this framework, a platform independent model (PIM)—the analysis model—is (automatically) transformed into a platform specific model (PSM)—the design model, which is itself (automatically) transformed into code. To allow (fully) automated transformations, MDA requires that tools “maintain the relationship between PIM and PSM, even when changes to the PSM are made. Changes in the PSM will thus be reflected in the PIM, and high-level documentation will remain consistent with the actual code.” [18] In practice, when such transformations are not (fully) automated, an essential requirement is that some form of traceability between the models must be created and maintained and support needs to be provided to facilitate the change of a PSM model when its corresponding PIM model is changed.

With the evolution of software systems, UML models undergo changes that address changed requirements and error corrections. If a change takes place at the higher, most abstract modeling level (e.g., analysis model, or original model version), caused for example by changed requirements, it will lead to subsequent changes on model elements

at lower modeling levels (e.g., design model, or refined model version). Similarly, if change takes place at the lower modeling levels, caused for example by some error correction, it will lead to subsequent changes on model elements at higher modeling levels.

Impact analysis is defined in [2] as the process of “identifying the potential consequences of a change, and estimating what needs to be modified to accomplish that change.” In the context of UML-based iterative development, we refine this notion and distinguish Horizontal Impact Analysis (HIA) from Vertical Impact Analysis (VIA). HIA focuses on changes and impacts at one level of abstraction, and corresponds to what people have generally been doing (e.g., [3, 4]), whereas VIA focuses on changes at one level of abstraction and their impacts at another level of abstraction. (This is similar to the notion of horizontal and vertical consistency between models [13].)

Both HIA and VIA require some level of traceability. Traceability is “the ability to trace between software artifacts generated and modified during the software product life cycle.” [2] In the case of vertical impact analysis, traceability must exist between model elements at the more abstract (analysis) level and model elements at the more refined (design) level.

In this thesis we describe an approach to support, in a semi-automated way, the vertical impact analysis of UML models and we formalize the notions of traceability (link) and refinement in that specific context. Our approach is motivated by two objectives: (1) Specify, in an unambiguous manner, possible types of refinements and traceability rules, (2) Facilitate its automation based on state-of-the-art, industry-strength modeling technology. An overview of the prototype tool implementing the approach and an initial case study are presented in this thesis as well.

This work’s main contribution is a methodology and automation strategy for establishing traceability links between two UML models at different levels of abstraction. Another contribution is that the methodology is formalized using metamodel and constraints, using the UML and the OCL, respectively. This has the advantage of facilitating the automation using available, industry modeling technology. In order to automatically

identify refinements, we provide a systematic and hierarchical classification for class diagram refinement which allows us to clearly define and formalize class diagram refinements as well as the corresponding traceability links. We made an effort to be as systematic as possible and also describe a mechanism to extend this classification. Another contribution towards an ease of automation is that refinements are (semi-)automatically identified instead of requiring that the user explicitly provide them in his/her models. Yet another contribution is that we made a conscious effort to facilitate future extensions. Although this is a first step towards vertical impact analysis, our metamodel allows for new atomic changes, refinements, and UML models to be considered. It also already supports horizontal and vertical impact analysis concepts.

2 DEFINITIONS AND CONCEPTS

This section generally defines terms that will be used in the rest of the thesis. Some of these definitions will be refined in our specific context in subsequent sections.

2.1 Views

A view is a representation of an entire system from the perspective of a related set of concerns [25]. UML-based development uses different views to clarify different important aspects of a system. For example, class diagrams, interaction diagrams and statecharts are different views, which are used to describe structural and behavioral aspects of a system.

2.2 Impact analysis

Impact analysis can be used for planning changes, making changes and tracing the effect of changes, as a measure of the cost of a change, and to drive regression testing. The major goal of impact analysis is to identify the software artifacts impacted by a set of (proposed) changes.

As we mentioned in Section 1, we refine the notion impact analysis and distinguish horizontal impact analysis (HIA) from vertical impact analysis (VIA): HIA focuses on changes and impacts at one level of abstraction, whereas VIA focuses on changes at one level of abstraction and their impacts at another level of abstraction. This is illustrated in Figure 1 where, for the sake of simplicity, we consider two levels of abstraction. A change to a sequence diagram at the analysis (abstraction) level may impact other analysis diagrams: this is horizontal impact analysis. The same change may also impact model elements at the design (abstraction) level: this is vertical impact analysis.

Figure 1 Horizontal vs. vertical impact analysis

2.3 Atomic change

An atomic change is a unitary and primitive change applied to a UML model context that cannot be decomposed into smaller atomic changes. For example, “added an association” and “deleted an attribute from a class” are atomic changes. Atomic changes are the elementary steps by which one UML model evolves to another.

2.4 Refinement

Refinement is defined as “a software development technique in which data and processing steps are defined broadly at first and then further defined with increasing detail.” [24] In the context of UML modeling, we define refinement as means of transforming a more abstract model into a more concrete model. It can be any one of the following:

1. Refining an analysis model into a design model;
2. Refining a version of a UML model into the next version of the same UML model;

3. Refining a version of a class diagram (or sequence diagram, etc.) into the next version of the same class diagram (or sequence diagram, etc.);
4. Refining a version of part of a class diagram (or sequence diagram, etc.) into the next version of the same part of the class diagram (or sequence diagram, etc.).

2.5 Traceability and traceability link

As we mentioned in Section 1, traceability must be established between model elements at different levels of abstraction. In our context, we define a traceability link as a relationship that describes the traceability connection between a model element of one UML model and a model element of another UML model. In order to identify traceability links, we must either capture (during model modifications) or determine (by comparison of models) the intent of the designer that lay behind changes when models are refined. In other words, traceability links are derived from the identification of refinements.

3 STATE OF THE ART

Since vertical impact analysis is an important activity of model evolution, automatically supporting it is required for UML CASE tools. However, almost all existing tools contributing to software evolution are primarily targeted to source code. Model evolution (supported by UML CASE tools, for example) is much less sophisticated. With the growing application of UML, the techniques and tools for dealing with the model evolution are urgently needed.

Recall from Section 2 that, in order to perform vertical impact analysis, atomic changes must be recorded during the process of refining UML models. Then a refinement is derived from these atomic changes. Again, traceability links are established since we assume we specified which traceability links should be established for a specific refinement beforehand. Last, vertical impact analysis can be performed after traceability links are established.

In this section of the thesis we address three important areas where vertical impact analysis requires support:

1. Classifying and identifying refinement.
2. Capturing traceability information.
3. Performing vertical impact analysis.

There are many texts and papers published describing model evolution, however, capturing traceability information for the purpose of performing vertical impact analysis on UML models has not been directly addressed in the research literature. Besides, most of existing approaches classify refinements at the level of atomic changes, rather than more complex levels such as the refinements derived from several atomic changes. As a result, they are not amenable to capturing the user's intent.

This section of the thesis details the latest research in automated support of vertical impact analysis. It provides a structured and comprehensive survey on the three issues discussed above. Section 3.4 summarizes some important issues that have to be addressed.

3.1 Classifying and identifying refinement

In order to establish traceability links between model elements of two UML models at different levels of abstraction, we have to classify and identify refinements which are possibly made by the user in order to refine a UML model into another one. How to classify and identify refinements determines which kind of traceability information we can derive and which kind of vertical impact analysis result we can provide to the user.

3.1.1 Mens et al. – Automating Support for Software Evolution in UML

Mens et al. [26] propose an approach to detect conflicts between parallel evolutions of the same UML model, such as a merge conflict which may be due to different designers independently and concurrently making changes to the same software artifact. Four different types of refinements are considered: *Addition*, *Removal*, *Connection* and *Disconnection*. The UML metamodel is modified and specific stereotypes are defined to explicitly represent modifications.

Figure 2 is adapted from [26]. This example is a merge conflict which arises from the combination of independent modifications leading to undesired interactions and occurs when two parallel modifications are made to the same model element.

Figure 2 Example merge conflict (from [26])

Parallel modification 1: **Set** is specialized into **SetWithSize** which overrides `insert()` operation so that it additionally accesses and updates attribute `size` each time a new element is added to the set. The dependency relationship (dashed line) specifies that

`SetWithSize` is incrementally obtained from `Set` by adding attribute `size` (Addition) and accessing the attribute `size` from operation `insert()` (Connection).

Parallel modification 2: `Set` evolves into new version `EfficientSet` by removing the call to `insert()` in `union()` for efficiency reasons. The refinement type is `Disconnection`.

To find out if upgrading `Set` into `EfficientSet` leads to unexpected results, we need to know whether `SetWithSize` is still a valid and meaningful specialization of `EfficientSet`. Since originally the invocation of `union()` in `SetWithSize` leads to an indirect update of `size`, this will not be the case anymore if we substitute `Set` with `EfficientSet` because operation `union()` in `EfficientSet` does not invoke `insert()` anymore. This is called “inconsistent operation conflict” in [26], and it occurs each time one modification is a `Disconnection` of an operation invocation (e.g., in Figure 2, operations `insert()` and `union()` are disconnected in `EfficientSet`) and the other modification is a `Connection` involving the same operation (e.g., in Figure 2, operation `insert()` is connected to attribute `size`).

The major problem with this approach is that designers are required to explicitly and manually represent their modifications in UML diagrams (e.g., dependency relationships and predefined stereotypes are used). This, however, is a significant burden to designers and eventually clutters diagrams. This approach still has other limitations, for example, an interface can only be evolved into an interface, rather than a class.

3.1.2 Engels et al. – Consistency-Preserving Model Evolution through Transformation

Engels et al. [12] propose an approach to preserve consistency during the evolution of UML-RT [32] models, a variation of UML specifically dedicated to real-time systems. Three kinds of modifications, namely *Creation*, *Deletion* and *Update* are identified. The paper focuses on four main model elements of UML-RT models, namely capsules, port, connectors, and protocols. Each atomic change is specified by two patterns representing the situation before and after the change. For example, Figure 3 describes two atomic

changes excerpted from [12], which assumes two capsules *A* and *B* with an unconnected port each (left part of Figure 3) and creates a connector between them (right part of Figure 3). This is atomic change Creation. When read from right to left, the atomic change is Deletion as it removes an existing connector from its ports.

Figure 3 Transformation rules for creation and deletion

After identifying possible evolution steps by means of atomic changes, for a certain property possessed by the original model, like deadlock freedom or protocol consistency, conditions of the application of atomic changes, which ensure the modified model enjoys a similar property, are formulated. Thanks to a (partial) mapping from UML-RT to Communicating Sequential Processes (CSP), the approach is able to identify under which conditions, modifications of these model elements maintain consistency. The paper restricts its analysis, for instance to non-hierarchical UML-RT models. It also mentions that atomic changes representing elementary evolution steps may be combined in various ways to achieve more complex changes; however no concrete approach is proposed. Another difficulty is that it is required to keep consistency between models and their CSP specification.

3.1.3 Shen et al. – Extending the UML Metamodel to Support Software

Refinement

Shen et al. [33] propose an approach to support UML class diagram refinement by extending the UML metamodel. Stereotypes are used to represent the refinement explicitly. The paper only concerns the relationship refinement in a class diagram, as it is assumed that a relationship refinement in a class diagram plays a crucial role and that in most cases a class diagram refinement can be inferred from the corresponding relationship refinement. Four types of relationship refinements are defined as follows:

- Generalization abstraction: a generalization relationship is refined into two generalization relationships plus a new class.

- Bidirectional association abstraction: a bidirectional association is refined into two bidirectional associations plus a new class.
- Unidirectional association abstraction: a unidirectional association is refined into two unidirectional associations plus a new class.
- Association composition abstraction: a composition association is refined into two composition associations plus a new class or a composition association is refined into one composition association, plus a generalization relationship, and a new class.

Each relationship is qualified with a predefined stereotype which distinguishes the original relationships from the refined relationships. Figure 4 is an example excerpted from this paper. The <<Refined_Asso>> and the <<Refining_Asso>> are predefined stereotypes which are used to qualify the associations.

Figure 4 Example the approach of Shen et al.

We can see that this approach just supports one kind of refinements of class diagram: relationship refinement. There are still a lot of other important types of refinements. Another difficulty of this approach is that the refinement must be explicitly represented using predefined stereotypes.

3.1.4 Hnatkowska et al. – Refinement relationship between collaborations

Hnatkowska et al. [15] propose a classification of nine class diagram refinements:

1. Adding a class;
2. Adding a class property (attribute or operation);
3. Modifying a class attributes;
4. Modifying a class operations;
5. Splitting a class into two classes with association between them;

6. Introducing a successor of a class (i.e., two classes with association between them);
7. Adding an association;
8. Modifying of association;
9. Introducing an intermediate class.

1, 2, 3, 4, 7 and 8 are actually atomic changes, basic kinds of refinement. 5, 6 and 9 are more complex. These structural refinements are then used to specify behavioral refinements in collaboration diagrams and how the collaboration refinements relate to the corresponding structural refinements. Only a few simple refinements are presented though, and it is not clear (at least this is not described) how those refinements can be detected by a tool.

3.1.5 Pons and Kutsche – Traceability Across Refinement Steps in UML modeling

Pons and Kutsche [30] present a number of refinements for class diagram and use cases. Class diagram refinements are of the following types:

- *Attribute Refinement*: adds a new attribute or replaces an existing attribute with another one.
- *Operation Refinement*: adds a new operation or replaces an existing operation with another one.
- *Refining by Specification*: adds generalization relationship.
- *Refining by Composition*: adds composite association.

Use Case refinements are of the following types:

- *Refining by Action Decomposition*: refines one single action into several actions to see more detail.
- *Refining by Specialization*: a use case specializes a more general one.

The paper utilizes a UML metamodel element, namely *Abstraction*, to link refined and refinement elements, thus allowing establishment of a (possibly formal) mapping. All of these refinements are required to be explicitly and manually represented using stereotype

<<refine>>. This paper doesn't provide a complete set of refinements for either class or use case diagrams.

3.1.6 Discussion

There are several issues about the existing approaches on the classification of refinement. Firstly, most of existing works do not support complex refinements which should be derived from more than one atomic changes, except for Hnatkowska et al. [15] who present several such refinements. Secondly, each work just provides a partial classification of refinements. For example, Shen et al. [33] only covers relationship refinements in class diagrams.

In terms of the identification of refinements, most of existing works require to explicitly represent refinements. Several works use stereotypes to do so. This kind of approach significantly increases the user's involvement and burden. It is therefore unlikely to be applicable in practice.

3.2 Capturing traceability information

In order to perform vertical impact analysis, traceability information between two UML models must be captured. Traceability links can be built after the identification of refinements which determine which traceability links must be established between which model elements involved in a given refinement.

3.2.1 Letelier – A Framework for Requirements Traceability in UML-based Projects

Letelier [21] proposes a framework for the specification of traceability links between high-level requirements and UML models. These traceability links between different types of specifications enable the verification that the system functionality covers the stakeholder's expectation, and impact analysis when requirements change. Although primarily intended to support stakeholders in tracing high-level (textual) requirements to various UML models during initial development phases, the framework also allows the definition of traceability links between UML model elements.

In this work, a metamodel is proposed, in which classes represent *entity types* (e.g., requirements, UML models and stakeholders), and associations represent types of traceability links (e.g., stakeholder ‘responsibleOf’ requirement, and requirement ‘traceTo’ UML model). Stereotypes are used to explicitly represent traceability links.

The major difficulty with this approach is that most of the traceability links should be established manually, even though the approach supports ‘implicit traceability links’ which can be derived from several existing, manually established traceability links. Vertical impact analysis can be performed based on these traceability links; however it is too coarse to perform meaningful vertical impact analysis between model elements of two model versions.

3.2.2 Judson et al. – Supporting Design by Pattern-based Transformation

Judson et al. [17] present an approach for specifying pattern-based transformations of UML models consisting of class and interaction diagrams. These transformations are specified as metamodels, which indicate, for example, newly introduced classes and existing classes removed by the transformation. Further constraints are defined along with the transformation metamodels, which are used to specify constraints on source and target model elements, and relationships that must be held between source and target model elements. The Abstract Factory pattern is used to illustrate the approach. The paper focuses on the specification of transformations at the metamodel level. How to derive traceability links is not addressed. However it is easy to understand that traceability links can be automatically established since one knows how a model is transformed.

The major difficulty of this kind of transformation-based approach is that the user is requested to select which specific transformation to apply and the model elements to which the transformation is applied.

3.2.3 Discussion

In terms of capturing traceability information, the existing works require to explicitly and manually establish or represent traceability links with the exception of the

transformation-based approach proposed in [17]. This is a serious drawback of these approaches. Another important issue is that some works do not explicitly indicate and formalize which kinds of traceability information should be captured during the refinement process.

3.3 Performing impact analysis

Most of impact analysis techniques rely on a graph representation of software artifacts (the nodes) and their dependencies (the edges). First of all, a graph is used to describe the relationships between software artifacts in an intuitive and visual way. Secondly the graph representation can be analyzed using existing techniques and algorithms from graph theory. The main issue with graph-based approaches is that the time complexity of the algorithm tends to grow exponentially with the number of edges. So the efficiency of these techniques may become problematic on large problems.

In this section, several existing approaches are introduced first. Then these approaches are compared in section 3.3.5 in which a set of criteria are defined and comparison results are presented in a table.

3.3.1 Briand et al. – Automated Impact Analysis of UML Models

In [4], an approach is proposed to support to the identification of changes made to UML model elements and the impact of these changes on other model elements. The approach is decomposed into four steps: (1) automatically detect and classify changes across different versions of UML models, (2) verify the consistency of changed diagrams, (3) perform an impact analysis to determine the potential side effects of changes in the design, (4) prioritize the results of impact analysis according to the likelihood of occurrence of predicted impacted elements. This paper also proposes an experimental method to evaluate the effectiveness of the impact analysis. A prototype tool *iACMTool* was developed to assess the feasibility and practicality of the approach.

The systematic approach proposed in [4] focuses on horizontal impact analysis. Before performing horizontal impact analysis, changes across different versions of UML models

are detected automatically. A change taxonomy is formalized under the form of a tree which contains ninety-seven (97) leaf changes. Each leaf change of the change taxonomy corresponds to one change detection rule. For example, “AddedAssociation” is a change, whose definition is that “in the changed model version there exists an association relationship that does not exist in the original version.” [4] In order to perform horizontal impact analysis, 97 impact analysis rules are defined corresponding to the leaf changes.

The impact analysis rules defined in [4] could be extended in order to get more precise and/or complete horizontal and vertical impact analysis results. Figure 5 presents an example where we assume that the association `subAsso` has been added (this is a change of type “AddedAssociation”). The changed element is the `subAsso` and, according to the impact analysis rules proposed in [4], the impacted elements obtained after performing once horizontal impact analysis are the classes `SubclassB` and `Client`. However, it is likely that the association `superAsso` between the classes `Superclass` and `Client` may be impacted. If there is no relationship between the classes `SubclassA` and `Client`, then it is not necessary to have the association `superAsso` anymore since classes `SubclassB` and `Client` are connected by the association `subAsso`. So we can obtain a more accurate initial set of impacted elements: the classes `Superclass`, `SubclassB`, `Client` and the association `superAsso`.

Figure 5 Example the possible improvement for the approach proposed in [4]

3.3.2 Li and J. Offutt – Algorithmic Analysis of the Impact of Changes to Object-Oriented Software

A code-based impact analysis approach is proposed in [22, 23]. It suggests a detailed analysis of the changes, organized in a change taxonomy, to precisely study how changes

propagate (if they do). This paper presents algorithms to analyze the potential impacts of changes to object-oriented software, taking into account encapsulation, inheritance, and polymorphism. This approach is graph-based and an object-oriented data dependency graph is created to support the impact analysis. This impact analysis technique includes a set of algorithms to calculate the change impact according to change impact rules defined beforehand.

All dependencies are stored in a directed dependency graph, where each node represents a program entity (e.g., variable, module and data type) and edges represent the different kinds of dependencies such as operation calls.

Figure 6 and Figure 7 present a simple example taken from [23] to explain how changes propagate among class members. Figure 6 shows a piece of code and Figure 7 presents its corresponding dependency graph. ClassA has six class members: `A_meth1()`, `A_meth2()`, `A_meth3()`, `A_field1`, `A_field2`, and `A_field3`. As shown in Figure 7, method `A_meth2()` references `A_field1`, `A_field2`, `A_field3`, and `A_meth1()`, data member `A_field1` is defined by both data member `A_field2` and `A_field3`. Data member `A_field2` is defined by `A_meth1()`. Assume that `A_meth1` is changed and triggers change propagation, it will impact `A_meth2()` and `A_field2` according to the dependency graph. `A_meth2()` and `A_field2` are directly impacted because of the change of `A_meth1()`. `A_field1` and `A_meth2()` are indirectly impacted because of the indirect impact on `A_field2`.

```
class ClassA {
public:
int A_meth1();
int A_meth2() {
    ...
    _A_field2 = A_meth1();
    ...
    _A_field1 = _A_field2 + _A_field3 * 8.0;
    ...
}
int A_meth3();
private:
float _A_field1;
int _A_field2;
int _A_field3;
};
```

Figure 6 Example dependency analysis – code

Figure 7 Example dependency analysis - dependency graph

3.3.3 Mens and D'Hondt – Automating Support for Software Evolution in UML

An automated approach is proposed to support UML model evolution in [26]. It is claimed to cover all the model evolution activities such as consistency checking, impact analysis, conflict detection and traceability management. However, only the evolution activity of conflict detection is explained in this paper. It does not explicitly address impact analysis.

3.3.4 von Knethen et al. – QuaTrace: A Tool Environment for (Semi-)Automatic Impact Analysis Based on Traces.

A tool environment is proposed in [34] for (semi-) automatic impact analysis based on traceabilities. The tool environment is built on two existing tools: *RequisitePro* (requirement management tool) and *Rhapsody* (UML case tool). In this approach, because UML model elements are transformed and represented as shadow-requirements (natural language), a lot of information in the UML models is lost, especially relationships among model elements. Besides, traceability links between requirements and UML model elements must be manually established. Name tracing is used to automatically establish implicit traceability links. Based on these traceability links, impact analysis can be performed. Three levels of impacts are defined: primary impacts which are all documentation entities that have to be changed, secondary impacts which are all requirements that have to be changed with a high probability, and tertiary impact which

are all documentation entities that might be changed. For each impact, simple impact analysis rules are defined.

3.3.5 Comparison

The comparison approach proposed in [1] is adapted for our use. Six evaluation criteria are defined:

- ***Artifact Of Change***
It defines the artifacts for the impact analysis such as UML model or code.
- ***Change Specification***
It is how the change is specified for the impact analysis approach.
- ***Intermediate Model***
It is used to define the objects and relationships (or dependencies) the approach uses to accomplish impact analysis. For example, dependency relationships can be modeled by a dependency graph.
- ***Impact Model***
It defines the rules or embedded assumptions reflecting the semantics about what affects what. For example, when one class is changed, we need to follow the rules (impact model) to derive impacted elements.
- ***Impact Approach***
It implements the impact model. It defines how objects and intermediate models are represented, how impact rules are captured, or the specific search algorithms used to find impacted artifacts.
- ***Distance Measure***
It is a way to determine the distance of other potential impacts from the original impact or the distance between a changed element and potentially impacted element.

Existing approaches are compared according to the above criteria and results are presented in Table 1. The following part of the section discusses the comparison results.

In terms of the change specification, three different ways are used to classify changes. In [4], 97 fine-grained change categories are specified using OCL expressions. For example,

“changed sequence diagram view – Added message” is a change category. There are three change actions: *add*, *delete* and *change*. The work in [26] defines 4 primitive evolution contracts: *addition*, *removal*, *connection* and *disconnection*, and 2 composite evolution contracts: *promotion* and *sequentialisation*. This approach requires the user to explicitly and manually represent the evolution contracts. The user’s involvement is as a result substantial. Changes are classified and defined in [22, 23]. These changes are fine-grained, for example “Change scope: Private->Public” is a change on a data member. In [34], the approach doesn’t need to classify changes since it is very coarse-grained and doesn’t support the automatic detection of changes.

In terms of the intermediate model, the UML metamodel and OCL are used by some approaches for impact analysis. In [4] the UML metamodel is used to help determine the possible changes that can occur. In [26], the authors extend the UML metamodel and uses UML extension mechanisms: stereotypes to incorporate evolution contracts in UML. In [34], the documentation model is used to represent documentation entities and their relationships. Besides, relationship and tracing guidelines are derived from the documentation model to support establishing traces of requirements items and the tool relies on these traces to perform impact analysis.

In terms of the impact model, a set of impact analysis rules are defined using OCL expressions in [4], and each impact analysis rule corresponds to each change category in the taxonomy. Each impact analysis rule is a specification of how to derive collections of elements that are potentially impacted by a particular change. Although in [26] the approach could be adapted to impact analysis, due to a lack of detailed information provided in this paper, we can not compare it with [4]. The work in [22, 23] defines incomplete change impact rules. In [34], an analysis algorithm is used to perform impact analysis.

A distance measure is defined in [4] and [22, 23]. In [4] the distance between a changed element and a given impacted element is defined at the number of impact analysis rules that had to be invoked to identify this impacted element. It implies all the impact analysis rules have the same weight. The proposed approach in [34] classifies the impacted

elements into three types: primary impacts, secondary impacts and tertiary impacts (see Section 3.3.4 for details).

Note that the work in [4] and [22, 23] focuses on horizontal impact analysis. Vertical impact analysis, although this terminology is not used by these authors, is suggested in [26]. No precise vertical impact analysis approach is described though. Even though [34] presents an approach to maintain traceability, it is restricted to traceability between high-level textual requirement descriptions and use cases (and use case descriptions).

Approach	Artifact Of Change	Change Specification	Intermediate Model	Impact Model	Impact Approach	HIA/VIA ²	Distance Measure
[4]	UML models	1.Change taxonomy 2.Change detection rules OCL expressions	1.UML metamodel 2.OCL	Impact analysis rules	Prerequisites: 1.Consistency checking 2.Change detection 3.Impact analysis 4.Prioritization of impacts	HIA	Yes.
[26]	UML models	1.Primitive evolution contracts 2.Composite evolution contracts 3.User-defined evolution contracts Stereotypes + OCL	1. UML metamodel 2. OCL	N/A (Extendable) Evolution contracts	N/A (Extendable)	VIA (Extendable)	N/A (Extendable)
[34]	1.High-level documentation entities(requirement, system components). 2.Low-level types of documentation entities (use case, system funtion).	No classification.	1.Documentation model 2. Relationship guidelines 3.Tracing guidelines ³	Analysis algorithm	1.Build up traceability among requirement items. 2.Based on established traces to derive impacted elements. 3.Distance measure is given.	VIA	No.
[22, 23]	Code	<u>Change category:</u> 1.Changes on Methods 2.Changes on Data Member 3.Others Changes Textual description.	1.Control Flow Graphs (CFGs) 2.Data Flow Graphs (DFGs) 3.Object-oriented data dependency graphs (OODDGs ⁴)	Change impact rules and algorithms	1.Convert CFGs and DFGs to OODDGs. 2.Apply algorithms to find all impacted elements. 3.Recursively apply algorithm.	HIA	Yes. (implicitly ⁵)

Table 1 The comparison of existing impact analysis approaches

² HIA stands for horizontal impact analysis. VIA stands for vertical impact analysis.

³ Relationships guidelines are derived from the documentation model for each relationship defined in the documentation model. The tracing guidelines give additional information to each relationship guideline. They are all used to establish traces among all documentation entities. After all these traces are established, then it is straightforward to perform impact analysis using existing tools.

⁴ In an OODDG, the nodes represent data items, such as classes, class members, variables and constants. The edges represent dependencies among these data items.

⁵ The paper did not mention any distance measure, but it is obvious that the approach supports the definition of distance measure.

3.4 Summary

In this section, we summarize important issues regarding existing approaches in terms of capturing traceability information and performing vertical impact analysis.

1. Most of existing approaches require to explicitly represent refinements. For example, stereotypes are used in [26] and [33] to explicitly represent refinements. In other words, users are requested to manually and explicitly represent the refinements while making changes to the models. The major disadvantage of these approaches is a significant overhead on the user's part and little automation. Another disadvantage is that the model becomes increasingly cluttered because of the extra information of capturing traceability information.
2. Most existing approaches do not support complex refinements which should be derived from several atomic changes rather than a single atomic change. The resulting problem is that the user's intent can not be captured at a higher level than atomic changes. Even though some approaches support more complex refinements, a systematic classification is not provided.
3. Most of existing approaches do not provide a systematic classification of refinements.
4. Most of existing approaches do not indicate or formalize which kinds of traceability information should be captured during the refinement process.
5. Some vertical impact analysis approaches focus on source code rather than UML models. Others focus on horizontal impact analysis rather than vertical impact analysis. Certain approaches are too coarse-grained to be adapted to the vertical impact analysis of UML models. There is no method that is specifically addressing the vertical impact analysis of UML models.

4 APPROACH TAKEN

Our objective is to perform vertical impact analysis of UML 2.0 models as automatically and efficiently as possible. To do so, we propose an approach which involves horizontal impact analysis and traceability information. First, atomic changes, which are the elementary steps by which one model evolves into another, are identified automatically. Second, refinements are derived from the identified atomic changes, thus capturing the user's intent at a higher level of abstraction than atomic changes. Third, traceability links are established between model elements of UML model versions automatically (e.g., from analysis model elements to design model elements), based on the identified refinements, to keep track of the user's intent. Finally, with two UML model versions, the corresponding traceability links, and a HIA approach in hand, VIA can be performed to answer the question: what is the impact on the refined model of changes to the original model? We intend to automate the above four activities as much as possible, without requiring the designer to explicitly specify refinements (as in [26] for instance). Though the user's input might be necessary for some decisions, we aim at minimizing the occurrence of such user queries. In order to automatically identify refinements, we provide a systematic and hierarchical classification for class diagram refinement. We made an effort to be as systematic as possible and also describe a mechanism to extend this classification.

It is important to note that, according to the four activities discussed above, a change to a model can be used to either identify a refinement and thus traceability links or perform HIA and/or VIA (once traceability links have been identified). The question is then to be able to distinguish between the two during the software development process. As a simplifying working assumption, and given that we intend to automate VIA and HIA in the context of a UML case tool such as Rational Rose Architect, we will assume the following scenario:

1. The designer working on a set of UML models tells the case tool when s/he starts refining those models. At this point in time, the case tool can refer to these models

as models at the first level of abstraction (say, analysis) and record modifications for the purpose of identifying refinements and traceability links.

2. When the refinement activity ends, the designer informs the case tool: the recording ends. At this point in time, the current UML models are considered as models at the second level of abstraction (say, design) by the tool. Refinements and traceability links have been identified.
3. Any modification to a model at either of the two abstraction levels then triggers some HIA and VIA. For instance, a modification to a model at the first level of abstraction triggers HIA (to identify the impacted elements at the same level of abstraction) and then VIA (to identify the impacted elements at the second level of abstraction).

Whether this simplifying assumption as to how HIA and VIA fit in a software development life cycle will be the subject of future investigations.

In the following, we formalize the notions of atomic change, refinement, traceability link, vertical impact analysis and horizontal impact analysis, by means of metamodels (Section 4.1). We then present taxonomies of atomic changes and refinements for class diagrams (Sections 4.2 and 4.3). Last, we show how we specify refinements and the corresponding traceability links (Section 4.4).

4.1 Metamodels

In this section, we present the different concepts of atomic changes, atomic and composite refinements, and traceability links under the form of metamodels. In order to keep the discussion focused, the metamodel is presented in a piecewise manner. New classes and relationships specific to each step are highlighted. The whole metamodel is given in Appendix A for reference. A dictionary describing each metaclass, its attribute(s) and association(s) is provided in Appendix B for reference.

4.1.1 Conceptual metamodel

The class diagram in Figure 8 illustrates the main concepts of our approach, the conceptual metamodel, which is used to present the relationships of the important concepts introduced in Section 2.

A `UMLModel` is composed of instances of `UMLDiagram` which can be a `ClassDiagram`, or any other valid UML diagram. A `UMLDiagram` is composed of instances of `Element` (i.e., `modelElements`), which is one of the meta-classes of the UML 2.0 metamodel [27]. This class is the bridge between our metamodel and the UML 2.0 metamodel. A `UMLModel` is associated with instances of `Refinement` by two associations since a model can be refined (`rolename toRefinedModel`) and at the same time be the refinement of another model (`rolename toOriginalModel`). A refinement is between the original model (`rolename originalModel`) and the refined model (`rolename refinedModel`). Instances of `TraceabilityLink` should be established for each `Refinement` instance. How to perform vertical impact analysis based on the established traceability links is presented in Section 4.1.5.

A refinement is either an `AtomicRefinement`, corresponding to a series of `AtomicChanges`, or a `CompositeRefinement` composed of `AtomicRefinements` and/or other `CompositeRefinements`. Detailed description of atomic and composite refinements will be given in Section 4.1.2, along with examples. We will see in Section 4.2 and 4.3 that `AtomicChange` and `AtomicRefinement` are the roots of hierarchies (taxonomy) of atomic changes and refinements, respectively.

Notice that the analyzed models may not contain enough information to identify a refinement, in which case the user's help is requested (class `UserHelp`). For a particular refinement which requires the user's help, we define specific format of user's help such as yes-no or multiple choices questions in order to minimize the user's involvement.

Figure 8 The conceptual metamodel

4.1.2 Metamodel for refinement

As shown in Figure 8, an AtomicRefinement is derived from a group of AtomicChanges that occur together. It can not be decomposed into other refinements. For example, refining a class by extracting some of its attributes into a new class which becomes the subclass of the class being refined is an atomic refinement. This refinement is derived from a group of atomic changes: “adding a new class”, and “moving an attribute from a class into another”, and “adding a generalization”. Notice that an atomic refinement may be derived from a single atomic change, in which case the atomic refinement is straightforward.

Notice that the composite design pattern is used to model refinements. A CompositeRefinement consists of more than one Refinements which can be AtomicRefinements or CompositeRefinements. The refinements grouped into a composite refinement are between the same original and refined models. In other words, we can write the following OCL constraints:

```

Context CompositeRefinement
self.containedRef->forall(n|n.originalModel = self.originalModel
                        and n.refinedModel = self.refinedModel)

```

Figure 9 and Figure 10 show a composite refinement example, which is adapted from [31]. Firstly, class ManagementDepartment of the original class diagram is refined into

class `ManagementDepartment` which aggregates classes `ClientManager`, `LoanManager` and `AccountManager`. Because of this refinement, it is necessary to refine the association keeps between the classes `ManagementDepartment` and `Account` in the original class diagram into the association between the classes `AccountManager` and `Account` in the refined class diagram. These two atomic refinements, namely `TopDownGen` and `RelocateAssociation` (Appendix E.1.1 and Appendix D), are grouped together as a composite refinement.

Figure 9 Example composite refinement - original class diagram (from [31])

Figure 10 Example composite refinement - refined class diagram (from [31])

4.1.3 Metamodel for atomic change

The class diagram in Figure 11 illustrates the metamodel for atomic change. An `AtomicChange` affects a model element (instance of `Element`) and is further described by a `ChangeDescription`. We consider four different kinds of `AtomicChanges`, as defined in enumeration `AtomicChangeTypes`: `changed`, `moved`, `deleted`, and `added`. The last two are self-explanatory: the `added` (`deleted`) element is the `affectedElement` in the refined (original) model. An element is `moved` when its location changes, e.g., an operation is moved from a class to another. For a moved element, `affectedElement` represents the element in the original version of the model, whereas `targetLocation` or `diagramLocation` associations from class `ChangeDescription` describe the new location. In the case the moved element belongs to another model element (e.g., an operation belonging to a class is moved), `targetLocation` is to be used. If instead the moved element belongs to a model (e.g., a class belongs to a class diagram),

diagramLocation is to be used. A changed element occurs, for instance, when a named element changes name, e.g., an attribute name changes. The name change is then recorded in attributes beforeValue and afterValue of class ChangeDescription. Obviously beforeValue and afterValue can not be same. This constraint is formalized using the following OCL expressions.

This discussion of the different kinds of atomic changes typically means that not every instance of Figure 11 is legal, i.e., that there exist constraints. Figure 12 presents those constraints on classes ChangeDescription and AtomicChange, specified using OCL expressions. These constraints are based on the conceptual metamodel (Figure 8) and the metamodel for atomic changes (Figure 11).

Figure 11 The metamodel for atomic change

In Appendix C, a list of example atomic changes is presented along with a description of the ChangeDescription and affectedElement links of each atomic change.

These notions are consistent with the compare&merge facility which is available in Rational Software Architect (RSA) [16]. The compare&merge facility is indeed the mechanism we intend to rely on for the detection of model changes to identify refinements.

```

Context ChangeDescription
not(self.beforeValue = self.afterValue)

Context AtomicChange
self.affectedElement->notEmpty()
and self.type=AtomicChangeTypes::added implies (
    self.changeDescription->isEmpty()
    and self.atomicRef.refinedModel.diagram.modelElements
        ->includes(self.affectedElement)
    and self.atomicRef.originalModel.diagram.modelElements
        ->excludes(self.affectedElement)
)
and self.type=AtomicChangeTypes::deleted implies (
    self.changeDescription->isEmpty()
    and self.atomicRef.originalModel.diagram.modelElements
        ->includes(self.affectedElement)
    and self.atomicRef.refinedModel.diagram.modelElements
        ->excludes(self.affectedElement)
)
and self.type=AtomicChangeTypes::changed implies (
    self.changeDescription->notEmpty()
    and self.changeDescription.targetLocation->isEmpty()
    and self.changeDescription.diagramLocation->isEmpty()
    and self.atomicRef.originalModel.diagram.modelElements
        ->includes(self.affectedElement)
    and self.atomicRef.refinedModel.diagram.modelElements
        ->excludes(self.affectedElement)
)
and self.type=AtomicChangeTypes::moved implies (
    self.changeDescription->notEmpty()
    and if(self.affectedElement.ocIsTypeOf(Classifier)) (
        self.changeDescription.diagramLocation->notEmpty()
        and self.changeDescription.targetLocation->isEmpty()
    ) else (
        self.changeDescription.diagramLocation->isEmpty()
        and self.changeDescription.targetLocation->notEmpty()
    )
    endif
    and self.atomicRef.originalModel.diagram.modelElements
        ->includes(self.affectedElement)
    and self.atomicRef.refinedModel.diagram.modelElements
        ->excludes(self.affectedElement)
)

```

Figure 12 The constraints of the metamodel for atomic change

4.1.4 Metamodel for traceability link

A traceability link between two model elements which belong to different UML models can be represented by a tuple of the form (Eo, Er, type, possibility) where Eo is a model element of the original model, Er is a model element of the refined model, type is the type of the traceability link (i.e., corresponding to a particular refinement), and possibility is a percentage which represents the likelihood that there is a traceability

link. Sometimes, according to the information available in models (e.g., a group of atomic changes, refinement identified and two UML models), it is not possible to guarantee at 100% that there is a refinement, so we assign a percentage to the traceability link which denotes the confidence that this is indeed a refinement. For example, one possible refinement is to merge a superclass and a subclass together when they are not very different. In order to identify this refinement, we have to compare attributes and operations of the merged class (i.e., a class of the refined model) and the deleted class (i.e., the class of the original model) which could be the superclass or subclass. The extent to which such a mapping of attributes and operations can be established indicates the likelihood of the refinement.

We use an example to show how to use the above tuple format to represent traceability links. Class A is refined by adding a new attribute `newAttri` (we call this refinement `AddedAttributeRef`): let us refer to this new version of A as A1. Then class A is refined by making it an abstract class (we call this refinement `ClassIsAbstractRef`): let us refer to this new version of A as A2. We can use the above tuple format to represent the traceability information between classes A, A1 and A2: (A, A1, `AddedAttributeRef`, 100%), and (A1, A2, `ClassIsAbstractRef`, 100%).

The concept of traceability link is modeled using the class diagram in Figure 13. Instances of `TraceabilityLink` are established for each `Refinement` instance, between the elements in the original model that are being refined (association to `Element` with rolename `origin`) and the elements of the target model that are the refinements (association to `Element` with rolename `target`). An element in one model (i.e., the original model or the refined model) can be connected to an element in another model (i.e., the refined model or the original model) via one or many traceability links. An element in one model (i.e., the original model or the refined model) can be connected to one or many elements in another model (i.e., the refined model or the original model). The origin and target of a traceability link are model elements of the original and refined models, respectively, of the corresponding refinement. In other words, we can write the following OCL constraints:

```

Context TraceabilityLink
  self.type.originalModel.diagram.modelElements
    ->includes(self.origin)
  and
  self.type.refinedModel.diagram.modelElements
    ->includes(self.target)
  and
  self.type.traceabilityLinks
    ->includes(self)

```

When traceability links can be established between a series of models, we can derive traceability links between the elements of the first (most abstract) model and the elements of the last (most refined) model, these links being modeled as instances of class `DerivedTraceabilityLink`. For instance, in the abstract example above, we can derive a traceability link between A and A2 from the two traceability links between A and A1, and between A1 and A2. Notice that class A1 is the target of the traceability link between A and A1, but also the origin of the traceability link between A1 and A2. We can therefore write the following OCL constraints:

```

Context DerivedTraceabilityLink
Sequence{1..self.containedTLinks->size()}->forAll(i,j:Integer|
  j=i+1 implies (
    containedTLinks->at(i).target
      = containedTLinks->at(j).origin
  )
)

```

Figure 13 The metamodel for traceability link

As shown in Figure 8, we rely on a group of atomic changes to identify a refinement. Corresponding traceability links are established for this refinement when it is identified. The identification of the refinement will be triggered when the user executes a command, e.g., saving the model after he/she finished the modifications.

4.1.5 Metamodel for performing vertical impact analysis

Once refinements between two model versions (say, the analysis original model and the design refined model) have been identified and the corresponding traceability links have been established, one can perform vertical impact analysis: class `VerticalImpact` in Figure 14. A `VerticalImpact` relies on the traceability links to identify the elements of the refined model (i.e., `impactedElement`) that may need to be changed because of a set of changes in the original model (i.e., `changedElements`). Since traceability links indicate how each original model element is refined, the changes to the original model are necessarily at the origin of some traceability links. Similarly, the set of elements impacted by the `VerticalImpact` is a subset of the targets of the traceability links. In other words, in the context of class `VerticalImpact`, we can write the following OCL constraints:

```
Context VerticalImpact
  self.traceabilityLinks.type.originalModel->asSet()->size()=1
  and self.traceabilityLinks.type.refinedModel->asSet()
    ->size()=1
  and self.traceabilityLinks.origin->asSet()
    ->includesAll(self.changedElements)
  and self.traceabilityLinks.target->asSet()
    ->includesAll(self.impactElements)
```

The changed elements in the original model can be the result of a HIA. Similarly, the elements of the refined model being impacted by the VIA can be the starting point of a HIA: modified elements in the original model impact elements of the refined models (VIA) which themselves may impact other elements of the refined model (HIA). This is modeled by the reflexive association connecting the class `Impact` to itself (i.e., `HIAimpacts`). HIA is modeled by classes `Change` and `HorizontalImpact`, and their associations, which we reuse from an earlier work on UML-based impact analysis [4]. We introduce two classes `VerticalImpact` and `HorizontalImpact` as the subclasses of `Impact` in order to distinguish the impacts caused by performing HIA from the impacts caused by performing VIA.

Figure 14 The metamodel for performing vertical impact analysis

4.2 Taxonomy of Atomic changes

In order to precisely specify (atomic) refinements we need to precisely specify the atomic changes they can be composed of first. Such a taxonomy already has been presented in [4], where each model element is defined by a set of properties (e.g., a class has attributes) among which core properties uniquely identify the element (e.g., the class name).

We adapted this taxonomy to account for the fact that we rely on the compare&merge facility of RSA to provide such atomic changes. There are two main reasons for this adaptation. First, in [4], changing the core properties of an element leads to the deletion of the element and the addition of a new element. On the other hand, using RSA, such a situation is classified as a change, i.e., as an atomic change of type *changed*. Second, moving an element from a location to another (e.g., an operation from a class to another) is classified as a deletion and an addition in [4], whereas in RSA we have the notion of moved element. In other words, we benefit from the precise, fine-grained identification of changes provided by RSA.

Though an *AtomicChange* can occur in any UML diagram, we focus in this thesis on class diagrams. Figure 15 shows an excerpt of the taxonomy: an *AtomicChange* in a class diagram can be the addition of a class, the deletion of an association, the move of an attribute between two classes, or the change of a class, which is a change of name or a

change of property `IsAbstract` [27], etc. The complete taxonomy for class diagram atomic changes currently contains 47 concrete changes, i.e., leaf nodes in the inheritance hierarchy rooted in `ClassDiagramAtomicChange`, and can be refined over time if necessary. It is presented in Appendix D.

Figure 15 Taxonomy of Atomic Changes

4.3 Taxonomy of Refinements

As shown in Figure 16, we also define a taxonomy of atomic refinements, again focusing on class diagram refinements in this thesis. Notice that using the composite design pattern we model the possibility that a refinement involves both class and sequence diagram atomic refinements. (Other diagrams could be added to Figure 16 using the same principle.) We defined our taxonomy of class diagram atomic refinements based on a careful and systematic study of the related literature (conference and journal articles, and text books such as [20]) or according to our own experience of UML-based software development. This taxonomy is also expected to be refined over time.

Figure 16 Taxonomy of Refinements

Figure 16 only shows an excerpt of the taxonomy which contains a total of 30 concrete class diagram atomic refinements, i.e., leaf nodes in the inheritance hierarchy rooted in `ClassDiagramRefinement`. As an example, `Class->Classes+Rels` refers to a family of refinements where a class is refined into a set of classes and their relationships. For instance, it is further specialized in the taxonomy into `TopDownGen` which corresponds to a refinement through generalization: the class being refined in added a subclass in the

refined model. Other refinements, not shown in Figure 16, describe for instance the refinement of a set of classes and their relationships into a single class or the refinement of a class into several classes (e.g., splitting of responsibilities). The complete taxonomy for class diagram refinements is presented in Appendix E.

4.4 Refinement/Traceability link specification

As indicated in Figure 8, an atomic refinement may be derived from one or more atomic changes. We distinguish them as they are formalized in different ways. These two types of refinements and their formalizations are discussed in Section 4.4.1 and 4.4.2, respectively.

4.4.1 Atomic refinements derived from a single atomic change

This is the simplest one: once such an atomic change has been detected, an atomic refinement, and corresponding traceability links can be detected automatically. As we discussed in Section 4.2 we rely on the compare&merge engine (Section 5.2.1) of RSA to detect atomic changes and as a result atomic refinements can be detected automatically. Each of this type of atomic refinements leads to creating a traceability link except the atomic refinements derived from a single added or deleted atomic change. The strategy for establishing traceability links is as follows.

Changed:

For the atomic refinement derived from a single atomic change of type `changed`, a traceability link between the original model element in the original model (i.e., the `affectedElement` of the atomic change) and the refined model element in the refined model should be established.

For example, a traceability link is specified in Figure 17 (b) for a `ClassIsAbstractRef` refinement, which is detected from a single atomic change of type `ChangedClassIsAbstract`: the class is changed into an abstract class (specified in Figure 17 (a)). The affected element of such a change is a `Class`. The refinement's unique traceability link is between the original class (i.e., the `affectedElement` of the

atomic change) and the refined class. We assume that the original model is refined into the refined model by the `ClassIsAbstractRef` refinement only. We can identify the refined class (referred to as `refClass`) by looking for the class in the refined model which has the same name as the original class (i.e., the affected element of the atomic change `ChangedClassIsAbstract`) (referred to as `origClass`).

```

Context: ClassIsAbstractRef
self.atomicChanges->size() = 1
and self.atomicChanges->exists(oclIsTypeOf(ChangedClassIsAbstract))

```

(a) Constraint on atomic changes

```

Context: ClassIsAbstractRef
let origClass = self.atomicChanges
    ->select(oclIsTypeOf(ChangedClassIsAbstract)).affectedElement.oclAsType(Class)
let refClass = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsType(Class))->select(name=origClass.name)
in
self.traceabilityLinks->size() = 1
and self.traceabilityLinks->exists(t| t.origin = origClass and t.target = refClass)

```

(b) Traceability links

Figure 17 Refinement `ClassIsAbstractRef`

Moved:

For the atomic refinement derived from a single atomic change of type `moved`, a traceability link between the original model element in the original model (i.e., the `affectedElement` of the atomic change) and the refined model element in the refined model (i.e., the model element moved to the `diagramLocation` or `targetLocation`) is established.

For example, a traceability link is specified in Figure 18 (b) for a `MovedAttributeRef` refinement, which is detected from a single atomic change of type `MovedAttribute`: the attribute is moved from a class into another (specified in Figure 18 (a)). The `affectedElement` of such a change is a `Property`. The traceability link is between the attribute in the original class (i.e., the `affectedElement` of the atomic change) and the attribute in the new location (i.e., the attribute in the `targetLocation` of the atomic change).

```

Context: MovedAttributeRef
self.atomicChanges->size() = 1
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))

```

(a) Constraint on atomic changes

```

Context: MovedAttributeRef
let origAttri = self.atomicChanges->
    select(oclIsTypeOf(MovedAttribute)).affectedElement.oclAsType(Property)
let refAttri = self.atomicChanges->
    select(oclIsTypeOf(MovedAttribute)).changeDescription.
    targetLocation.oclAsType(Class).ownedAttribute->select(name = origAttri.name)
in
self.traceabilityLinks->size() = 1
and self.traceabilityLinks->exists(t| t.origin = origAttri and t.target = refAttri)

```

(b) Traceability links

Figure 18 Refinement MovedAttributeRef

Added or Deleted:

No traceability link should be established for the atomic refinements derived from a single Added atomic change, since there is no model element in the original model which can be linked to.

Similarly, no traceability link should be established for the atomic refinements derived from a single Deleted atomic change, since there is no model element in the refined model which can be linked from.

4.4.2 Atomic refinements derived from several atomic changes

Atomic refinements derived from several atomic changes are more complex to handle. Therefore, a systematic strategy for formalizing this kind of atomic refinements is required, and is introduced in this section. The specification and formalization of all concrete class diagram atomic refinements that appear in the taxonomy of Section 4.3 are presented in Appendix E. Some of them are exemplified in the case study section (Section 6).

Each concrete refinement in the taxonomy is rigorously specified, following a template description containing: a general description of the refinement; a description of the user's

intent; the list of atomic changes that must be present, and the constraints they must satisfy to identify such a refinement; and a description of the corresponding traceability links. Constraints on atomic changes and traceability links are described using the OCL. We believe that, if we want such research to converge over time and other researchers to build on it, the method employed for detecting changes, refinements and establishing traceability links needs to be rigorously specified.

When a type of atomic refinement is specified, we assume that the original model is refined into the refined model by this type of refinement only. It means that no other refinements are performed before or after this refinement on the original model. This assumption applies to all specifications of atomic refinements. Of course, there is the case in which several independent refinements need to be identified together and corresponding traceability links need to be established. There exists an order in which these refinements should be identified. Finding such an order is however part of our future work and we currently rely on a multi-pass heuristic: OCL rules identifying refinements are all evaluated once, twice, and so on, until no new traceability link is established.

As an example, consider the class diagram atomic refinement `Class->Classes+Rels` (Figure 16) which refers to a family of refinements where a class is refined into a set of classes and relationships. One example of such a refinement, is called `TopDownGen` (Figure 16): the class is added a subclass (a class is refined by means of a top-down generalization).

The specification of refinement `TopDownGen`, i.e., the characterization of its atomic changes and their relations, is shown as the OCL invariant for class `TopDownGen` in Figure 19 (a). The expression indicates that a `TopDownGen` refinement is composed of two atomic changes of type `AddedClass` and `AddedGeneralization` (first three terms in the conjunction). Additionally, the newly added generalization relationship connects the newly added class (as the subclass) to the class being refined (last conjunct).

For such a refinement, two traceability links have to be established: one between the original class and the superclass of the added generalization; one between the original

class and the added subclass. The rationale is that if a change to the original class (in the original model) is performed, or if this class is impacted by some horizontal impact analysis, then both the super class and the child class of the added generalization (in the refined model) may need to be updated.

These traceability links are specified in the OCL expression of Figure 19 (b). The first four `let` expressions define local variables for the rest of the constraint: `newGen` refers to the newly added generalization; `superClass` and `subClass` refer to the parent and child classes of the added generalization, respectively; `origClass` refers to the class in the original model that is being refined which is identified by looking for the class in the original model which has the same name as the `superClass`. Using these local variables, the rest of the expression (after the `in` keyword) indicates that there are two traceability links for the `TopDownGen` refinement, one between `origClass` and `superClass`, and one between `origClass` and `subClass`.

Context: TopDownGen <code>self.atomicChanges->size() = 2</code> <code>and self.atomicChanges->exists(oclIsTypeOf(AddedClass))</code> <code>and self.atomicChanges->exists(oclIsTypeOf(AddedGeneralization))</code> <code>and self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)).affectedElement. oclAsType(Generalization).specific->includes(self.atomicChanges-> select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))</code>
(a) Constraint on atomic changes
Context: TopDownGen <code>let newGen = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)). affectedElement.oclAsType(Generalization)</code> <code>let superClass = newGen.general</code> <code>let subClass = newGen.specific</code> <code>let origClass = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class))->select(name = superClass.name)</code> <code>in</code> <code>self.traceabilityLinks->size() = 2</code> <code>and self.traceabilityLink->exists(origin = origClass and target = superClass)</code> <code>and self.traceabilityLink->exists(origin = origClass and target = subClass)</code>
(b) Traceability links

Figure 19 Refinement TopDownGen

5 AUTOMATION

Our approach is implemented in a tool named `VIATool` (Vertical Impact Analysis Tool). The tool is composed of two subsystems as illustrated in Figure 20: `VIATraceability` and `VIAPerform`. Subsystem `VIATraceability` identifies refinements and establishes traceability links between two UML models. The `VIAPerform` subsystem performs vertical impact analysis with the traceability links as input.

In the `VIATraceability` subsystem, the `VIA Eclipse Plugin` is a plugin to the Eclipse platform that interacts with two other Eclipse plugins, namely `Eclipse UML2` [11] and `Eclipse EMF`, which will be further discussed in Section 5.1.1. The `Eclipse UML2` project is an EMF-based implementation of the UML 2.0 metamodel [27] for the Eclipse platform, and is integrated into IBM's Rational Software Architect (RSA) [16].

`VIA Eclipse Plugin` also interacts with the `VIA Capturing Traceability Engine` which is responsible for identifying refinements and establishing traceability links. The `VIA Capturing Traceability Engine` obtains a group of atomic changes from the `CompareMerge Engine`, which is part of RSA, for identifying atomic changes [16]. The `AtomicChange Model` is an EMF-based implementation of the atomic change concepts discussed in Section 4.1.3. The model will be instantiated according to the deltas obtained from the `CompareMerge Engine`, then it will be used by the `VIA Capturing Traceability Engine` to identify refinements. The `VIA Capturing Traceability Engine` identifies a refinement by checking refinements in the `Refinement Repository` against the group of atomic changes and UML models. Last it adds new traceability links to the `Traceability Repository`. The `Refinement Repository` is used to model refinements. The `Traceability Repository` is used to model traceability links. They are both based on EMF.

Figure 20 VIATool Architecture Overview

In the VIAPerform subsystem, the VIA Performing Engine interacts with the VIA Eclipse Plugin to obtain the UML models to be analyzed. Vertical impact analysis is triggered by a change (the Change subsystem), which is obtained using the CompareMerge Engine. The VIA Performing Engine performs vertical impact analysis with two UML models, a change, and traceability links (stored in the Traceability Repository) as inputs. Then a report is generated, Reporting Results to show the analysis results. The UML models to be analyzed are also instantiated using the Eclipse UML2 project.

The following sections further detail the design of the system. We start with a short description of the Eclipse platform and its related projects.

5.1 The Eclipse Platform

Eclipse is an open source, robust, full-featured, industry platform for the development of highly integrated tools and applications. The plug-in based framework makes it easier to create, integrate and utilize software tools. The objective of the Eclipse project is to become an industry platform and to meet the needs of the Eclipse tool building community.

The Eclipse project is composed of itself many subprojects or categories, e.g., The Eclipse Project, The Eclipse Tools Project [9], The Eclipse Technology Project [8]. The two categories of interest for this thesis are the Eclipse Project and the Eclipse Tools Project. The Eclipse Project contains both the Eclipse platform technology, and a set of tools that together form the software development kit (SDK) for building Eclipse-based tools: The Java Development Tooling, or Java IDE [6] and the Plug-in Development Environment [10]. These tools are used to develop the initial prototype of the VIATool and are used in the execution of the tool. The Eclipse Tools Project contains several smaller projects not essential to the Eclipse Platform, but can be seen as value added features. Two of these projects are critical in the implementation of the VIATool, namely the Eclipse Modeling Framework (Section 5.1.1) and the UML2 Project ([11]).

The Eclipse platform provides the foundation from which many commercial tools have been developed (e.g., IBM RSA). VIATool also makes use of the OCL engine (Section 5.1.2) which is a component of the IBM RSA.

5.1.1 Eclipse Modeling Framework (EMF)

The Eclipse Modeling Framework (EMF) is a modeling and code generation engine for building applications based on a structured data model. Using EMF, a developer can define a data model and get a set of Java classes, automatically generated by the EMF facility, to create and manipulate instances of the data model. EMF also produces a set of adapter classes to enable viewing and editing the model, and a basic editor, which is itself an Eclipse plugin [7]. The data model can be specified using annotated Java, XML documents, modeling tools like Rational Rose, or directly use the EMF editor which is provided along with RSA. We use this EMF editor to build VIATool models which will be discussed in Section 5.3. From a model definition, EMF can generate Java implementation code including UI, XML Schemas, Eclipse projects, and plug-ins. A typical EMF usage scenario could be:

1. Create an Ecore model. You can choose to import it from UML (e.g., Rational Rose with Ecore profile, .mdl file), an XML Schema, or an Ecore model directly using EMF's Ecore editor;

2. Generate a generator model which provides access to all of the data needed for code generation. Besides, it is automatically kept in synch with the Ecore model. Code generation options can be specified at this time as well;
3. Generate Model, Edit, Editor and Test code separately or generate all of them together. Each set of code is an Eclipse plug-in. EMF functionality for data persistence is added when the EMF java code is generated;
4. Instantiate the model with instance data using the generated EMF model editor. These instances can be serialized into XML and deserialized from XML as well;
5. Iteratively refine the model (and regenerate code) and develop the corresponding java application;
6. Optionally, use the generated *Edit* to build customized user interface.

The EMF technology is used in our VIATool to build the Refinement Repository, Traceability Repository and AtomicChange Model which will be further discussed in Section 5.3.

5.1.2 The OCL Engine

Along with EMF, IBM has defined an OCL Engine which has been included in the IBM RSA version 6. The OCL Engine can be used to evaluate an OCL statement (i.e., String object) to query the characteristics of your metamodel. For example, you can evaluate an OCL statement that returns a simple type, such as a Boolean value, or you can evaluate an OCL statement that returns a list of metamodel objects.

In VIATool, the OCL engine is used to evaluate and query constraints for identifying refinements and establishing traceability links. These constraints are specified using OCL expressions and provided along with the instances of the Refinement Repository model.

5.2 Rational Software Architect

IBM RSA is an integrated design and development tool that leverages model-driven development with the UML for creating well-architected applications and services. RSA unifies all aspects of software design and development into one powerful and easy to use tool. It supports understanding, designing, managing and evolving enterprise solutions and services.

RSA leverages the Eclipse open source APIs, including EMF and the UML 2 metamodels. It supports the major UML 2 diagrams. OCL is supported for specifying constraints as well (Section 5.1.2).

Since IBM RSA is built upon the Eclipse integrated development environment, it inherits Eclipse's compare support work flows. IBM RSA is itself built using the EMF, which essentially means that it contains complex structured data and cannot successfully be understood as text. Therefore, a custom EMF and UML compare support has been implemented, namely the compare&merge engine (Section 5.2.1).

RSA is built on the top of the open and extensible Eclipse platform and it provides an open and extensible modeling platform. We choose RSA as the platform for our VIATool's development due to the following reasons:

1. RSA supports graphically editing and querying UML 2 models;
2. RSA has compare support which is used to obtain atomic changes in our VIATool;
3. RSA supports the evaluation of OCL expressions which facilitates greatly the implementation of our VIATool.

5.2.1 Compare&merge engine

The compare&merge engine is developed by IBM and it is used in two common scenarios:

- ***Compare with local history***, which is useful for looking at the evolution of a model over time. Local history is a check-point where each saved version is retained for an unspecified period of time. This is the scenario we are using in the VIATool.
- ***Compare with each other***, which allows for comparison between two or three versions of a model in your workspace.

The compare&merge engine, as its name indicates, also supports merging two versions of UML models. Since this is not the case that we are interested in, we will not discuss this functionality any further.

5.3 EMF Models in VIATool

The VIATool contains three EMF models: `Refinement Repository`, `Traceability Repository` and `AtomicChange Model`. These models were described in Section 4.1.1, Section 4.1.4, and Section 4.1.3 respectively. Instantiating these models is automated using EMF. As mentioned in Section 5.1.1, EMF can generate a basic editor for the models generated by EMF. The EMF editor is an Eclipse plugin and once integrated into Eclipse the EMF models can be generated under existing projects (Figure 21).

We use the `Refinement Repository` model here to exemplify how EMF models work. The use of the editor of the `Refinement Repository` model will be illustrated using an example: the `TopDownGen` refinement discussed in Section 4.4.2. The model instance is created with the `AtomicRefinement` (i.e., `Atomic Ref` in Figure 22) object as the root of the tree. The *Properties* view allows the developer to fill the attributes of the object.

Then the instance of the `Refinement Repository` model is populated by the atomic changes required to identify it, the traceability links which should be established for the refinement, and the user's help if required (Figure 23). Once all the required objects for the model are created the information for each object can be edited in the properties view (Figure 24).

Figure 21 Creating a new refinement repository model

Figure 22 Creating a TopDownGen refinement object

Figure 23 Creating new objects using the editor

Figure 24 Editing Attributes and Associations using the editor

6 CASE STUDY

Figure 25 is a case study we selected from [20]. Figure 25 (a) shows the analysis model, whereas Figure 25 (b) shows the design model. The analysis model has been transformed into the design model by applying 12 refinements, from a set of seven refinement types. The changes made to the design model are the following: Class `Payment` has been transformed into an abstract class and new subclasses (e.g., `CashPayment`); The association between `Payment` and `Sale` has been transformed into new classes (e.g., `Customer`) and associations; Attribute `price` in class `ProductDescription` has been turned into a class, namely `ProductPrice`; A number of associations have been updated: change of navigability (e.g., between `Store` and `Sale`), change of multiplicity (e.g., between `ProductDescription` and `SalesLineItem`), change of association type (e.g., between `Sale` and `SalesLineItem`). These changes correspond to the following atomic changes in our taxonomy: `ChangedClassIsAbstract`, `AddedClass`, `Added-Generalization`, `DeletedAssociation`, `Added-Association`, `DeletedAttribute`, `ChangedAssoEndMultiplicity`, `ChangedAssoEndIsNavigable`, and `ChangedAsso-EndType`.

These atomic changes are used to identify 12 refinements, corresponding to seven refinements types, namely: `TopDownGen`, `ClassIsAbstractRef`, `DetailAssoFunctionality`, `TurnAttriIntoClass`, `AssoEndMultiplicityRef`, `AssoEndIsNavigableRef`, and `AssoEndTypeRef`. We have already described the specification of the first two of those refinements in Section 4.4, along with their rules to establish traceability links. In this section, we address the remaining five refinement types.

(a) Analysis model

(b) Design model

Figure 25 Case Study (from [20])

6.1 DetailAssoFunctionality

Figure 26 shows the specification of refinement `DetailAssoFunctionality`, whose purpose is to refine an association by adding new classes and associations. The general idea for identifying such a refinement is to be able to find, in the refined class diagram, at

least one path between the classes at the two ends of the association⁶ being deleted in the original model. Referring to the example of Figure 25 (b), we are interested in paths between abstract class `Payment` (and its three subclasses) and class `Sale`. We need to rely on already identified refinements here, i.e., the refinements of the two ends of the deleted association.

As specified in Figure 26 (a), such a refinement is at least made of one `DeletedAssociation` atomic change: the deleted association (in the original model) is referred to as `deletedAsso`. The next `let` expressions are used to identify the two ends of the deleted association in the original model (`origA` and `origB`) and how they may have been refined (`refA` and `refB`). Last, we use operation `exists()` of class `Path` to identify whether there is a path between `refA` and `refB` in the refined model. Class `Path` does not appear in our metamodel as it is only a helper class used to shorten our OCL expressions. Its formalization is given in Appendix F. A `Path` instance is associated with a sequence of `Elements`, i.e., a path is a sequence of UML model elements. Operation `exists(endA,endB)`, `endA` and `endB` being classes of the same model, returns true if and only if there exists a path between these two classes. Operation `exists(endSetA,endSetB)`, where the two parameters are sets of classes, is a similar variant: it returns true if we can find a path between any pair of classes, each class in the pair belonging to one of the two sets. It is this latter form that is used in Figure 26 (a) since `refA` and `refB` are sets in this case. In our example, one of the two sets is `{Sale}` and the other is `{Payment, CashPayment, CreditPayment, CheckPayment}` (class `Payment` in the analysis model has been refined using the `TopDownGen` refinement).

Figure 26 (b) specifies how traceability links are established for refinement `DetailAssoFunctionality`. For each path that we can find in the refined model between `refA` and `refB` (we use operation `getPaths()` of class `Path`), we establish a traceability link between the removed association `origAsso` (in the original model) and each element of the path (i.e., associations and classes). In our example, this results in a traceability link between the association between `Payment` and `Sale` (analysis model)

⁶ In this article, we assume associations are binary, although n-ary associations can be handled following the same principles. Future work will adapt our OCL expressions to account for n-ary associations.

and CreditPayment, CreditCard, CheckPayment, DriverLicense, Customer, and their relationships, in the design model.

```

Context: DetailAssoFunctionality
let deletedAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation))
    .affectedElement.oclAsType(Association)
let origA = deletedAsso.memberEnd.class->any(true)
let origB = deletedAsso.memberEnd.class->excluding(origA)
let refA = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origA.name)
let refB = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origB.name)
in
self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation))
and Path.exists(refA, refB)

```

(a) Constraint on atomic changes

```

Context: DetailAssoFunctionality
let origAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation))
    .affectedElement.oclAsType(Association)
let origA = origAsso.memberEnd.class->any(true)
let origB = origAsso.memberEnd.class->excluding(origA)
let refA = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(t|name=origA.name)
let refB = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(t|name=origB.name)
in
Path.getPaths(refA, refB)->forAll(p:Path|
    Sequence{1..p.elements->size()->forAll(i|
        self.TraceabilityLink->exists(origin = origAsso and target = p.elements->at(i))
    )
}
)

```

(b) Traceability links

Figure 26 Refinement DetailAssoFunctionality

6.2 TurnAttriIntoClass

A TurnAttriIntoClass refinement means that an attribute of a class has been removed, a class has been added, and an association has been added between the added class and the class from which the attribute has been removed (Figure 27 (a)). The refinement is thus based on three atomic changes of types AddedClass, AddedAssociation and DeletedAttribute. In addition, one end of the added association should be the added class, and the other end should be the refinement of the class from which the attribute has

been removed (this check is the purpose of the last five lines of the expression). Referring to Figure 25, Attribute `price` in class `ProductDescription` has been turned into a class, namely `ProductPrice` according to the `TurnAttriIntoClass` refinement type.

Once a `TurnAttriIntoClass` has been detected, three traceability links have to be established (Figure 27 (b)): between the original class (`origClass`) and the new class (`newClass`) and association (`newAsso`), and between the original class and its corresponding refined class (`refinedClass`) in the refined model. Indeed, we need those three traceability links since if changes are made to the original class (e.g., changing its attributes), we may have to update the refined class, the added association and the added class (e.g., if some attributes are added to the original class, a subset of those may have to be moved to the added class in the refined model).

Note that we do not need to establish similar traceability links between the deleted attribute and the added association and class. Indeed, if a change is made to this attribute in the original model, its class will be “horizontal” impacted. As a result, thanks to the three established traceability links, the added association and class will be “vertical” impacted.

```

Context: TurnAttriIntoClass

let newAsso = self.atomicChanges->select(oclIsTypeOf(AddedAssociation)).
    affectedElement.oclAsType(Association)
let deletedAttribute = self.atomicChanges->select(oclIsTypeOf(DeletedAttribute)).
    affectedElement.oclAsType(Property)

in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges->exists(oclIsTypeOf(AddedAssociation))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAttribute))
and newAsso.memberEnd.class->includes(self.atomicChanges
    ->select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newAsso.memberEnd.class->includes(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(t | name = deletedAttribute.class.name))

```

(a) Constraint on atomic changes

```

Context: TurnAttriIntoClass

let delAtt = self.atomicChanges->
    select(oclIsTypeOf(DeletedAttribute)).affectedElement.oclAsType(Property)
let newClass = self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)
let newAsso = self.atomicChanges->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
let refinedClass = newAsso.memberEnd.class->excluding(newClass)
let origClass = delAtt.class

in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origClass and target = newClass)
and self.traceabilityLink->exists(origin = origClass and target = newAsso)
and self.traceabilityLink->exists(origin = origClass and target = refinedClass)

```

(b) Traceability links

Figure 27 Refinement TurnAttriIntoClass

6.3 AssoEndMultiplicityRef

An AssoEndMultiplicityRef refinement is simple as it is detected, as specified in Figure 28 (a), from a single atomic change of type ChangedAssoEndMultiplicity (the affected element of such a change is an Association). Referring to Figure 25, the multiplicity on the class Register end of the association between classes Store and Register is refined according to the AssoEndMultiplicityRef refinement type: the original multiplicity of 1 is changed into 1..*. A similar refinement has also taken place

on the class SalesLineItem end of the association between class ProductDescription and SalesLineItem.

Once such an atomic change has been detected, a refinement, and corresponding traceability links can be specified: Figure 28 (b). The refinement's unique traceability link is between the original association (i.e., the affectedElement of the atomic change) and the refined association, e.g., between the association between classes Store and Register in Figure 25 (a) and the association between classes Store and Register in Figure 25 (b). The refined association in the refined model is identified by looking for the association end being refined (referred to as refAssoEnd) in the refined model. The class owning the association end (Property) has the same name as the class owning the original association end (referred to as origAssoEnd), the class owning the other association end of the association has the same name as the class owning the other association end of the original association, and the multiplicity (i.e., upper and/or lower) of the original association end is changed, in order to establish a new traceability link corresponding to the AssoEndMultiplicityRef refinement.

```

Context: AssoEndMultiplicityRef
self.atomicChanges->size() = 1
and self.atomicChanges->exists(oclIsTypeOf(ChangedAssoEndMultiplicity))

```

(a) Constraint on atomic changes

```

Context: AssoEndMultiplicityRef
let origAssoEnd = self.atomicChanges->select(oclIsTypeOf(ChangedAssoEndMultiplicity))
    .affectedElement.oclAsType(Property)
let refAssoEnd = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsType(Property))->
    select(p| p.class.name = origAssoEnd.class.name
        and p.association.memberEnd->excluding(p).class.name =
            origAssoEnd.association.memberEnd->excluding(origAssoEnd).class.name
        and (p.upper<>origAssoEnd.upper or p.lower<>origAssoEnd.lower))
in
self.traceabilityLinks->size() = 1
and self.traceabilityLinks->exists{t| t.origin = origAssoEnd.association
    and t.target = refAssoEnd.association}

```

(b) Traceability links

Figure 28 Refinement AssoEndMultiplicityRef

6.4 AssoEndIsNavigableRef

An `AssoEndIsNavigableRef` refinement is simple as it is detected, as specified in Figure 29 (a), from a single atomic change of type `ChangedAssoEndIsNavigable` (the affected element of such a change is an `Association`): one of the association ends of the association is changed from navigable to non-navigable, or from non-navigable to navigable. Referring to Figure 25, the only navigable end of the association between classes `Store` and `Register` (i.e., the class `Register` end) is refined into a non-navigable end according to the `AssoEndIsNavigableRef` refinement type. A similar refinement has also taken place on the class `Sale` end of the association between classes `Register` and `Sale` and on the class `ProductDescription` end of the association between class `ProductDescription` and `SalesLineItem`.

Once such an atomic change has been detected, a refinement, and corresponding traceability links can be specified: Figure 29 (b). The refinement's unique traceability link is between the original association (i.e., the `affectedElement` of the atomic change) and the refined association, e.g., between the association between classes `Store` and `Register` in Figure 25 (a) and the association between classes `Store` and `Register` in Figure 25 (b). Similarly to the previous refinement, the refined association in the refined model is identified by looking for the association end being refined (referred to as `refAssoEnd`) in the refined model. The class owning the association end (`Property`) has the same name as the class owning the original association end (referred to as `origAssoEnd`), the class owning the other association end of the association has the same name as the class owning the other association end of the original association, and the number of the `navigableOwnedEnd` of the association is changed, in order to establish a new traceability link corresponding to the `AssoEndIsNavigableRef` refinement.

```

Context: AssoEndIsNavigableRef
self.atomicChanges->size() = 1
and self.atomicChanges->exists(oclIsTypeOf(ChangedAssoEndIsNavigable))

```

(a) Constraint on atomic changes

```

Context: AssoEndIsNavigableRef

let origAssoEnd = self.atomicChanges->select(oclIsTypeOf(ChangedAssoEndIsNavigable))
    .affectedElement.oclAsType(Property)

let refAssoEnd = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsType(Property))->
    select(p| p.class.name = origAssoEnd.class.name
    and p.association.memberEnd->excluding(p).class.name =
    origAssoEnd.association.memberEnd->excluding(origAssoEnd).class.name
    and (p.association.navigableOwnedEnd->size()
    <>origAssoEnd.association.navigableOwnedEnd).size())

in
self.traceabilityLinks->size() = 1
and self.traceabilityLinks->exists(t| t.origin = origAssoEnd.association
    and t.target = refAssoEnd.association)

```

(b) Traceability links

Figure 29 Refinement AssoEndIsNavigableRef

6.5 AssoEndTypeRef

An AssoEndTypeRef refinement is simple as it is detected, as specified in Figure 30 (a), from a single atomic change of type ChangedAssoEndType (the affected element of such a change is an Association). Referring to Figure 25, the association between classes ProductCatalog and ProductDescription is refined into a composition association according to the AssoEndTypeRef refinement type: the aggregation type of one of the association ends of the association is changed. A similar refinement has also taken place on the association between classes Sale and SalesLineItem.

Once such an atomic change has been detected, a refinement, and corresponding traceability links can be specified: Figure 30 (b). The refinement's unique traceability link is between the original association (i.e., the affectedElement of the atomic change) and the refined association, e.g., between the association between classes ProductCatalog and ProductDescription in Figure 25 (a) and the association between classes ProductCatalog and ProductDescription in Figure 25 (b). Similarly to the previous refinement, the refined association in the refined model is

identified by looking for the association end being refined (referred to as `refAssoEnd`) in the refined model. The class owning the association end (`Property`) has the same name as the class owning the original association end (referred to as `origAssoEnd`), the class owning the other association end of the association has the same name as the class owning the other association end of the original association, and the `AggregationKind` of the association is changed, in order to establish a new traceability link corresponding to the `AssoEndTypeRef` refinement.

```

Context: AssoEndTypeRef
self.atomicChanges->size() = 1
and self.atomicChanges->exists(oclIsTypeOf(ChangedAssoEndType))

```

(a) Constraint on atomic changes

```

Context: AssoEndTypeRef
let origAssoEnd = self.atomicChanges->
    select(oclIsTypeOf(ChangedAssoEndType)).affectedElement.oclAsType(Property)
let refAssoEnd = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsType(Property))->
    select(p| p.class.name = origAssoEnd.class.name
    and p.association.memberEnd->excluding(p).class.name =
    origAssoEnd.association.memberEnd->excluding(origAssoEnd).class.name
    and (p.aggregation<>origAssoEnd.aggregation)
in
self.traceabilityLinks->size() = 1
and self.traceabilityLinks->exists(t| t.origin = origAssoEnd.association
    and t.target = refAssoEnd.association)

```

(b) Traceability links

Figure 30 Refinement `AssoEndTypeRef`

7 CONCLUSION

UML models are, for typical systems, very complex artifacts. Modern development practices are iterative and rely on the stepwise refinement of analysis models into increasingly detailed design models, all the way down to implementation. However, changes are typically taking place at the same time as refinements and this results into a complex change management problem. How, under those conditions, can one ensure that models at different levels of abstractions remain consistent, especially in a context where changes and refinements are performed by different individuals in the context of large teams?

This thesis proposes a methodology and automation strategy. It is based on a careful classification of changes and refinements (capturing the changes' intent) in UML models and an automated identification of refinements based on detected changes. For each refinement, traceability links are then automatically established and can then be used to control the impact of changes in more abstract models on more refined models. We refer to this process as Vertical Impact Analysis. This work complements and extends earlier work on the impact analysis across UML diagrams within the same model, referred to as Horizontal Impact Analysis. Another contribution of this thesis is of methodological nature: we provide a way, which is based on metamodeling and constraints in the Object Constraint Language (OCL), to formally define change types, relate them to change intents (refinements) and formally specify the derivation of traceability links. This approach, while allowing for a rigorous and formal specification, has the advantage of facilitating the automation (the metamodel and constraints are a starting point for tool design) and is implementable using available, industry-strength modeling technology.

The thesis is only a first step as it only considers VIA for class diagrams. Much more work is under way to extend the work to the complete set of UML diagrams. But a first case study, based on a refined design model that was proposed independently from this research, shows that our classification and algorithms are complete and can accommodate all present changes.

As introduced in the conceptual metamodel (see Section 4.1.1), the mechanism we proposed supports not only class diagram, but also other diagrams, e.g., sequence diagram. In this work, only class diagram refinements are considered (i.e., classified and formalized). One of our future works is to extend the work to the complete set of UML diagrams, e.g., sequence diagram.

As shown in the metamodel for refinement (see Section 4.1.2), a composite refinement is composed of a series of atomic refinements and/or other composite refinements. Although we provide a way to model them, we have not addressed their identification, which will be part of our future work. One possible area of investigation is perhaps to identify constraints that may exist among the atomic refinements and/or composite refinements contained by the composite refinement.

We provide a hierarchical taxonomy of class diagram atomic refinements based on a careful and systematic study of the related literature (conference and journal articles, and text books) or according to our own experience of UML-based software development. We made an effort to be as systematic as possible; however this taxonomy is also expected to be refined over time.

We propose to adapt the approach proposed in [4] (i.e., horizontal impact analysis) for vertical impact analysis (see Section 4.1.5). However in order to get more precise and/or complete horizontal and vertical impact analysis results, the HIA approach proposed in [4] has to be extended as we discussed in Section 3.3.1.

As we mentioned in Section 4.4.2, there exists an order in which refinements should be identified, finding such an order is however part of our future work as we currently rely on a multi-pass heuristic: OCL rules identifying refinements are all evaluated once, twice, and so on, until no new traceability link is established.

In our work, an initial framework for performing vertical impact analysis is introduced. However, how to perform VIA based on the traceability links established between two models has not been sufficiently addressed. For example, we may establish more than one traceability links between two identical model elements of these two models because

it is possible that more than one refinements have been performed on the same model element. When VIA is performed, we have to choose which traceability link to follow to identify impacts. How to choose traceability link(s) to follow, and whether different kinds of links have different impacts, will be one of our future works. Besides, how to combine HIA and VIA together is not sufficiently addressed and will be a future work as well.

REFERENCES

- [1] Arnold R. S. and Bohner S. A., "Impact analysis-Towards a framework for comparison," *Proc. Conference on Software Maintenance*, pp. 292-301, 1993.
- [2] Bohner S. A. and Arnold R. S., "An Introduction to Software Change Impact Analysis," in S. A. Bohner and R. S. Arnold, Eds., *Software Change Impact Analysis*, IEEE Computer Society, pp. 1-25, 1996.
- [3] Bohner S. A. and Arnold R. S., *Software Change Impact Analysis*, IEEE Computer Society Press, 1996.
- [4] Briand L. C., Labiche Y., O'Sullivan L. and Sowka M., "Automated Impact Analysis of UML Models," *Journal of Systems and Software*, vol. 79 (3), pp. 339-352, 2006.
- [5] Bruegge B. and Dutoit A. H., *Object-Oriented Software Engineering Using UML, Patterns, and Java*, Prentice Hall, 2nd Edition, 2004.
- [6] Eclipse Foundation, Eclipse Java Development Tools (JDT), www.eclipse.org/jdt (Last accessed May 2006)
- [7] Eclipse Foundation, Eclipse Modeling Framework, www.eclipse.org/emf/ (Last accessed May 2006)
- [8] Eclipse Foundation, Eclipse Technology Project, www.eclipse.org/technology/index.php (Last accessed May 2006)
- [9] Eclipse Foundation, Eclipse Tools Project, www.eclipse.org/tools/ (Last accessed May 2006)
- [10] Eclipse Foundation, Plug-in Development Environment (PDE), www.eclipse.org/pde (Last accessed May 2006)
- [11] Eclipse Foundation, UML2: EMF-Based UML 2.0 Metamodel Implementation, www.eclipse.org/uml2/ (Last accessed May 2006)
- [12] Engels G., Heckel R., Kuster J. M. and Groenewegen L., "Consistency-Preserving Model Evolution through Transformation," *Proc. Unified Modeling Language. Model Engineering, Concepts, and Tools. LNCS*, 2460, pp. 212-26, 2002.
- [13] Engels G., Kuster J. M. and Groenewegen L., "Consistent Interaction of Software Components," *Proc. Integrated Design and Process Technology*, 2002.
- [14] Fowler M., *Refactoring Improving The Design of Existing Code*, The Addison-Wesley Object Technology Series, Addison-Wesley, 1999.

- [15] Hnatkowska B., Huzar Z., Kuzniarz L. and Tuzinkiewicz L., "Refinement Relationship between Collaborations," *Proc. Workshop on Consistency Problems in UML-based Software Development, UML?3*, 2003.
- [16] IBM-Rational: Rational Software Architect, 2005. [www-306-ibm.com/software/awdtools/architect/swarchitect/](http://www-306.ibm.com/software/awdtools/architect/swarchitect/).
- [17] Judson S. R., France R. B. and Carver R. H., "Supporting Rigorous Evolution of UML Models," *Proc. IEEE International Conference on Engineering of Complex Computer Systems*, pp. 128-137, 2004.
- [18] Kleppe A., Warmer J. and Bast W., *MDA Explained - The Model Driven Architecture: Practice and Promise*, Addison-Wesley, 2003.
- [19] Kroll P. and Kruchten P., *The Rational Unified Process Made Easy: A Practitioner's Guide to the RUP*, Addison-Wesley, 2003.
- [20] Larman C., *Applying UML and Patterns*, Prentice-Hall, 3rd Edition, 2004.
- [21] Letelier P., "A Framework for Requirements Traceability in UML-Based Projects," *Proc. International Workshop on Traceability in Emerging Forms of Software Engineering, in Conjunction with ASE*, 2002.
- [22] Li L. and Offutt A. J., "Algorithmic analysis of the impact of changes to object-oriented software," *Proc. IEEE International Conference on Software Maintenance*, pp. 171-184, 1996.
- [23] Li L. and Offutt A. J., "Algorithmic analysis of the impact of changes to object-oriented software," George Mason University ISSE Department Technical Report ISSE-TR-96-02, 1996.
- [24] Marciniak J. J., *Encyclopedia of Software Engineering*, Wiley-Interscience, 2nd Edition, 2001.
- [25] Mens T., Software Engineering Terminology from <http://staff.umh.ac.be/Mens.Tom/> (Last accessed 1 December 2004)
- [26] Mens T. and D'Hondt T., "Automating Support for Software Evolution in UML," *Automated Software Engineering (Springer)*, vol. 7 (1), pp. 39-59, 2000.
- [27] OMG, "UML 2.0 Superstructure Specification," Object Management Group, Final Adopted Specification ptc/03-08-02, 2003.
- [28] OMG, *OMG Unified Modeling Language Specification, version 2.0*, <http://www.omg.org/technology/documents/formal/uml.htm>, October, 2004.
- [29] Pender T., *UML Bible*, Wiley, 2003.

- [30] Pons C. and Kutsche R.-D., "Traceability across Refinement Steps in UML Modeling," *Proc. Workshop on Software Model Engineering, in conjunction with UML'04*, 2004.
- [31] Pons C., Perez G., Giandini R. and Kutsche R., "Understanding Refinement and Specialization in the UML," *Proc. 2nd International Workshop on Managing SPecialization/Generalization Hierarchies.*, 2004.
- [32] Selic B., "Using UML for Modeling Complex Real-Time Systems," *Proc. ACM SIGPLAN Workshop on Languages, Compilers and Tools for Embedded Systems*, LNCS 1474, pp. 250-260, 1998.
- [33] Shen W., Lu Y. and Low W. L., "Extending the UML Metamodel to Support Software Refinement," *Proc. Workshop on Consistency Problems in UML-Based Software Development, in conjunction with UML*, 2002.
- [34] von Knethen A. and Grund M., "QuaTrace: A Tool Environment for (Semi-)Automatic Impact Analysis Based on Traces," *Proc. International Conference on Software Maintenance*, pp. 246-255, 2003.

Appendix A Metamodel

Figure 31 The complete metamodel

Appendix B Dictionary For Metamodel

This appendix specifies the metaclasses of the metamodel presented in the Figure 8, Figure 11, Figure 13, and Figure 14, listed in alphabetical order. The description for each metaclass is broken down into sub-sections corresponding to different aspects. The following sub-sections and conventions are used to specify a metaclass.

- ◆ The *heading* gives the name of the metaclass.
- ◆ The “Description” sub-section gives a brief textual description of the meaning of a metaclass.
- ◆ All the direct generalizations of the metaclass are listed in the “Generalizations” sub-section.
- ◆ A detailed description of the purpose of the metaclass is given in the “Purpose” sub-section.
- ◆ The “Attributes” sub-section lists each of the attributes that are defined for that metaclass. Each attribute is specified by its name, its type, and multiplicity. This is followed by a textual description of the purpose and meaning of the attribute.
- ◆ The “Associations” sub-section lists all the association ends owned by the metaclass. The format for these is the same as the one for attributes described above.

B.1 AtomicChange

Description

The metaclass `AtomicChange` represents the concept of atomic change defined in Section 2.3: a unitary and primitive change applied to a UML model that cannot be decomposed into other atomic changes.

Generalizations

- ◆ none

Purpose

Atomic changes are used to identify refinements.

Attributes

- ◆ `type: AtomicChangeTypes`

It specifies the type of an atomic change. Refer to the description for `AtomicChangeTypes` for more information.

Associations

- ◆ `changeDescription: ChangeDescription [1]`

It specifies more detailed information of an atomic change except the type of the atomic change. Refer to the description for `ChangeDescription` for more information.

- ◆ `affectedElement: Element [1]`

It specifies the directly affected element of the atomic change.

B.2 AtomicChangeTypes

Description

`AtomicChangeTypes` specifies the different possible types of an atomic change. It is an enumeration type of the following literal values:

- ◆ `changed` Indicates that the affected element of an atomic change is changed.
- ◆ `moved` Indicates that the affected element of an atomic change is moved from one location to another location.
- ◆ `deleted` Indicates that the affected element of an atomic change is deleted.
- ◆ `added` Indicates that the affected element of an atomic change is added.

Generalizations

- ◆ `none`

B.3 AtomicRefinement

Description

The metaclass `AtomicRefinement` represents the concept of atomic refinement defined in Section 4.1.2: a refinement which can not be decomposed into other refinements.

Generalizations

- ◆ Refinement

Purpose

Atomic refinements are used to represent those refinements which can not be decomposed into other refinements. Atomic refinements can be used to constitute composite refinements (refer to the description for `CompositeRefinement`).

Attributes

No attribute.

Associations

- ◆ `atomicChanges: AtomicChange [1..*]`

It indicates a group of atomic changes used to derive an atomic refinement.

B.4 Change

Description

A change can be any modification performed on the UML model.

Generalizations

- ◆ none

Purpose

A change is used during horizontal impact analysis to identify which elements are impacted and how these elements are impacted because of this change.

Attributes

No attribute.

Associations

- ◆ `changedElement: Element [*]`

It indicates the group of changed elements defined on a change. This concept is adapted from [4] in its Section 4.1.2. The criteria of identifying changed elements are given in [4] as well.

- ◆ impacts: Impact [*]

It indicates the group of impacted elements resulting from the change. This concept is adapted from [4] in its Section 7.6.

B.5 ChangeDescription

Description

The metaclass `ChangeDescription` provides a detailed description of an atomic change.

Generalizations

- ◆ none

Purpose

See description.

Attributes

- ◆ afterValue: String

It specifies the value after an atomic change of type `changed` (see `AtomicChangeTypes`) is made.

- ◆ beforeValue: String

It specifies the value before an atomic change of type `changed` (see `AtomicChangeTypes`) is made.

Associations

- ◆ targetLocation: Element [0..1]

This denotes the element, in the refined model, that owns the affected element (see `affectedElements` in class `AtomicChange`) for an atomic change of type `moved` (see `AtomicChangeTypes`) when this owner element is itself an element.

- ◆ diagramLocation: UMLDiagram [0..2]

This denotes the diagram, in the original or refined model, that owns the affected element (see `affectedElements` in class `AtomicChange`) for an atomic change of type `moved` (see `AtomicChangeTypes`) when this owner element is not an element (it is a diagram).

B.6 ClassDiagram

Description

`ClassDiagram` is one of the subclasses of the metaclass `UMLDiagram`. It is used to represent a class diagram view of a UML model.

Generalizations

- ◆ `UMLDiagram`

Purpose

See description.

Attributes

No attribute.

Associations

No association.

B.7 CompositeRefinement

Description

The metaclass `CompositeRefinement` represents the concept of composite refinement defined in Section 4.1.2: refinements which are composed of several refinements which can be atomic refinements and/or composite refinements.

Generalizations

- ◆ `Refinement`

Purpose

The composite refinement is used to group refinements.

Attributes

No attribute.

Associations

- ◆ `containedRef: Refinement [2..*]`

It specifies the refinements contained in a composite refinement.

B.8 DerivedTraceabilityLink

Description

`DerivedTraceabilityLink` is a traceability link derived from a sequence of traceability links.

Generalizations

- ◆ `TraceabilityLink`

Purpose

It is used to derive a traceability link from a sequence of traceability links: a link can be established between the origin of the first traceability link in the sequence and the target of the last traceability link in the sequence.

Attributes

No attributes.

Associations

- ◆ `containedTLinks: TraceabilityLink [2..*]`

It indicates a sequence (ordered association) of traceability links from which the derived traceability link is derived.

B.9 Element

Description

`Element` is an abstract metaclass. This class belongs to the UML 2.0 metamodel [28] and is therefore the bridge between our metamodel and the UML 2.0 metamodel.

Generalizations

- ◆ none

Purpose

In the UML 2.0 metamodel, an element is a constituent of a model. As such, it has the capability of owning other elements [28]. In our metamodel, an element is the bridge

connecting our metamodel with the UML 2.0 metamodel. All the model elements of the UML model on which we perform our vertical impact analysis are instances of the metaclass `Element`.

Attributes

No attribute.

Associations

The associations in the UML 2.0 metamodel are not described here.

B.10 HorizontalImpact

Description

A `HorizontalImpact` is an impact caused by a change when horizontal impact analysis is performed.

Generalizations

`Impact`

Purpose

See description.

Attributes

No attribute.

B.11 Impact

Description

An `Impact` is caused by a particular change. This concept is adapted from [4].

Generalizations

◆ none

Purpose

See description.

Attributes

No attribute.

Associations

- ◆ HIAImpacts: Impact [*]

It indicates the group of impacts caused by horizontal impact analysis. This association models the fact that an impact to a model element can result in other impacts.

- ◆ impactedElements: Element [*]

It indicates the group of impacted elements caused by an impact.

- ◆ changedElements: Element [*]

It indicates the group of changed elements caused by a change.

B.12 Refinement

Description

Refinement is an abstract metaclass. It is used as the common superclass for all metaclasses in our metamodel which represents the concept of refinement.

Generalizations

- ◆ none

Purpose

The metaclass Refinement is used to organize the different types of refinements as the abstract superclass of the composite design pattern.

Attributes

No attribute.

Associations

- ◆ traceabilityLinks: TraceabilityLink [*]

It indicates the traceability links that should be established for a refinement.

- ◆ originalModel: UMLModel [1]

It indicates the original model being refined.

- ◆ `refinedModel: UMLModel [1]`

It indicates the refined model.

- ◆ `userhelp: UserHelp [*]`

It indicates the user help needed for identifying a refinement or establishing a traceability link.

B.13 TraceabilityLink

Description

`TraceabilityLink` is an association class which is used to represent the concept defined in Section 2.5: a relationship that describes the traceability connection between a model element in one UML model and a model element of another UML model.

Generalizations

- ◆ none

Purpose

Traceability links are used to establish relationships between two UML models at different levels of abstraction. Traceability links have to be established before performing vertical impact analysis.

Attributes

- ◆ `possibility: Integer`

It specifies the possibility of establishing the traceability link (see Section 4.1.4).

Associations

- ◆ `target: Element [1..*]`

- ◆ It indicates the model element of the refined model which traceability link points to. Notice that it is possible that an `origin` element is connected to more than one `target` elements through more than one traceability links.

- ◆ `origin: Element [1..*]`

- ◆ It indicates the model element of the original model, which the traceability link originates from. Notice that it is possible that a target element is connected to more than one origin elements through more than one traceability links.

- ◆ type: Refinement [1]

It indicates the refinement for which the traceability link is established.

B.14 UMLDiagram

Description

UMLDiagram is an abstract metaclass, which is used as the superclass for all metaclasses in our metamodel which represent different views of UML model (e.g., ClassDiagram).

Generalizations

- ◆ none

Purpose

In our metamodel, UMLDiagram is used to represent different views of UML model on which refinements are performed.

Attributes

No attribute.

Associations

- ◆ modelElements: Element [1..*]

It indicates the model elements owned by the UML diagram.

B.15 UMLModel

Description

UMLModel is a metaclass used to group UML diagrams. We assume that the diagrams contained in a UML model are consistent. From the aspect of the software lifecycle, this group of diagrams should be in the same phase of the lifecycle.

Generalizations

- ◆ none

Purpose

See description.

Attributes

No attribute.

Associations

- ◆ toRefinedModel: Refinement [*]

It indicates the refinements which relate the model to its refined model(s). The rolename denotes that the model is connected to its refined model through the refinements.

- ◆ toOriginalModel: Refinement [*]

It indicates the refinements which relate the model to its original model(s). The rolename denotes that the model is connected to its original model through the refinements.

- ◆ diagram: UMLDiagram [1..*]

It indicates the diagrams contained in the UML model.

B.16 UserHelp**Description**

UserHelp is an abstract metaclass. It represents the user help that may be required for identifying some refinements or establishing the traceability links for these refinements.

Generalizations

- ◆ none.

Purpose

See description.

Attributes

No attribute.

Associations

No attribute.

B.17 VerticalImpact

Description

A `VerticalImpact` is an impact caused by a change through traceability links when vertical impact analysis is performed.

Generalizations

Impact

Purpose

See description.

Attributes

No attribute.

Associations

- ◆ `traceabilityLinks: TraceabilityLink [*]`

It indicates all traceability links between two UML models on which vertical impact analysis is performed.

Appendix C Example Atomic Changes

This appendix provides a list of example atomic changes. The `affectedElement` and/or `changeDescription` are indicated for each example.

C.1 Added

1. `AddedClass`
Example: Added `classA` to `classDiagramA`
`affectedElement: classA`
`diagramLocation: classDiagramA`
2. `AddedAttribute`
Example: Added `attributeA` to `classA`
`affectedElement: attributeA`
3. `AddedOperation`
Example: Added `operationA` to `classA`
`affectedElement: operationA`
4. `AddedAssociation`
Example: Added `associationA` between `classA` and `classB`
`affectedElement: associationA`
5. `AddedAssociationClass`
Example: Added `associationClassA` between `classA` and `classB`
`affectedElement: associationClassA`
6. `AddedGeneralization`
Example: Added `generalization` between `classA` (superclass) and `classB` (subclass)
`affectedElement: <generalization>`
7. `AddedInterface`
Example: Added `interfaceA` to `classDiagramA`
`affectedElement: interfaceA`
`diagramLocation: classDiagramA`
8. `AddedDependency`
Example: Added `dependency` between `classA` (supplier) and `classB` (client)
`affectedElement: <Dependency>`

C.2 Deleted

1. `DeletedClass`
Example: Deleted `classA` from `classDiagramA`
`affectedElement: classA`
`diagramLocation: classDiagramA`

2. DeletedAttribute
Example: Deleted attributeA from classA
affectedElement: attributeA
3. DeletedOperation
Example: Deleted operationA from classA
affectedElement: operationA
4. DeletedAssociation
Example: Deleted associationA between classA and classB
affectedElement: associationA
5. DeletedAssociationClass
Example: Deleted associationClassA between classA and classB
affectedElement: associationClassA
6. DeletedGeneralization
Example: Deleted generalization between classA (superclass) and classB (subclass)
affectedElement: <generalization>
7. DeletedInterface
Example: Deleted interfaceA from classDiagramA
affectedElement: interfaceA

diagramLocation: classDiagramA
8. DeletedDependency
Example: Deleted dependency between classA (supplier) and classB (client)
affectedElement: <Dependency>

C.3 Changed

C.3.1 ChangedClass

1. RenameClass
Example: Rename classA to classB
affectedElement: classA
beforeValue: classA
afterValue: classB
2. ChangedClassIsAbstract
Example: Changed classA's property isAbstract from false to true
affectedElement: classA
beforeValue: false
afterValue: true

3. **ChangedClassVisibility**
Example: Changed classA's property visibility from public to private
affectedElement: classA
beforeValue: public
afterValue: private
4. **ChangedClassIsActive**
Example: Changed classA's property isActive from false to true
affectedElement: classA
beforeValue: false
afterValue: true
5. **ChangedClassIsLeaf**
Example: Changed classA's property isLeaf from false to true
affectedElement: classA
beforeValue: false
afterValue: true

C.3.2 ChangedAttribute

1. **RenameAttribute**
Example: Rename attribute1 to attribute2
affectedElement: attribute1
beforeValue: attribute1
afterValue: attribute2
2. **ChangedAttriType**
Example: Changed attributeA's type from String to Integer
affectedElement: attributeA
beforeValue: String
afterValue: Integer
3. **ChangedAttriMultiplicity**
Example: Changed attributeA's multiplicity from 1 to *
affectedElement: attributeA
beforeValue: 1
afterValue: *
4. **ChangedAttriVisibility**
Example: Changed attributeA's visibility from public to private
affectedElement: attributeA
beforeValue: public
afterValue: private

5. **ChangedAttriInitialValue**
Example: Changed attributeA's initialValue from a to b
affectedElement: attributeA
beforeValue: a
afterValue: b
6. **ChangedAttriIsOrdered**
Example: Changed attributeA's property isOrdered from false to true
affectedElement: attributeA
beforeValue: false
afterValue: true

C.3.3 ChangedOperation

1. **RenameOperation**
Example: Rename operation1 to operation2
affectedElement: operation1
beforeValue: operation1
afterValue: operation2
2. **ChangedOprIsAbstract**
Example: Changed operationA's property isAbstract from false to true
affectedElement: operationA
beforeValue: false
afterValue: true
3. **ChangedOprParameter**
Example: Changed one of parameters of the operationA
affectedElement: operationA
4. **ChangedOprVisibility**
Example: Changed operationA's visibility from public to private
affectedElement: operationA
beforeValue: public
afterValue: private
5. **ChangedOprReturnType**
Example: Changed operationA's return type from a to b
affectedElement: operationA
beforeValue: a
afterValue: b

C.3.4 ChangedAssociation

1. **ChangedAssoEndType**
 Example: Changed associationA's association end classA's property aggregation from none to composite
 affectedElement: associationA's association end
 beforeValue: none
 afterValue: composite
2. **ChangedAssoEndMultiplicity**
 Example: Changed associationA's association end classA's property multiplicity from 1 to *
 affectedElement: associationA's association end
 beforeValue: 1
 afterValue: *
3. **ChangedAssoEndIsNavigable**
 Example: Changed associationA's association end classA's property isNavigable from false to true
 affectedElement: associationA's association end
 beforeValue: false
 afterValue: true

C.3.5 ChangedGeneralization

1. **ChangedGenIsSubstitutable**
 Example: Changed generalization's property isSubstitutable from false to true
 affectedElement: <Generalization>
 beforeValue: false
 afterValue: true

C.3.6 ChangedInterface

1. **RenameInterface**
 Example: Rename interfaceA to interfaceB
 affectedElement: interfaceA
 beforeValue: interfaceA
 afterValue: interfaceB
2. **ChangedInterfaceIsAbstract**
 Example: Changed interfaceA's property isAbstract from false to true
 affectedElement: interfaceA
 beforeValue: false
 afterValue: true
3. **ChangedInterfaceVisibility**
 Example: Changed interfaceA's property visibility from public to private
 affectedElement: interfaceA
 beforeValue: public
 afterValue: private

4. ChangedInterfaceIsActive
 Example: Changed interfaceA's property isActive from false to true
 affectedElement: interfaceA
 beforeValue: false
 afterValue: true
5. ChangedInterfaceIsLeaf
 Example: Changed interfaceA's property isLeaf from false to true
 affectedElement: interfaceA
 beforeValue: false
 afterValue: true

C.3.7 ChangedDependency

1. RenameDependency
 Example: Rename dependencyA to dependencyB
 affectedElement: dependencyA
 beforeValue: dependencyA
 afterValue: dependencyB

C.4 Moved

1. MovedAttribute
 Example: Moved attributeA from classA to classB
 affectedElement: attributeA
 targetLocation: classB
2. MovedOperation
 Example: Moved operationA from classA to classB
 affectedElement: operationA
 targetLocation: classB
3. RelocateAssociation
 Example: associationA has two association ends: classA and classB. Moved one association end from classB to classC
 affectedElement: associationA
 targetLocation: classC
4. RelocateGeneralization
 Example: the generalization connects classA and classB. Moved one end from classB to classC
 affectedElement: <Generalization>
 targetLocation: classC
5. RelocateDependency
 Example: the dependencyA connects classA and classB. Moved one end from classB to classC
 affectedElement: dependencyA

targetLocation: classC

Appendix D Taxonomy For Atomic Changes

Figure 32 shows the top level of taxonomy which contains eight concrete atomic changes of type added, eight concrete atomic changes of type deleted, five concrete atomic changes of type moved, and seven abstract atomic changes of type changed. For these abstract changes of type changed, sub-classifications are provided in Figure 33, Figure 34, Figure 35, Figure 36, Figure 37, Figure 38, and Figure 39. A textual description of each concrete atomic change is provided as follows.

1. AddedClass: the addition of a class.
2. AddedAttribute: the addition of an attribute to a class.
3. AddedOperation: the addition of an operation to a classifier.
4. AddedAssociation: the addition of an association between two classes.
5. AddedGeneralization: the addition of a generalization relationship between two classes.
6. AddedInterface: the addition of an interface.
7. AddedDependency: the addition of a dependency relationship.
8. AddedAssociationClass: the addition of an association class.
9. DeletedClass: the deletion of a class.
10. DeletedAttribute: the deletion of an attribute from a class.
11. DeletedOperation: the deletion of an operation from a classifier.
12. DeletedAssociation: the deletion of an association between two classes.
13. DeletedGeneralization: the deletion of a generalization relationship between two classes.
14. DeletedInterface: the deletion of an interface.
15. DeletedDependency: the deletion of a dependency relationship.
16. DeletedAssociationClass: the deletion of an association class.
17. MovedAttribute: the move of an attribute between two classifiers.
18. MovedOperation: the move of an operation between two classifiers.
19. RelocateAssociation: the move of one of the association ends of an association from a classifier to another classifier.

20. RelocateGeneralization: the move of the general classifier or specializing classifier of a generalization relationship from a classifier to another classifier.
21. RelocateDependency: the move of the supplier end or client end of a dependency relationship between two model elements.
22. RenamedClass: the change of a class name.
23. ChangedClassVisibility: the change of property visibility [27] of a class.
24. ChangedClassIsAbstract: the change of property isAbstract [27] of a class.
25. ChangedClassIsActive: the change of property isActive [27] of a class.
26. ChangedClassIsLeaf: the change of property isLeaf [27] of a class.
27. RenamedAttribute: the change of an attribute's name.
28. ChangedAttriType: the change of an attribute's type.
29. ChangedAttriMultiplicity: the change of property multiplicity [27] of an attribute.
30. ChangedAttriVisibility: the change of property visibility of an attribute.
31. ChangedAttriInitialValue: the change of property default [27] of an attribute.
32. ChangedAttriIsOrdered: the change of property isOrdered [27] of an attribute.
33. RenamedOperation: the change of an operation's name.
34. ChangedOprIsAbstract: the change of property isAbstract of an operation.
35. ChangedOprParameter: the change of an operation's parameter list.
36. ChangedOprVisibility: the change of property visibility of an operation.
37. ChangedOprReturnType: the change of an operation's return type.
38. ChangedAssoEndType: the change of property aggregation [27] of an association end.
39. ChangedAssoEndMultiplicity: the change of property multiplicity of an association end.
40. ChangedAssoEndIsNavigable: the change of the navigability of an association end.
41. ChangedGenIsSubstitutable: the change of property isSubstitutable [27] of a generalization relationship.
42. RenamedInterface: the change of an interface name.

- 43. ChangedInterfaceIsAbstract: the change of property isAbstract of an interface.
- 44. ChangedClassVisibility: the change of property visibility of an interface.
- 45. ChangedClassIsActive: the change of property isActive of an interface.
- 46. ChangedClassIsLeaf: the change of property isLeaf of an interface.
- 47. RenamedDependency: the change of a dependency relationship name.

Figure 32 Complete Taxonomy for Atomic Changes – Top Level

Figure 33 Taxonomy for Atomic Changes of Type `ChangedClass`

Figure 34 Taxonomy for Atomic Changes of Type `ChangedAttribute`

Figure 35 Taxonomy for Atomic Changes of Type `ChangedOperation`

Figure 36 Taxonomy for Atomic Changes of Type `ChangedAssociation`

Figure 37 Taxonomy for Atomic Changes of Type `ChangedGeneralization`

Figure 38 Taxonomy for Atomic Changes of Type ChangedInterface

Figure 39 Taxonomy for Atomic Changes of Type ChangedDependency

Appendix E Taxonomy and formalization for refinements

Since a class diagram is a diagram showing a collection of classes and interfaces, along with the collaborations and relationships among classes and interfaces, we can classify class diagram refinements according to the way these classes, interfaces and relationships are changed and transformed. Classifying class diagram refinements this way helps ensure the completeness of the classification. Figure 40 shows the top level of the taxonomy which contains eight abstract refinements. For each abstract refinement, a second level of classification is provided in the following subsections.

Figure 40 Taxonomy for Refinements - Top Level

Note that we do not have any **Classes->Class** not **Class->Classes** abstract classes in our refinement taxonomy. The former family of refinement would refine several classes into a class, whereas the latter would refine a single class into several classes. It is impossible to have these kinds of refinements since the definitions would imply that the classes are isolated without relationship to connect them with other model elements of the diagram. For instance, in the former refinement, the classes being refined into one class should be related by some relationships. The refinement would then be **Classes+Rels->Class**, which already appears in the taxonomy.

Refinements `Class->Classes+Rels`, `Classes+Rels->Class`, `Classes+Rels->Classes+Rels`, `Rel->Classes+Rels`, `Classes+Rels->Rel`, `Rels->Rel`, `Rel->Rels`, and `InterfaceRefinement` are further described in Sections E.1, E.2, E.3, E.4, E.5, E.6, E.7, and E.8, respectively.

E.1 `Class->Classes+Rels`

This refinement refines a single class into several classes and relationships. The general purpose of this kind of refinement is to extend or split the functionality of the class being refined by introducing more classes and relationships. Figure 41 provides a refined classification (i.e., second level of classification) involving seven types of concrete atomic refinements.

Figure 41 Taxonomy for Refinement of Type `Class->Classes+Rels`

A class can be refined into several classes and their relationships for three main reasons. First, the rationale is to detail the responsibility of one class (in the original model) by adding more classes and relationships. `TopDownGen` (Section E.1.1) and `TopDownCom` (Section E.1.2) belong to this group: `TopDownGen` introduces more classes using generalization, and `TopDownCom` introduces more classes using composition. A second possible reason is to split the responsibility of one class and distribute this responsibility over several (new) classes. `ExtractClass` (Section E.1.3) and `TurnAttrIntoClass` (Section E.1.5) as well as `ExtractSubclass` (Section E.1.4) and `TurnAttrIntoSubclass` (Section E.1.6) belong to this group: `ExtractClass` and `TurnAttrIntoClass` extract some attributes and/or operations from the original class

to form a new class that is associated with the original class; `ExtractSubclass` and `TurnAttriIntoSubclass` extract some attributes and/or operations from the original class to form a subclass that specializes the original class. A third possible rationale is to refine an operation of the original class. `TurnOprIntoRel` (Section E.1.7) belongs to this group: `TurnOprIntoRel` refines an operation of the original class into a relationship which connects to the original class.

E.1.1 TopDownGen

Description: Introduce subclasses to the class being refined using generalization to suggest general-specific relationships.

Specification: The class `OriginalClass` of the original model is refined into the superclass `Superclass` and its subclass `Subclass`, as shown in Figure 42.

Figure 42 TopDownGen - Specification⁷⁸

User's Intention: Detail the responsibility of the original class by introducing subclasses using generalization, because these subclasses, though similar, have significant differences in the interface or services they provide.

Atomic Changes: Two kinds of atomic changes are required to derive the refinement: `AddedClass` and `AddedGeneralization`. Note that we only account for the situation in which only one subclass is added. If more than one subclass is added, more than one occurrence of the refinement of type `TopDownGen` is identified. The specification of

⁷ The two dependency relationships with label `TraceabilityLink: TopDownGen` are presented in the specification class diagram, but it does not mean that these traceability links must be explicitly represented or manually established. It is just for the purpose of clear explanation. It is same for the rest of atomic refinements in this appendix.

⁸ The model elements in the refined model are highlighted in order to distinguish them from the model elements of the original model.

refinement TopDownGen, i.e., the characterization of its atomic changes and their relations, is shown as the OCL invariant for class TopDownGen in Figure 43 (a).

Traceability Links: Two traceability links have to be established: one between the original class and the superclass of the added generalization; one between the original class and the added subclass. These traceability links are specified in the OCL expression in Figure 43 (b).

User Help: none.

<p>Context: TopDownGen</p> <pre> self.atomicChanges->size() = 2 and self.atomicChanges->exists(oclIsTypeOf(AddedClass)) and self.atomicChanges->exists(oclIsTypeOf(AddedGeneralization)) and self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)).affectedElement. oclAsType(Generalization).specific->includes(self.atomicChanges-> select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)) </pre>
<p>(a) Constraint on atomic changes</p>
<p>Context: TopDownGen</p> <pre> let newGen = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)) .affectedElement. oclAsType(Generalization) let superClass = newGen.general let subClass = newGen.specific let origClass = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class))->select(name = superClass.name) in self.traceabilityLinks->size() = 2 and self.traceabilityLink->exists(origin = origClass and target = superClass) and self.traceabilityLink->exists(origin = origClass and target = subClass) </pre>
<p>(b) Traceability links</p>

Figure 43 Refinement TopDownGen

Example: The example shown in Figure 44 comes from [20]. The class Payment of the analysis model is refined into the abstract class Payment plus the three subclasses: CashPayment, CreditPayment and CheckPayment. Three traceability links are established. Notice that this example presents a composite refinement which contains two types of atomic refinements: ClassIsAbstractRef which is derived from a single atomic change of type ChangedClassIsAbstract (performed once) and TopDownGen (performed three times).

Figure 44 TopDownGen - Example

E.1.2 TopDownCom

Description: Introduces new classes using composition associations to suggest whole-part relationships between the class being refined and the new added classes.

Specification: The class `OriginalClass` of the original model is refined into the classes `ComposedClass` and `ComposingClass`, as shown in Figure 45. The class `ComposedClass` is connected to the new added class `ComposingClass` by the composition association `newCom`.

Figure 45 TopDownCom - Specification

User's Intention: Detail the responsibility of the original class by introducing new classes using composition associations to suggest whole-part relationships. The instance of the part (i.e., new class) belongs to only one composite instance (i.e., original class) at a time. The part must always belong to a composite and the composite is responsible for the creation and deletion of its parts.

Atomic Changes: Two kinds of atomic changes are required to derive the refinement: `AddedClass` and `AddedAssociation`, such that the association has a composition end and the non-composition part of the added association points to the added class. The specification of refinement `TopDownCom` is shown as the OCL invariant for class `TopDownCom` in Figure 46 (a).

Traceability Links: Three traceability links have to be established: one between the original class and the composing class of the added composition association; one between the original class and the composed class; one between the original class and the added

composition association. These traceability links are specified in the OCL expressions in Figure 46 (b).

User Help: none.

<pre> Context: TopDownCom self.atomicChanges->size() = 2 and self.atomicChanges->exists(oclIsTypeOf(AddedClass)) and self.atomicChanges->exists(oclIsTypeOf(AddedAssociation)) and self.atomicChanges->select(oclIsTypeOf(AddedAssociation)) .affectedElement.oclAsType(Association).memberEnd-> exists(aggregation=Aggregation::composite)) and self.atomicChanges->select(oclIsTypeOf(AddedAssociation)) .affectedElement.oclAsType(Association).memberEnd-> select(aggregation<>Aggregation::none).class->includes(self.atomicChanges-> select(oclIsTypeOf(AddedClass)).oclAsType(Class)) </pre>
<p>(a) Constraint on atomic changes</p> <pre> Context: TopDownCom let newCom = self.atomicChanges->select(oclIsTypeOf(AddedAssociation)). affectedElement.oclAsType(Association) let composedClass = newCom.memberEnd->select(aggregation=Aggregation::composition) .class let composingClass = self.atomicChanges->select(oclIsTypeOf(AddedClass)) .affectedElement.oclAsType(Class) let origClass = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class))->select(name = composedClass.name) in self.traceabilityLinks->size() = 3 and self.traceabilityLink->exists(origin = origClass and target = composedClass) and self.traceabilityLink->exists(origin = origClass and target = composingClass) and self.traceabilityLink->exists(origin = origClass and target = newCom) </pre>
<p>(b) Traceability links</p>

Figure 46 Refinement TopDownCom

Example: Figure 47 presents an example. The new class *Finger* is added and connected to the class *Hand* by a composition association. Thus, an instance of the class *Hand* is composed of several instances of the class *Finger*.

Figure 47 TopDownCom - Example

E.1.3 ExtractClass

Description: Introduces a new class associated to the class being refined and moves some attributes and/or operations from the class being refined to the new class, thus splitting the responsibilities of the class being refined.

Specification: The attribute `movedAttribute` of the class `OriginalClass` is moved into the newly added class `NewClass` and the new association `newAsso` is added to connect the classes `RefinedClass` and `NewClass`, as shown in Figure 48. Notice that the class `OriginalClass`'s operations may be moved to the class `NewClass`, even though we do not show this situation in Figure 48.

Figure 48 ExtractClass - Specification

User's Intention: To split the responsibilities of the original class into two classes. When a class burdens many responsibilities and becomes too complicated, we may think of splitting this class into two classes so that each class handles a few clearer responsibilities.

Atomic Changes: Three or four kinds of atomic changes may be used to derive the refinement: AddedClass, AddedAssociation (between the added class and the class which the attribute/operation has been moved from), and MovedAttribute and/or MovedOperation (to the added class). However, it is not required to have both MovedAttribute and MovedOperation at the same time since sometimes only some attributes are moved or only some operations are moved. Figure 49 (a) only presents the case that only one MovedAttribute is included in the group of atomic changes in order

to make the OCL expressions more concise. (Accounting for moved operations is very similar.)

Traceability Links: Three traceability links have to be established: one between the original class and the refined class; one between the original class and the newly added class; one between the original class and the newly added association. These traceability links are specified in the OCL expressions in Figure 49 (b). Note that we do not establish traceability links at the (moved) attribute or operation level since we consider that a change to the attribute (or operation) in the original model may result in changes to both the refined class and the added class in the target model. Future work on vertical impact analysis will look into whether this is.

User Help: none.

```

Context: ExtractClass

let newAsso = self.atomicChanges->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
let movedAttribute = self.atomicChanges->select(oclIsTypeOf(MovedAttribute)).
    affectedElement.oclAsType(Property)
in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges->exists(oclIsTypeOf(AddedAssociation))
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))
and self.atomicChanges->select(oclIsTypeOf(MovedAttribute)).changeDescripton
    .targetLocation.oclAsType(Class)->equals(self.atomicChanges->
        select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newAsso.memberEnd.class->includes(self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newAsso.memberEnd.class->includes(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(t | name = movedAttribute.class.name))

```

(a) Constraint on atomic changes

```

Context: ExtractClass

let newClass = self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)
let newAsso = self.atomicChanges->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
let refinedClass = newAsso.memberEnd.class->excluding(newClass)
let origClass = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = refinedClass.name)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origClass and target = refinedClass)
and self.traceabilityLink->exists(origin = origClass and target = newClass)
and self.traceabilityLink->exists(origin = origClass and target = newAsso)

```

(b) Traceability links

Figure 49 Refinement ExtractClass

Example: Figure 50 presents an example excerpted from [14]. The class Person in the original model is refined into the classes Person and TelephoneNumber and the association officeTelephone. The attributes officeAreaCode and officeNumber are moved from the class Person into the newly added class TelephoneNumber. Note that in this example, these two attributes are renamed after the refinement ExtractClass is performed in which case a composite refinement is formed.

Figure 50 ExtractClass – Example

E.1.4 ExtractSubclass

Description: Introduces subclasses to the class being refined using generalization and moves some attributes and/or operations from the class being refined into the new subclasses.

Specification: As shown in Figure 51, the attribute `movedAttribute` of the class `OriginalClass` is moved into the newly added subclass `NewSubclass`. Note that the `OriginalClass`'s operations may be moved into the `NewSubclass`, even though we do not show this case in Figure 51.

Figure 51 ExtractSubclass - Specification

User's Intention: Since a class has attributes and/or operations that are used only in some of its instances, it is necessary to create a subclass for that subset of attributes and/or operations.

Atomic Changes: Three or four kinds of atomic changes are used to derive the refinement: `AddedClass`, `AddedGeneralization` (between the added class and the class which the attribute/operation has been moved from), `MovedAttribute` and/or `MovedOperation` (to the added class). However, it is not required to have both `MovedAttribute` and `MovedOperation` at the same time since sometimes only some attributes are moved or only some operations are moved. Figure 52 (a) only presents the case that only one `MovedAttribute` is included in the group of atomic changes in order to make the OCL expressions more concise.

Traceability Links: Two traceability links have to be established: one between the original class and the refined class; one between the original class and the new added class. These traceability links are specified in the OCL expressions in Figure 52 (b).

User Help: none.

<p>Context: ExtractSubclass</p> <pre> let newGen = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)). affectedElement.oclAsType(Generalization) let movedAttribute = self.atomicChanges->select(oclIsTypeOf(MovedAttribute)). affectedElement.oclAsType(Property) in self.atomicChanges->size() = 3 and self.atomicChanges->exists(oclIsTypeOf(AddedClass)) and self.atomicChanges->exists(oclIsTypeOf(AddedGeneralization)) and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute)) and self.atomicChanges->select(oclIsTypeOf(MovedAttribute)).changedDescripton. targetLocation.oclAsType(Class)->equals(self.atomicChanges-> select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)) and newGen.specific->includes(self.atomicChanges-> select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)) and newGen.general->includes(self.refinedModel.diagram-> select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))-> select(name = movedAttribute.class.name)) </pre>
<p>(a) Constraint on atomic changes</p> <hr/> <p>Context: ExtractSubclass</p> <pre> let newSubclass = self.atomicChanges-> select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class) let newGen = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)). affectedElement.oclAsType(Generalization) let refinedClass = newGen.general let origClass = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class))->select(name = refinedClass.name) in self.traceabilityLinks->size() = 2 and self.traceabilityLink->exists(origin = origClass and target = refinedClass) and self.traceabilityLink->exists(origin = origClass and target = newSubclass) </pre>
<p>(b) Traceability links</p>

Figure 52 Refinement ExtractSubclass

Example: The example shown in Figure 53 is adapted from [20]. The original class AuthorizationService has four attributes and one operation. Since the attribute creditCard and the operation getCreditCard() are specific to the credit card

authorization service, the new subclass CreditAuthorizationService is added and used to model this specific authorization service.

Figure 53 ExtractSubclass – Example

E.1.5 TurnAttriIntoClass

Description: Transforms an attribute of the class being refined into a class of its own, which is then associated to the class being refined.

Specification: As shown in Figure 54, the attribute `attribute1` of the class `OriginalClass` is refined into the newly added class `Attribute1`. The new association `newAsso` should be added to associate the class `Attribute1` with the class `RefinedClass`.

Figure 54 TurnAttriIntoClass - Specification

User's Intention: The attribute being refined contains too much information which has to be modeled using a class.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: AddedClass, AddedAssociation (between the added class and the class which the attribute is deleted from) and DeletedAttribute. The specification of refinement TurnAttriIntoClass is shown as the OCL invariant for class TurnAttriIntoClass in Figure 55 (a).

Traceability Links: Three traceability links have to be established: one between the original class and the refined class; one between the original class and the new added class; one between the original class and the new added association. These traceability links are specified in the OCL expressions in Figure 55 (b).

User Help: The user's help is required for identifying the refinement because it is very hard to guess that the deleted attribute is refined into the new added class based on the current resource we have.

```

Context: TurnAttriIntoClass

let newAsso = self.atomicChanges->select(oclIsTypeOf(AddedAssociation)).
    affectedElement.oclAsType(Association)
let deletedAttribute = self.atomicChanges->select(oclIsTypeOf(DeletedAttribute)).
    affectedElement.oclAsType(Property)

in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges->exists(oclIsTypeOf(AddedAssociation))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAttribute))
and newAsso.memberEnd.class->includes(self.atomicChanges
    ->select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newAsso.memberEnd.class->includes(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(t | name = deletedAttribute.class.name))

```

(a) Constraint on atomic changes

```

Context: TurnAttriIntoClass

let delAtt = self.atomicChanges->
    select(oclIsTypeOf(DeletedAttribute)).affectedElement.oclAsType(Property)
let newClass = self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)
let newAsso = self.atomicChanges->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
let refinedClass = newAsso.memberEnd.class->excluding(newClass)
let origClass = delAtt.class

in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origClass and target = newClass)
and self.traceabilityLink->exists(origin = origClass and target = newAsso)
and self.traceabilityLink->exists(origin = origClass and target = refinedClass)

```

(b) Traceability links

Figure 55 Refinement TurnAttriIntoClass

Examples: The attribute customer of the class Order (Figure 56(a)) is refined into the class Customer and the association between the classes Order and Customer (Figure 56(b)).

(a) original class diagram

(b) refined class diagram

Figure 56 TurnAttriIntoClass - Example

E.1.6 TurnAttriIntoSubclass

Description: Refines one attribute of the class being refined into its subclass.

Specification: As shown in Figure 57, the attribute `attribute1` of the class `OriginalClass` is refined into the newly added subclass `Attribute1`. The new generalization should be added between the classes `Attribute1` and `RefinedClass`.

Figure 57 TurnAttriIntoSubclass - Specification

User's Intention: The attribute being refined contains too much information which has to be modeled using a class which can be the subclass of the class containing the deleted attribute originally.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: `AddedClass`, `AddedGeneralization` (between the added class and the class which the attribute has been deleted from) and `DeletedAttribute`. The specification of refinement `TurnAttriIntoSubclass` is shown as the OCL invariant for class `TurnAttriIntoSubclass` in Figure 58 (a).

Traceability Links: Two traceability links have to be established: one between the original class and the refined class and the new added class. These traceability links are specified in the OCL expressions in Figure 58 (b).

User Help: The user's help is required for identifying the refinement because it is very hard to guess that the deleted attribute is refined into the new added subclass based on the current resource we have.

```

Context: TurnAttriIntoSubclass

let newGen = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)).
    affectedElement.oclAsType(Generalization)
let deletedAttribute = self.atomicChanges->select(oclIsTypeOf(DeletedAttribute)).
    affectedElement.oclAsType(Property)

in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges->exists(oclIsTypeOf(AddedGeneralization))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAttribute))
and newGen.specific->includes(self.atomicChanges
    ->select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newGen.general->includes(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(name = deletedAttribute.class.name))

```

(a) Constraint on atomic changes

```

Context: TurnAttriIntoSubclass

let delAtt = self.atomicChanges->
    select(oclIsTypeOf(DeletedAttribute)).affectedElement.oclAsType(Property)
let newClass = self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)
let newGen = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization))
    .affectedElement.oclAsType(Generalization)
let refinedClass = newGen.general
let origClass = delAtt.class

in
self.traceabilityLinks->size() = 2
and self.traceabilityLink->exists(origin = origClass and target = newClass)
and self.traceabilityLink->exists(origin = origClass and target = refinedClass)

```

(b) Traceability links

Figure 58 Refinement TurnAttriIntoSubclass

Examples: Figure 59 provides an example. The class Employee of the original model (Figure 59 (a)) has two attributes: Engineer and Salesman. The attribute Engineer is refined into the subclass Engineer of the refined model (Figure 59 (b)). The attribute Salesman is refined into the subclass Salesman of the refined model (Figure 59 (b)). In this example, the refinement TurnAttriIntoSubclass is applied twice.

(a) original class diagram

(b) refined class diagram

Figure 59 TurnAttriIntoClass - Example

E.1.7 TurnOprIntoRel

Description: Refines one operation of the class being refined into a relationship connecting to it.

Specification: As shown in Figure 60, the operation `Operation1()` of the class `OriginalClass` is refined into the newly added association `newRel` which is associated to the class `RefinedClass` which is refined from the class `OriginalClass`.

Figure 60 TurnOprIntoRel - Specification

User's Intention: The operation being refined can be more accurately modeled using an association instead.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: AddedAssociation, AddedClass, and DeletedOperation. The specification is shown as the OCL invariant for class TurnOprIntoRel in Figure 61 (a).

Traceability Links: Three traceability links have to be established: one between the original class and the refined class; one between the deleted operation and the new added association; one between the deleted operation and the added class. These traceability links are specified in the OCL expressions in Figure 61 (b).

User Help: The user's help is required for identifying the refinement because it is very hard to guess that the deleted operation is refined into the new added association based on the current resource we have.

```

Context: TurnOprIntoRel

let newAsso = self.atomicChanges->select(oclIsTypeOf(AddedAssociation)).
    affectedElement.oclAsType(Association)
let origOpr = self.atomicChanges->select(oclIsTypeOf(DeletedOperation)).
    affectedElement.oclAsType(Operation)

in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(AddedAssociation))
and self.atomicChanges->exists(oclIsTypeOf(DeletedOperation))
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and newAsso.memberEnd.class->includes(self.atomicChanges->select(
    oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newAsso.memberEnd.class->includes(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(name = origOpr.class.name))

```

(a) Constraint on atomic changes

```

Context: TurnOprIntoRel

let delOpr = self.atomicChanges->
    select(oclIsTypeOf(DeletedOperation)).affectedElement.oclAsType(Operation)
let newAsso = self.atomicChanges->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
let newClass = self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)
let refinedClass = newAsso.memberEnd.class->excluding(newClass)
let origClass = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = refinedClass.name)

in
self.traceabilityLinks->size() = 2
and self.traceabilityLink->exists(origin = delOpr and target = newAsso)
and self.traceabilityLink->exists(origin = origClass and target = refinedClass)
and self.traceabilityLink->exists(origin = delOpr and target = addedClass)

```

(b) Traceability links

Figure 61 Refinement TurnOprIntoRel

E.2 Classes+Rels→Class

The general purpose of this kind of refinement, where a group of classes and their relationships is refined into a single class, is to eliminate useless classes and relationships. Figure 62 provides a refined classification involving five types of refinements.

Figure 62 Taxonomy for Refinements of Type Classes+Rels->Class

We identify three sub-categories. A first type of purpose is that two classes are not very different and are thus merged. `CollapseHierarchy` (Section E.2.1) and `InlineClass` (Section E.2.2) fall into this group: `CollapseHierarchy` merges a superclass and subclass together because they are not very different, and `InlineClass` merges two classes together because one isn't doing very much. A second possible purpose is that it is not necessary to have classes and relationships to model what a single attribute can do. `CollapseHierarchyIntoAttri` (Section E.2.3) and `TurnClasses+AssoIntoAttri` (Section E.2.4) belong to this group: `CollapseHierarchyIntoAttri` refines several subclasses into an attribute of a superclass, and `TurnClasses+AssoIntoAttri` refines several classes and associations into an attribute of one of these classes. A third possible rationale is that a constructor is used to model what was originally modeled by several classes and relationships. `TurnClasses+RelsIntoConstructor` belongs to this group (Section E.2.5).

E.2.1 CollapseHierarchy

Description: Merges a superclass and its subclass together because they are not very different.

Specification: As shown in Figure 63, the classes OriginalSuperclass and OriginalSubclass of the original model are merged into the class SingleClass of the refined model.

Figure 63 CollapseHierarchy - Specification

User's Intention: See description.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: DeletedClass, DeletedGeneralization (which links the deleted class) and MovedAttribute (to the undeleted class involved in the generalization). If the class OriginalSuperclass is deleted, some or all of its attributes and/or operations are moved to the class OriginalSubclass. Otherwise, if the class OriginalSubclass is deleted, some or all of its attributes and/or operations are moved to the class OriginalSuperclass. Figure 64 (a) only presents the latter case with only one moved attribute.

Traceability Links: Two traceability links have to be established: one between the classes OriginalSuperclass (referred to as origSuperclass) and SingleClass (referred to as singleClass); one between the classes OriginalSubclass (referred to as origSubclass) and SingleClass. These traceability links are specified in the OCL expressions using Figure 64 (b).

User Help: none.

Context: CollapseHierarchy

```
let deletedGen = self.atomicChanges->select(oclIsTypeOf(DeletedGeneralization)).
    affectedElement.oclAsType(Generalization)
let movedAttriAT = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(DeletedClass))
and self.atomicChanges->exists(oclIsTypeOf(DeletedGeneralization))
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))
and movedAttriAT.affectedElement.oclAsType(Property).class->equals(self.atomicChanges
    ->select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class))
and movedAttriAT.changeDescription.targetLocation.oclAsType(Class)->
    includes(self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
        modelElements->select(oclIsTypeOf(Class))->
            select(name = deletedGen.general.name))
and deletedGen.specific->equals(self.atomicChanges->
    select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class))
```

(a) Constraint on atomic changes

Context: CollapseHierarchy

```
let origSubclass = self.atomicChanges->select(oclIsTypeOf(DeletedClass))
    .affectedElement.oclAsType(Class)
let deletedGen = self.atomicChanges->select(oclIsTypeOf(DeletedGeneralization))
    .affectedElement.oclAsType(Generalization)
let origSuperclass = deletedGen.general
let singleClass = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name=origSuperclass.name)
in
self.traceabilityLinks->size() = 2
and self.traceabilityLink->exists(origin = origSubclass and target = singleClass)
and self.traceabilityLink->exists(origin = origSuperclass and target = singleClass)
```

(b) Traceability links

Figure 64 Refinement CollapseHierarchy

E.2.2 InlineClass

Description: Merges two associated classes together because one of them isn't doing very much.

Specification: As shown in Figure 65, the classes OriginalClass1 and OriginalClass2 of the original model are merged into the class SingleClass of the refined model.

Figure 65 InlineClass - Specification

User's Intention: See description.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: DeletedClass, DeletedAssociation (involving the deleted class) and MovedAttribute (from the deleted class to the other class involved in the deleted association). The specification is shown as the OCL invariant for class InlineClass in Figure 66 (a). We assume that the class OriginalClass2 is deleted and one of attributes of the class OriginalClass2 is moved to the class OriginalClass1 even though there are situations in which more than one or all attributes and/or operations are moved.

Traceability Links: Three traceability links have to be established: one between the classes OriginalClass1 (referred to as origClass1) and SingleClass (referred to as singleClass); one between the classes OriginalClass2 (referred to as origSubclass2) and SingleClass; one between the association originalAsso (referred to as origAsso) and the class SingleClass. These traceability links are specified using the OCL expressions in Figure 66 (b).

User Help: none.

Context: InlineClass

```
let deletedAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)).
    affectedElement.oclAsType(Association)
let movedAttriAT = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(DeletedClass))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation))
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))
and movedAttriAT.affectedElement.oclAsType(Property).class->equals(self.atomicChanges
    ->select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class))
and deletedAsso.memberEnd.class->includes(self.atomicChanges->
    select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class))
and deletedAsso.memberEnd.class->includes(self.originalModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(name = movedAttri.changeDescription.targetLocation.
        oclAsType(Class).name))
```

(a) Constraint on atomic changes

Context: InlineClass

```
let origAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation))
    .affectedElement.oclAsType(Association)
let origClass2 = self.atomicChanges->select(oclIsTypeOf(DeletedClass))
    .affectedElement.oclAsType(Class)
let singleClass = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
    .changeDescription.targetLocation.oclAsType(Class)
let origClass1 = origAsso.memberEnd.class->excluding(origClass2)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origClass1 and target = singleClass)
and self.traceabilityLink->exists(origin = origClass2 and target = singleClass)
and self.traceabilityLink->exists(origin = origAsso and target = singleClass)
```

(b) Traceability links

Figure 66 Refinement InlineClass

Example: Figure 67 provides an example. The classes Person and Telephone Number are connected by the association officeTelephone in the original class diagram (Figure 67 (a)). Since the class Telephone Number is not doing very much, we can move all attributes of the class Telephone Number into the class Person and delete the class Telephone Number (Figure 67 (b)).

Figure 67 InlineClass – Example

E.2.3 CollapseHierarchyIntoAttri

Description: Refines several subclasses of a superclass into one of the attributes of the superclass.

Specification: As shown in Figure 68, the subclasses Subclass1 and Subclass2 are refined into the attribute newAttribute of the class RefinedClass which is refined from the class OriginalSuperclass.

Figure 68 CollapseHierarchyIntoAttri - Specification

User's Intention: An attribute can be used to model what the two subclasses do. For example, these two subclasses have no their own attributes or operations.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: DeletedClass, DeletedGeneralization (linking the deleted class and the class receiving the added attribute) and AddedAttribute. The specification is shown as the OCL invariant for class CollapseHierarchyIntoAttri in Figure 69 (a). Note that the atomic changes DeletedClass and DeletedGeneralization may appear twice or more. In the OCL expressions in Figure 69, we assume that these two atomic changes perform twice only in order to make the OCL expression more concise.

Traceability Links: Three traceability links have to be established: one between the classes OriginalSuperclass (referred to as origSuperclass) and RefinedClass (referred to as refinedClass); one between the class Subclass1 (referred to as origSubclass1) and the attribute newAttribute (referred to as newAttri) of the class

RefinedClass; one between the class Subclass2 (referred to as origSubclass2) and the attribute newAttribute of the class RefinedClass. These traceability links are specified in the OCL expressions in Figure 69 (b).

User Help: the user's help is required, since we can not distinguish the user's intent of adding a new attribute to the superclass.

Context: CollapseHierarchyIntoAttri

```

let deletedGens = self.atomicChanges->select(oclIsTypeOf(DeletedGeneralization)).
    affectedElement.oclAsType(Generalization)
let addedAttri = self.atomicChanges->select(oclIsTypeOf(AddedAttribute)).
    affectedElement.oclAsType(Property)
in
self.atomicChanges->size() = 5
and self.atomicChanges->select(oclIsTypeOf(DeletedClass))->size()=2
and self.atomicChanges->select(oclIsTypeOf(DeletedGeneralization))->size()=2
and self.atomicChanges->exists(oclIsTypeOf(AddedAttribute))
and deletedGens.specific->includesAll(self.atomicChanges->
    select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class))
and deletedGen.general->includes(self.originalModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(name = addedAttri.class.name))

```

(a) Constraint on atomic changes

Context: CollapseHierarchyIntoAttri

```

let newAttri = self.atomicChanges->
    select(oclIsTypeOf(AddedAttribute)).affectedElement.oclAsType(Property)
let refinedClass = self.atomicChanges->select(oclIsTypeOf(AddedAttribute))
    .affectedElement.oclAsType(Property).class
let origSubclass1 = self.atomicChanges->select(oclIsTypeOf(DeletedClass))
    .affectedElement->any(true).oclAsType(Class)
let origSubclass2 = self.atomicChanges->select(oclIsTypeOf(DeletedClass))
    .affectedElement.oclAsType(Class)->excluding(origSubclass1)
let origSupclass = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = refinedClass.name)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origSupclass and target = refinedClass)
and self.traceabilityLink->exists(origin = origSubclass1 and target = newAttri)
and self.traceabilityLink->exists(origin = origSubclass2 and target = newAttri)

```

(b) Traceability links

Figure 69 Refinement CollapseHierarchyIntoAttri

E.2.4 TurnClasses+AssoIntoAttri

Description: Refines several classes and associations into an attribute of one of these classes.

Specification: As shown in Figure 70, the class OriginalClass2 and the association origAsso are refined into the attribute newAttribute of the class RefinedClass which is refined from the class OriginalClass1.

Figure 70 TurnClasses+AssoIntoAttri - Specification

User's Intention: An attribute can be used to model what several classes and associations do.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: DeletedClass, DeletedAssociation (between the deleted class and the class receiving the new attribute) and AddedAttribute. The specification is shown as the OCL invariant for class TurnClasses+AssoIntoAttri in Figure 71 (a). Note that the atomic changes DeletedClass and DeletedAssociation may appear once or more. In the OCL expressions in Figure 71, we assume that these two atomic changes appear once only in order to make the OCL expression more concise.

Traceability Links: Three traceability links have to be established: one between the classes OriginalClass1 (referred to as origClass1) and RefinedClass (referred to as refinedClass); one between the class OriginalClass2 (referred to as origClass2) and the attribute newAttribute (referred to as newAttri) of the class RefinedClass;

one between the association origAsso (referred to as origAsso) and the attribute newAttribute of the class RefinedClass. These traceability links are specified in the OCL expressions in Figure 71 (b).

User Help: The user's help is required, since we can not distinguish the user's intent of adding a new attribute to the superclass.

Context: TurnClasses+AssoIntoAttri

```

let deletedAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)).
    affectedElement.oclAsType(Association)
let newAttri = self.atomicChanges->select(oclIsTypeOf(AddedAttribute)).
    affectedElement.oclAsType(Property)
in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(DeletedClass))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation))
and self.atomicChanges->exists(oclIsTypeOf(AddedAttribute))
and deletedAsso.memberEnd.class->includes(self.atomicChanges
    ->select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class))
and deletedAsso.memberEnd.class->includes(self.originalModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(name = newAttri.class.name))

```

(a) Constraint on atomic changes

Context: TurnClasses+AssoIntoAttri

```

let newAttri = self.atomicChanges->
    select(oclIsTypeOf(AddedAttribute)).affectedElement.oclAsType(Property)
let refinedClass = self.atomicChanges->select(oclIsTypeOf(AddedAttribute))
    .affectedElement.oclAsType(Property).class
let origClass2 = self.atomicChanges->
    select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class)
let origAsso = self.atomicChanges->
    select(oclIsTypeOf(DeletedAssociation)).affectedElement.oclAsType(Association)
let origClass1 = origAsso.memberEnd.class->excluding(origClass2)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origClass1 and target = refinedClass)
and self.traceabilityLink->exists(origin = origClass2 and target = newAttri)
and self.traceabilityLink->exists(origin = origAsso and target = newAttri)

```

(b) Traceability links

Figure 71 Refinement TurnClasses+AssoIntoAttri

E.2.5 TurnClasses+RelsIntoConstructor

Descripton: Refines several classes and relationships into a constructor of one of these classes.

Specification: As shown in Figure 72, the class OriginalClass2 and the association origAsso are refined into the constructor RefinedClass () of the class RefinedClass which is refined from the class OriginalClass1.

Figure 72 TurnClasses+RelsIntoConstructor - Specification

User's Intention: The constructor of a class can be used to model what the class and the association do.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: DeletedClass, DeletedAssociation (between the deleted class and the class receiving the new constructor) and AddedOperation. The specification is shown as the OCL invariant for class TurnClasses+AssoIntoConstructor in Figure 73 (a). Note that the atomic changes DeletedClass and DeletedAssociation may appear once or more. In the OCL expressions in Figure 73, we assume that these two atomic changes appear once only in order to make the OCL expression more concise.

Traceability Links: Three traceability links have to be established: one between the classes OriginalClass1 (referred to as origClass1) and RefinedClass (referred to as refinedClass); one between the class OriginalClass2 (referred to as origClass2) and the constructor RefinedClass () (referred to as newConstructor) of the class RefinedClass; one between the association origAsso (referred to as origAsso) and

the constructor `RefinedClass()` of the class `RefinedClass`. These traceability links are specified in the OCL expressions in Figure 73 (b).

User Help: The user's help is required, since we can not distinguish the user's intent of adding a new constructor for the class being refined.

```

Context: TurnClasses+AssoIntoConstructor
let deletedAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)).
    affectedElement.oclAsType(Association)
let newConstructor = self.atomicChanges->select(oclIsTypeOf(AddedOperation)).
    affectedElement.oclAsType(Operation)
in
self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(DeletedClass))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation))
and self.atomicChanges->exists(oclIsTypeOf(AddedOperation))
and deletedAsso.memberEnd.class->includes(self.atomicChanges
    ->select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class))
and deletedAsso.memberEnd.class->includes(self.originalModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(name = newConstructor.class.name))

```

(a) Constraint on atomic changes

```

Context: TurnClasses+AssoIntoConstructor
let newConstructor = self.atomicChanges->select(oclIsTypeOf(AddedOperation))
    .affectedElement.oclAsType(Operation)
let refinedClass = newConstructor.class
let origClass1 = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = refinedClass.name)
let origClass2 = self.atomicChanges->
    select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class)
let origAsso = self.atomicChanges->
    select(oclIsTypeOf(DeletedAssociation)).affectedElement.oclAsType(Association)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origClass1 and target = refinedClass)
and self.traceabilityLink->exists(origin = origClass2 and target = newConstructor)
and self.traceabilityLink->exists(origin = origAsso and target = newConstructor)

```

(b) Traceability links

Figure 73 Refinement `TurnClasses+AssoIntoConstructor`

E.3 Classes+Rels→Classes+Rels

This refinement refines a class diagram in order to improve its efficiency and reusability. It can be very complex and it may affect numerous classes and relationships. Figure 74 provides a refined classification involving seven types of refinements. PullUpAttribute (Section E.3.1), PullUpOperation (Section E.3.2), PushDownAttribute (Section E.3.3), and PushDownOperation (Section E.3.4) are refinements operating on attributes and operations of two classes connecting by generalization relationship. EliminateDupliByInheritance (Section E.3.5), EliminateDupliByComposition (Section E.3.6) and SplitSubclass (Section E.3.7) are refinements simply changing the structure of the diagram.

Figure 74 Taxonomy for Refinements of Type Classes+Rels→Classes+Rels

E.3.1 PullUpAttribute

Description: Pulls up one attribute common to all subclasses of a superclass to the superclass.

Specification: As shown in Figure 75, the common attribute `CommonAttribute` of the classes `Subclass1` and `Subclass2` is moved into the superclass `RefinedSuperClass` which is refined from the class `Superclass`.

Figure 75 PullUpAttribute – Specification

User's Intention: Duplicate attributes exist in subclasses. By pulling up these attributes into the superclass, duplication can be reduced.

Atomic Changes: Two kinds of atomic changes are used to derive the refinement: `MovedAttribute` and `DeletedAttribute`. The specification is shown as the OCL invariant for class `PullUpAttribute` in Figure 76 (a). Note that the atomic changes `DeletedAttribute` may appear more than once because it is possible to pull up the common attribute from more than two subclasses. In the OCL expressions in Figure 76, we assume that these two atomic changes appear once only, the attribute `CommonAttribute` of the class `Subclass1` is moved into the superclass, and the

CommonAttribute of the class Subclass2 is deleted, in order to make the OCL expression more concise.

Traceability Links: Five traceability links have to be established (Figure 76 (b)):

- one between the classes SuperClass (referred to as origSup) and RefinedSuperclass (referred to as refinedSup);
- one between the classes Subclass1 (referred to as origSub) and RefinedSubclass1 (referred to as refinedSub1);
- one between the classes Subclass2 (referred to as origSub2) and RefinedSubclass2 (referred to as refinedSub2);
- one between the attribute CommonAttribute (referred to as comAttriOfOrigSub1) of the class Subclass1 and the attribute CommonAttribute (referred to as comAttriRefinedSup) of the class RefinedSuperclass;
- one between the attribute CommonAttribute(referred to as comAttriOfOrigSub2) of the class Subclass2 and the attribute CommonAttribute of the class RefinedSuperclass.

These traceability links are specified in the OCL expressions in Figure 76 (b).

User Help: none.

```

Context: PullUpAttribute

let movedAttriAT = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
let deletedAttri = self.atomicChanges->select(oclIsTypeOf(AddedAttribute)).
    affectedElement.oclAsType(Property)

in
self.atomicChanges->size() = 2
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAttribute))
and movedAttriAT.affectedElement.oclAsType(Property).class.generalization.general->
    includes(self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
        modelElements->select(oclIsTypeOf(Class))->
        select(name=movedAttriAT.changeDescription.targetLocation.oclAsType(Class).name))
and deletedAttri.class.generalization.general->includes(self.originalModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(t|name=movedAttriAT.changeDescription.targetLocation.oclAsType(Class).name))
and movedAttriAT.affectedElement.oclAsType(Property).class <> deletedAttri.class

```

(a) Constraint on atomic changes

```

Context: PullUpAttribute

let comAttriOfOrigSub1 = self.atomicChanges->select(oclIsTypeOf(MovedAttribute)).
    affectedElement.oclAsType(Property)
let comAttriOfOrigSub2 = self.atomicChanges->select(oclIsTypeOf(DeletedAttribute)).
    affectedElement.oclAsType(Property)

let origSub1 = comAttriOfOrigSub1.class
let origSub2 = comAttriOfOrigSub2.class
let refinedSup = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
    .changeDescription.targetLocation.oclAsType(class)
let refinedSub1 = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = origSub1.name)
let refinedSub2 = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = origSub2.name)
let origSup = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name=refinedSup.name)
let comAttriOfRefinedSup = refinedSup.ownedAttribute ->
    select(name=comAttriOfOrigSub1.name)

in
self.traceabilityLinks->size() = 5
and self.traceabilityLink->exists(origin = origSup and target = refinedSup)
and self.traceabilityLink->exists(origin = origSub1 and target = refinedSub1)
and self.traceabilityLink->exists(origin = origSub2 and target = refinedSub2)
and self.traceabilityLink->exists(origin = comAttriOfOrigSub1
    and target = comAttriOfRefinedSup)
and self.traceabilityLink->exists(origin = comAttriOfOrigSub2
    and target = comAttriOfRefinedSup)

```

(b) Traceability links

Figure 76 Refinement PullUpAttribute

E.3.2 PullUpOperation

Description: Pulls up one operation common to all subclasses of a superclass to the superclass.

Specification: As shown in Figure 77, the common operation `CommonOperation()` of the classes `Subclass1` and `Subclass2` is moved into the superclass `RefinedSuperClass` which is refined from the class `Superclass`.

Figure 77 PullUpOperation – Specification

User's Intention: Duplicate operations exist in subclasses. By pulling up these operations into the superclass, duplication can be reduced.

Atomic Changes: Two kinds of atomic changes are used to derive the refinement: `MovedOperation` and `DeletedOperation`. The specification is shown as the OCL invariant for class `PullUpOperation` in Figure 78 (a). Note that the atomic change `DeletedOperation` may appear more than once because it is possible to pull up the common operation from more than two subclasses. In the OCL expressions in Figure 78, we assume that these two atomic changes appear once only, the operation `CommonOperation()` of the class `Subclass1` is moved into the superclass, and the

`CommonOperation()` of the class `Subclass2` is deleted, in order to make the OCL expression more concise.

Traceability Links: Five traceability links have to be established:

- one between the classes `SuperClass` (referred to as `origSup`) and `RefinedSuperclass` (referred to as `refinedSup`);
- one between the classes `Subclass1` (referred to as `refinedorigSub`) and `RefinedSubclass1` (referred to as `refinedSub1`);
- one between the classes `Subclass2` (referred to as `origrefinedSub2`) and `RefinedSubclass2` (referred to as `refinedSub2`);
- one between the attribute `CommonOperation()` (referred to as `comOprOfOrigSub1`) of the class `Subclass1` and the attribute `CommonOperation()` (referred to as `comOprOfRefinedSup`) of the class `RefinedSuperclass`;
- one between the attribute `CommonOperation()` (referred to as `comOprOfOrigSub2`) of the class `Subclass2` and the attribute `CommonOperation()` of the class `RefinedSuperclass`.

These traceability links are specified in the OCL expressions in Figure 78 (b).

User Help: none.

Context: PullUpOperation

```
let movedOprAT = self.atomicChanges->select(oclIsTypeOf(MovedOperation))
let deletedOpr = self.atomicChanges->select(oclIsTypeOf(AddedOperation)).
    affectedElement.oclAsType(Operation)
in
self.atomicChanges->size() = 2
and self.atomicChanges->exists(oclIsTypeOf(MovedOperation))
and self.atomicChanges->exists(oclIsTypeOf(DeletedOperation))
and movedOprAT.affectedElement.oclAsType(Operation).class.generalization.general->
    includes(self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
        modelElements->select(oclIsTypeOf(Class))->
        select(name=movedOprAT.changeDescription.targetLocation.oclAsType(Class).name))
and deletedOpr.class.generalization.general->includes(self.originalModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
    select(name=movedOprAT.changeDescription.targetLocation.oclAsType(Class).name))
and movedOprAT.affectedElement.oclAsType(Operation).class <> deletedOpr.class
```

(a) Constraint on atomic changes

Context: PullUpOperation

```
let comOprOfOrigSub1 = self.atomicChanges->select(oclIsTypeOf(MovedOperation)).
    affectedElement.oclAsType(Operation)
let comOprOfOrigSub2 = self.atomicChanges->select(oclIsTypeOf(DeletedOperation)).
    affectedElement.oclAsType(Operation)
let origSub1 = comOprOfOrigSub1.class
let origSub2 = comOprOfOrigSub2.class
let refinedSup = self.atomicChanges->select(oclIsTypeOf(MovedOperation))
    .changeDescription.targetLocation.oclAsType(class)
let refinedSub1 = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(t | name = origSub1.name)
let refinedSub2 = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(t | name = origSub2.name)
let origSup = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(t|name=refinedSup.name)
let comOprOfRefinedSup=refinedSup.ownedOperation -> select(name=comOprOfOrigSub1.name)
in
self.traceabilityLinks->size() = 5
and self.traceabilityLink->exists(origin = origSup and target = refinedSup)
and self.traceabilityLink->exists(origin = origSub1 and target = refinedSub1)
and self.traceabilityLink->exists(origin = origSub2 and target = refinedSub2)
and self.traceabilityLink->exists(origin =comOprOfOrigSub1
    and target = comOprOfRefinedSup)
and self.traceabilityLink->exists(origin = comOprOfOrigSub2
    and target = comOprOfRefinedSup)
```

(b) Traceability links

Figure 78 Refinement PullUpOperation

E.3.3 PushDownAttribute

Description: Pushes down one of the attributes of a superclass to one of its subclasses, because this attribute is used only by this subclass.

Specification: As shown in Figure 79, the common attribute `Attribute` of the superclass `Superclass` is moved into the subclass `RefinedSubclass` which is refined from the class `Subclass`.

Figure 79 PushDownAttribute – Specification

User's Intention: This refinement is the opposite of `PullUpAttribute`. Because the attributes are not used in the superclass anymore but only in a subclass, the attributes can be pushed down to the subclass.

Atomic Changes: One kind of atomic change is used to derive the refinement: `MovedAttribute`. The specification is shown as the OCL invariant for class `PushDownAttribute` in Figure 80 (a).

Traceability Links: Three traceability links have to be established: one between the classes `SuperClass` (referred to as `origSup`) and `RefinedSuperclass` (referred to as `refinedSup`); one between the classes `Subclass` (referred to as `origSub`) and `RefinedSubclass` (referred to as `refinedSub`); one between the attribute `Attribute` (referred to as `attriOfOrigSup`) of the class `Superclass` and the attribute `Attribute` (referred to as `attriOfRefinedSup`) of the class `RefinedSubclass`. These traceability links are specified in the OCL expressions in Figure 80 (b).

User Help: none.

```

Context: PushDownAttribute

let movedAttriAT = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
in
self.atomicChanges->size() = 1
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))
and movedAttriAT.affectedElement.oclAsType(Property).class.generalization.specific->
    includes(self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram))).
    modelElements->select(oclIsTypeOf(Class))->select(name=movedAttriAT.
        changeDescription.targetLocation.oclAsType(Class).name))

```

(a) Constraint on atomic changes

```

Context: PushDownAttribute

let attriOfOrigSup = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
    .affectedElement.oclAsType(Property)
let refinedSub = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
    .changeDescription.targetLocation.oclAsType(Class)
let attriOfRefinedSub = refinedSub.ownedAttributes->select(name=attriOfOrigSup)
let origSub = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = refinedSub.name)
let origSup = self.atomicChanges->
    select(oclIsTypeOf(MovedAttribute)).affectedElement.oclAsType(Property).class
let refinedSup = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = origSup.name)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origSup and target = refinedSup)
and self.traceabilityLink->exists(origin = origSub and target = refinedSub)
and self.traceabilityLink->exists(origin = attriOfOrigSup
    and target = attriOfRefinedSub)

```

(b) Traceability links

Figure 80 Refinement PushDownAttribute

E.3.4 PushDownOperation

Description: Pushes down one of the operations of a superclass to one of its subclasses, because this operation is used only by this subclass.

Specification: As shown in Figure 81, the common operation `Operation()` of the superclass `Superclass` is moved into the subclass `RefinedSubclass` which is refined from the class `Subclass`.

Figure 81 PushDownOperation – Specification

User's Intention: This refinement is the opposite of `PullUpOperation`. Because the operations are not used in the superclass anymore but only in subclass, the operations can be pushed down to the subclass.

Atomic Changes: One kind of atomic change is used to derive the refinement: `MovedOperation`. The specification is shown as the OCL invariant for class `PushDownOperation` in Figure 82 (a).

Traceability Links: Three traceability links have to be established: one between the classes `SuperClass` (referred to as `origSup`) and `RefinedSuperclass` (referred to as `refinedSup`); one between the classes `Subclass` (referred to as `origSub`) and `RefinedSubclass` (referred to as `refinedSub`); one between the operation `Operation()` (referred to as `oprOfOrigSup`) of the class `Superclass` and the operation `Operation()` (referred to as `oprOfRefinedSup`) of the class `RefinedSubclass`. These traceability links are specified in the OCL expressions in Figure 82 (b).

User Help: none.

Context: PushDownOperation

```
let movedOprAT = self.atomicChanges->select(oclIsTypeOf(MovedOperation))
in
self.atomicChanges->size() = 1
and self.atomicChanges->exists(oclIsTypeOf(MovedOperation))
and movedOprAT.affectedElement.oclAsType(Operation).class.generalization.specific->
    includes(self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram))).
    modelElements->select(oclIsTypeOf(Class))->select(name=movedOprAT.
        changeDescription.targetLocation.oclAsType(Class).name))
```

(a) Constraint on atomic changes

Context: PushDownOperation

```
let oprOfOrigSup = self.atomicChanges->select(oclIsTypeOf(MovedOperation))
    .affectedElement.oclAsType(Operation)
let refinedSub = self.atomicChanges->select(oclIsTypeOf(MovedOperation))
    .changeDescription.targetLocation.oclAsType(Class)
let oprOfRefinedSub = refinedSub.ownedOperations->select(name=oprOfOrigSup.name)
let origSub = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = refinedSub.name)
let origSup = self.atomicChanges->
    select(oclIsTypeOf(MovedOperation)).affectedElement.oclAsType(Operation).class
let refinedSup = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name = origSup.name)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origSup and target = refinedSup)
and self.traceabilityLink->exists(origin = origSub and target = refinedSub)
and self.traceabilityLink->exists(origin = oprOfOrigSup
    and target = oprOfRefinedSub)
```

(b) Traceability links

Figure 82 Refinement PushDownOperation

E.3.5 EliminateDupliByInheritance

Description: Extracts out the common attributes and operations of several classes, and create a superclass for these classes to store these common attributes and operations.

Specification: As shown in Figure 83, the attribute `CommonAttribute` and the operation `CommonOperation()` of the classes `OriginalClass1` and `OriginalClass2` are extracted out and put into the newly added superclass `SuperClass`. The class `RefinedClass1` is refined from the class `OriginalClass1`, and the class `RefinedClass2` is refined from the class `OriginalClass2`.

Figure 83 EliminateDupliByInheritance - Specification

User's Intention: Because two classes have similar attribute(s) and/or operation(s), a superclass can be created to contain the similar attribute(s) and/or operation(s).

Atomic Changes: Six kinds of atomic changes are used to derive the refinement: `MovedAttribute`, `MovedOperation`, `AddedClass`, `AddedGeneralization`, `DeletedAttribute`, and `DeletedOperation`. The specification is shown as the OCL invariant for class `EliminateDupliByInheritance` in Figure 84 (a). Note that the atomic changes `DeletedAttribute` and `DeletedOperation` may appear more than once because it is possible to extract out the common attribute and operation from more

than two classes. In the OCL expressions in Figure 84 (a) and Figure 85 (b), we assume that these two atomic changes appear once only, the attribute `CommonAttribute` and the operation `CommonOperation()` of the class `OriginalClass1` are moved into the superclass, and the attribute `CommonAttribute` and `CommonOperation()` of the class `OriginalClass2` are deleted, in order to make the OCL expression more concise.

Traceability Links: Four traceability links have to be established: one between the classes `OriginalClass1` (referred to as `origClass1`) and `RefinedClass1` (referred to as `subclass1`); one between the classes `OriginalClass2` (referred to as `origClass2`) and `RefinedClass2` (referred to as `subclass2`); one between the classes `OriginalClass1` and `Superclass` (referred to as `superclass`); one between the classes `OriginalClass2` and `Superclass`. These traceability links are specified in the OCL expressions in Figure 85 (b).

User Help: none.

```

Context: EliminateDupliByInheritance

let newGen = self.atomicChanges ->
    select(oclIsTypeOf(AddedGeneralization)).affectedElement.oclAsType(Generalization)
let origClass1 = self.atomicChanges -> select(oclIsTypeOf(MovedAttribute)).
    affectedElement.oclAsType(Property).class -> union(self.atomicChanges->
        select(oclIsTypeOf(MovedOperation)).affectedElement.oclAsType(Operation).class)
let origClass2 = self.atomicChanges -> select(oclIsTypeOf(DeletedAttribute)).
    affectedElement.oclAsType(Property).class -> union(self.atomicChanges ->
        select(oclIsTypeOf(DeletedOperation)).affectedElement.oclAsType(Operation).class)
in
self.atomicChanges->size() = 7
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))
and self.atomicChanges->exists(oclIsTypeOf(MovedOperation))
and self.atomicChanges->select(oclIsTypeOf(AddedGeneralization))->size()=2
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAttribute))
and self.atomicChanges->exists(oclIsTypeOf(DeletedOperation))
and self.atomicChanges
    ->select(oclIsTypeOf(MovedAttribute) or oclIsTypeOf(MovedOperation)).
        changeDescription.targetLocation.oclAsType(Class)->includes(self.atomicChanges
            ->select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newGen.general -> includes(self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(class))
and newGen.specific -> includesAll(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
        Select(name=origClass1.name))
and newGen.specific -> includesAll(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
        Select(name=origClass2.name))

```

(a) Constraint on atomic changes

Figure 84 (a) Refinement EliminateDupliByInheritance (part A)

Context: EliminateDupliByInheritance

```

let superclass = self.atomicChanges->select(oclIsTypeOf(AddedClass)).
    affectedElement.oclAsType(Class)
let subclass1 = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
    .changeDescription.targetLocation.oclAsType(class)
let subclass2 = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization))
    affectedElement.oclAsType(Generalization).specific -> excluding(subclass1)
let origClass1 = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
    .affectedElement.oclAsType(Property).class
let origClass2 = self.atomicChanges->select(oclIsTypeOf(DeletedAttribute))
    .affectedElement.oclAsType(Property).class
in
self.traceabilityLinks->size() = 4
and self.traceabilityLink->exists(origin = origClass1 and target = subclass1)
and self.traceabilityLink->exists(origin = origClass2 and target = subclass2)
and self.traceabilityLink->exists(origin = origClass1 and target = superclass)
and self.traceabilityLink->exists(origin = origClass2 and target = superclass)

```

(b) Traceability links

Figure 85 (b) Refinement EliminateDupliByInheritance (part B)

E.3.6 EliminateDupliByComposition

Decription: Extracts out the common attributes and operations of several classes, and creates a new class connecting to these classes by composition relationships to store these common attributes and operations.

Specification: As shown in Figure 86, the attribute CommonAttribute and the operation CommonOperation() of the class OriginalClass1 and OriginalClass2 are extracted out and put into the newly added class NewClass which is connected with the class RefinedClass1 and RefinedClass2 by composition associations. The class RefinedClass1 is refined from the class OriginalClass1, and the class RefinedClass2 is refined from the class OriginalClass2.

Figure 86 EliminateDupliByComposition - Specification

User's Intention: Because composition association suggests whole-part relationships. Similar attribute(s) and/or operation(s) can be extracted out to the instance of the whole (i.e. new added class).

Atomic Changes: Six kinds of atomic changes are used to derive the refinement: MovedAttribute, MovedOperation, AddedClass, AddedAssociation, DeletedAttribute, and DeletedOperation. The specification is shown as the OCL invariant for class EliminateDupliByComposition in Figure 87 (a). Note that the atomic changes DeletedAttribute and DeletedOperation may appear more than

once because it is possible to extract out the common attribute and operation from more than two classes. In the OCL expressions in Figure 87 (a) and Figure 88 (b), we assume that these two atomic changes appear once only, the attribute `CommonAttribute` and the operation `CommonOperation()` of the class `OriginalClass1` are moved into the new added class, and the attribute `CommonAttribute` and `CommonOperation()` of the class `OriginalClass2` are deleted, in order to make the OCL expression more concise.

Traceability Links: Four traceability links have to be established: one between the classes `OriginalClass1` (referred to as `origClass1`) and `RefinedClass1` (referred to as `refinedClass1`); one between the classes `OriginalClass2` (referred to as `origClass2`) and `RefinedClass2` (referred to as `refinedClass2`); one between the classes `OriginalClass1` and `NewClass` (referred to as `newClass`); one between the classes `OriginalClass2` and `NewClass`. These traceability links are specified in the OCL expressions in Figure 88 (b).

User Help: none.

```

Context: EliminateDupliByComposition
let newAsso = self.atomicChanges ->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
let origClass1 = self.atomicChanges -> select(oclIsTypeOf(MovedAttribute)).
    affectedElement.oclAsType(Property).class -> union(self.atomicChanges ->
        select(oclIsTypeOf(MovedOperation)).affectedElement.oclAsType(Property).class)
let origClass2 = self.atomicChanges -> select(oclIsTypeOf(DeletedAttribute)).
    affectedElement.oclAsType(Property).class -> union(self.atomicChanges ->
        select(oclIsTypeOf(DeletedOperation)).affectedElement.oclAsType(Operation).class)
in
self.atomicChanges->size() = 7
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))
and self.atomicChanges->exists(oclIsTypeOf(MovedOperation))
and self.atomicChanges->select(oclIsTypeOf(AddedAssociation))->size()=2
and self.atomicChanges -> select(oclIsTypeOf(AddedAssociation)).affectedElement.
    oclAsType(Association) -> forAll(memberEnd ->
        exists(aggregation<>Aggregation::none)
            and memberEnd->exists(aggregation=Aggregation::composition))
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAttribute))
and self.atomicChanges->exists(oclIsTypeOf(DeletedOperation))
and self.atomicChanges
    ->select(oclIsTypeOf(MovedAttribute) or oclIsTypeOf(MovedOperation)).
        changeDescription.targetLocation.oclAsType(Class)->includes(self.atomicChanges
            ->select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newAsso.memberEnd.class -> includes(self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(class))
and newAsso.specific -> includesAll(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
        Select(t|name=origClass1.name))
and newAsso.specific -> includesAll(self.refinedModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))->
        Select(t|name=origClass2.name))

```

(a) Constraint on atomic changes

Figure 87 (a) Refinement EliminateDupliByComposition (part A)

```

Context: EliminateDupliByComposition
let newClass = self.atomicChanges->select(oclIsTypeOf(AddedClass)).
    affectedElement.oclAsType(Class)
let refinedClass1 = self.atomicChanges->select(oclIsTypeOf(MovedOperation))
    .changeDescription.targetLocation.oclAsType(class)
let refinedClass2 = self.atomicChanges->select(oclIsTypeOf(AddedAssociation))
    affectedElement.oclAsType(Association).memberEnd.class -> excluding(refinedClass1)
let origClass1 = self.atomicChanges->select(oclIsTypeOf(MovedAttribute))
    .affectedElement.oclAsType(Property).class
let origClass2 =self.atomicChanges->select(oclIsTypeOf(DeletedAttribute))
    .affectedElement.oclAsType(Property).class
in
self.traceabilityLinks->size() = 4
and self.traceabilityLink->exists(origin = origClass1 and target = refinedClass1)
and self.traceabilityLink->exists(origin = origClass2 and target = refinedClass2)
and self.traceabilityLink->exists(origin = origClass1 and target = superclass)
and self.traceabilityLink->exists(origin = origClass2 and target = newClass)

```

(b) Traceability links

Figure 88 (b) Refinement EliminateDupliByComposition (part B)

E.3.7 SplitSubclass

Description: Splits one of the subclasses of a superclass into two subclasses of the same superclass.

Specification: As shown in Figure 89, the subclass Subclass is split into the classes RefinedSubclass and NewSubclass. The class RefinedSubclass is refined from the class Subclass. The class NewSubclass is a newly added subclass. The class Superclass is refined into RefinedSuperclass. The attribute Attribute2 and the operation Operation2() of the subclass Subclass are moved into the class NewSubclass.

Figure 89 SplitSubclass – Specification

User's Intention: A subclass takes too much responsibility which makes the hierarchy structure not clear. Splitting the responsibility and letting two or more subclasses to share it will make the generalization hierarchy clearer.

Atomic Changes: Four kinds of atomic changes are used to derive the refinement: MovedAttribute, MovedOperation, AddedClass, and AddedGeneralization. The specification is shown as the OCL invariant for class SplitSubclass in Figure 90 (a). Note that the atomic changes MovedAttribute and MovedOperation may appear more than once because it is possible that more than one attribute or operation is split to the new subclass. In the OCL expressions in Figure 90, we assume that these two atomic changes appear once only in order to make the OCL expression more concise.

Traceability Links: Three traceability links have to be established: one between the classes Superclass (referred to as origSuper) and RefinedSuperclass (referred to as refinedSuper); one between the classes Subclass (referred to as origSub) and RefinedSubclass (referred to as refinedSub); one between the classes Subclass and NewSubclass (referred to as newSub). These traceability links are specified in the OCL expressions in Figure 90 (b).

User Help: none.

Context: SplitSubclass

```

let newGen = self.atomicChanges ->
    select(oclIsTypeOf(AddedGeneralization)).affectedElement.oclAsType(Generalization)
let origSup = self.atomicChanges -> select(oclIsTypeOf(MovedAttribute)).
    affectedElement.oclAsType(Property).class.generalization.general
in
self.atomicChanges->size() = 4
and self.atomicChanges->exists(oclIsTypeOf(MovedAttribute))
and self.atomicChanges->exists(oclIsTypeOf(MovedOperation))
and self.atomicChanges->select(oclIsTypeOf(MovedAttribute)).affectedElement.
    oclAsType(Property).class->equals(self.atomicChanges->
        select(oclIsTypeOf(MovedOperation)).affectedElement.oclAsType(Operation).class)
and self.atomicChanges->exists(oclIsTypeOf(AddedGeneralization))
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges
    ->select(oclIsTypeOf(MovedAttribute) or oclIsTypeOf(MovedOperation))
    .changeDescription.targetLocation.oclAsType(Class)->includes(self.atomicChanges
    ->select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newGen.specific->includes(self.atomicChanges->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newGen.general ->
    includes(self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
        modelElements->select(oclIsTypeOf(Class)) -> Select(name=origSup.name))

```

(a) Constraint on atomic changes

Context: SplitSubclass

```

let newSub = self.atomicChanges->select(oclIsTypeOf(AddedClass)).
    affectedElement.oclAsType(Class)
let origSub = self.atomicChanges->
    select(oclIsTypeOf(MovedAttribute)).affectedElement.oclAsType(Property).class
let refinedSub = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(t | name = origSub.name)
let refinedSuper = newSub.generalization.general
let origSuper = origSub.generalization.general
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origSuper and target = refinedSuper)
and self.traceabilityLink->exists(origin = origSub and target = refinedSub)
and self.traceabilityLink->exists(origin = origSub and target = newSub)

```

(b) Traceability links

Figure 90 Refinement SplitSubclass

E.4 Rel→Classes+Rels

This refinement kind refines a single relationship into several classes and relationships. Figure 91 provides a refined classification involving four types of refinements.

Figure 91 Taxonomy for Refinements of Type Rel→Classes+Rels

A first purpose is to detail a relationship by adding new classes and associations. `DetailAssoFunctionality` belongs to this type (Section E.4.1). The second possible purpose is that a new bridge class is added on the path from the one class to the other, for instance to improve structure of the model. `AddBridgeClass` belongs to this type (Section E.4.2). The third purpose is that an existing class is used as the bridge class. `ByBridgeClass` belongs to this type (Section E.4.3). The last one is that an association class is used to refine the association. `AssoRefUsingAssociationClass` belongs to this type (Section E.4.4).

We introduce a new class, called `Path`, which has four operations: `exists(endA, endB)`, `exists(endSetA, endSetB)`, `getPaths(endA, endB)`, and `getPaths(endSetA, endSetB)`. The class `Path` does not appear in our metamodel as it is only a helper class used to shorten our OCL expressions. The formalization of the class `Path` is given in Appendix F.

E.4.1 DetailAssoFunctionality

Description: Refines an association into paths by adding new classes and relationships.

Specification: As shown in Figure 92, the association `origAsso`, which connects the classes `OriginalA` and `OriginalB`, is refined into a path which starts from the class `RefinedA`, traverses the association `newAssoAC`, the class `NewC` and the association `newAssoCB`, and ends at the class `RefinedB`. Note that the association may be refined into several paths although this case is not shown in Figure 92. The general idea for identifying such a refinement is to be able to find, in the refined class diagram, at least one path between the classes at the two ends of the association⁹ being deleted in the original model.

Figure 92 DetailAssoFunctionality – Specification

User's Intention: This kind of refinement happens usually when the association being refined in the original model has to be detailed by introducing more classes and associations along with the evolution of model.

Atomic Changes: As specified in Figure 93 (a), such a refinement is at least made of one DeletedAssociation atomic change: the deleted association (in the original model) is referred to as `origAsso`. The next let expressions are used to identify the two ends of the deleted association in the original model (`origA` and `origB`) and how they may have been refined (`refA` and `refB`). Last, we use operation `exists()` of class `Path` to identify

⁹ In this thesis, we assume associations are binary, although n-ary associations can be handled following the same principles.

whether there is a path between `refA` and `refB` in the refined model. The operation `exists(endSetA, endSetB)` is used in Figure 93 (a) since `refA` and `refB` are sets in this case.

Traceability Links: Figure 93 (b) specifies how traceability links are established for refinement `DetailAssoFunctionality`. For each path that we can find in the refined model between `refA` and `refB` (we use operation `getPaths(refA, refB)` of class `Path`), we establish a traceability link between the removed association `origAsso` (in the original model) and each element of the path.

User Help: The user's help is required because we have to ask the user to indicate which path(s) are the path(s) actually refining the deleted association.

```

Context: DetailAssoFunctionality

let deletedAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation))
    .affectedElement.oclAsType(Association)
let origA = deletedAsso.memberEnd.class->any(true)
let origB = deletedAsso.memberEnd.class->excluding(origA)
let refA = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origA.name)
let refB = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origB.name)

in
self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation))
and Path.exists(refA, refB)

```

(a) Constraint on atomic changes

```

Context: DetailAssoFunctionality

let origAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation))
    .affectedElement.oclAsType(Association)
let origA = origAsso.memberEnd.class->any(true)
let origB = origAsso.memberEnd.class->excluding(origA)
let refA = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(t|name=origA.name)
let refB = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(t|name=origB.name)

in
Path.getPaths(refA, refB)->forAll(p:Path|
    Sequence{1..p.elements->size()}->forAll(i|
        self.TraceabilityLink->exists(origin = origAsso and target = p.elements->at(i))
    )
)

```

(b) Traceability links

Figure 93 Refinement DetailAssoFunctionality

Example: Figure 94 and Figure 95 provide an example which is adapted from [33]. The association between the classes ATM and Customer is refined into five paths:

1. ATM→CardReader→Card→Customer
2. ATM→Console→Customer
3. ATM→Slot→Customer
4. ATM→Dispenser→Customer
5. ATM→Transaction→Customer

Figure 94 Example DetailAssoFunctionality – the original class diagram

Figure 95 Example DetailAssoFunctionality – the refined class diagram

E.4.2 AddBridgeClass

Description: Adds a new bridge class between the association ends of the association being refined in order to improve the model structure.

Specification: As shown in Figure 96, the new bridge class NewBridgeClass is added between the classes RefinedClassA and RefinedClassB. The class RefinedClassA is refined from the class OriginalClassA and the class RefinedClassB is refined from the class OriginalClassB.

Figure 96 AddBridgeClass - Specification

User's Intention: See description.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: AddedClass, AddedAssociation, and DeletedAssociation. The specification is shown as the OCL invariant for class AddBridgeClass in Figure 97 (a). Note that the atomic changes AddedAssociation appears twice in order to connect the newly added class with the existing two classes. One of the association ends of the originalAsso may be relocated to class NewBridgeClass. In such situation, an atomic change RelocatedAssociation appears instead of a DeletedAssociation atomic change and an AddedAssociation atomic change. In the OCL expressions in Figure 97, we assume that no atomic change RelocatedAssociation appears, in order to make the OCL expression more concise.

Traceability Links: Five traceability links have to be established:

- one between the classes OriginalClassA (referred to as origClassA) and RefinedClassA (referred to as refinedClassA);
- one between the classes OriginalClassB (referred to as origClassB) and RefinedClassB (referred to as refinedClassB);
- one between the association originalAsso (referred to as origAsso) and the class NewBridgeclass (referred to as newBridgeClass);
- one between the associations originalAsso and assoANew (referred to as assoANew);
- one between the associations originalAsso and assoBNew (referred to as assoBNew).

These traceability links are specified in the OCL expressions in Figure 97 (b).

User Help: none.

```

Context: AddBridgeClass

let origAssoEndA = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)).
    affectedElement.oclAsType(Association).memberEnd.class->any(true)
let origAssoEndB = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)).
    affectedElement.oclAsType(Association).memberEnd.class->excluding(origAssoEndA)
let newAssoes = self.atomicChanges->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
in
self.atomicChanges->size() = 4
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation))
and self.atomicChanges->select(oclIsTypeOf(AddedAssociation))->size()=2
and newAssoes.memberEnd.class -> includesAll(self.atomicChanges ->
    select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class))
and newAssoes.memberEnd.class -> includesAll(self.refinedModel.diagram ->
    select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class)) ->
    select(name=origAssoEndA.name or name = origAssoEndB.name))

```

(a) Constraint on atomic changes

```

Context: AddBridgeClass

let origAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)).
    affectedElement.oclAsType(Association)
let newBridgeClass = self.atomicChanges->select(oclIsTypeOf(AddedClass)).
    affectedElement.oclAsType(Class)
let assoANew = self.atomicChanges->select(oclIsTypeOf(AddedAssociation)).
    affectedElement.oclAsType(Association) -> any(true)
let assoBNew = self.atomicChanges->select(oclIsTypeOf(AddedAssociation)).
    affectedElement.oclAsType(Association) -> excluding(assoANew)
let refinedClassA = assoANew.class->excluding(newBridgeClass)
let refinedClassB = assoBNew.class->excluding(newBridgeClass)
let origClassA = origAsso.memberEnd.class -> select(name = refinedClassA.name)
let origClassB = origAsso.memberEnd.class -> select(name = refinedClassB.name)
in
self.traceabilityLinks->size() = 5
and self.traceabilityLink->exists(origin = origClassA and target = refinedClassA)
and self.traceabilityLink->exists(origin = origClassB and target = refinedClassB)
and self.traceabilityLink->exists(origin = origAsso and target = newBridgeClass)
and self.traceabilityLink->exists(origin = origAsso and target = assoANew)
and self.traceabilityLink->exists(origin = origAsso and target = assoBNew)

```

(b) Traceability links

Figure 97 Refinement AddBridgeClass

E.4.3 ByBridgeClass

Description: Uses an existing class as the bridge class between the association ends of the association being refined in order to improve the model structure.

Specification: As shown in Figure 98, the bridge class BridgeClass is used to associate the classes RefinedClassA and RefinedClassB. The class RefinedClassA is refined from the class OriginalClassA and the class RefinedClassB is refined from the class OriginalClassB. The association originalAsso is refined into the path which starts from the class RefinedClassA, traverses the association assoANew, the class BridgeClass and the association assoB, and finally ends at the class RefinedClassB.

Figure 98 ByBridgeClass - Specification

User's Intention: See description.

Atomic Changes: The specification is given in Figure 99 (a). Two kinds of atomic changes are used to derive the refinement: AddedAssociation and DeletedAssociation. Note that the atomic change AddedAssociation should appear once or two in order to connect the classes RefinedClassA and RefinedClassB with the class BridgeClass. The association originalAsso may be relocated to class NewBridgeClass. In such situation, an atomic change RelocatedAssociation appears instead of a DeletedAssociation atomic change and an AddedAssociation atomic change. In the OCL expressions in Figure 99, we assume that no atomic change

RelocatedAssociation appears, in order to make the OCL expression more concise. We also assume that the association assoB exists already and the association assoANew is a newly added association.

Traceability Links: Figure 99 (b) specifies how traceability links are established for refinement ByBridgeClass. For each path that we can find in the refined model between refA and refB (we use operation `getPaths (refA, refB)` of class Path), we establish a traceability link between the removed association origAsso (in the original model) and each element of the path.

User Help: The user's help is required because we have to ask the user to distinguish this refinement with the other Rel->classes+Rels refinements.

<p>Context: ByBridgeClass</p> <pre> let origAssoEndA = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)). affectedElement.oclAsType(Association).memberEnd.class->any(true) let origAssoEndB = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)). affectedElement.oclAsType(Association).memberEnd.class->excluding(origAssoEndA) let newAsso = self.atomicChanges-> select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association) let refA = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class)) -> Select(name=origAssoEndA.name) let refB = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class)) -> Select(name=origAssoEndB.name) in self.atomicChanges->size() = 2 and self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation)) and self.atomicChanges->exists(oclIsTypeOf(AddedAssociation)) and newAsso.memberEnd.class -> includesAll(self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).modelElements->select(oclIsTypeOf(Class))-> select(name=origAssoEndA.name)) and Path.exists(refA, refB) </pre>
(a) Constraint on atomic changes
<p>Context: ByBridgeClass</p> <pre> let origAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)) .affectedElement.oclAsType(Association) let origA = origAsso.memberEnd.class->any(true) let origB = origAsso.memberEnd.class->excluding(origA) let refA = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class)) -> Select(name=origA.name) let refB = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class)) -> Select(name=origB.name) in Path.getPaths(refA, refB)->forAll(p:Path Sequence{1..p.elements->size()}->forAll(i self.TraceabilityLink->exists(origin = origAsso and target = p.elements->at(i)))) </pre>
(b) Traceability links

Figure 99 Refinement ByBridgeClass

Example: Figure 100 and Figure 101 provide an example. The association between the classes Session and CustomerConsole is refined into the path traversing the existing class ATM which is the bridge class.

Figure 100 Example ByBridgeClass – the original class diagram

Figure 101 Example ByBridgeClass – the refined class diagram

E.4.4 AssoRefUsingAssociationEnd

Description: Transforms an association into an association class.

Specification: As shown in Figure 102, the association class `NewAssociationClass` is used to associate the classes `RefinedClassA` and `RefinedClassB`. The class `RefinedClassA` is refined from the class `OriginalClassA` and the class `RefinedClassB` is refined from the class `OriginalClassB`.

Figure 102 AssoRefUsingAssociationClass - Specification

User's Intention: An association is refined to have its own set of features; that is, features that do not belong to any of the connected classes but rather to the association itself.

Atomic Changes: Two kinds of atomic changes are used to derive the refinement: `AddedAssociationClass` and `DeletedAssociation`. The specification is shown as the OCL invariant for class `AssoRefUsingAssociationClass` in Figure 103 (a).

Traceability Links: Three traceability links have to be established: one between the classes `OriginalClassA` (referred to as `origClassA`) and `RefinedClassA` (referred to as `refinedClassA`); one between the classes `OriginalClassB` (referred to as `origClassB`) and `RefinedClassB` (referred to as `refinedClassB`); one between the association `origAsso` (referred to as `origAsso`) and the association class

NewAssociationClass (referred to as newAssoClass). These traceability links are specified in the OCL expressions in Figure 103 (b).

User Help: none.

<pre> Context: AssoRefUsingAssociationClass let origAssoEnds = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)). affectedElement.oclAsType(Association).memberEnd.class let origAssoEndA = origAssoEnds->any(true) let origAssoEndB = origAssoEnds->excluding(origAssoEndA) let refinedAssoEndA = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class)) -> Select(t name=origAssoEndA.name) let refinedAssoEndB = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)). modelElements->select(oclIsTypeOf(Class)) -> Select(t name=origAssoEndB.name) in self.atomicChanges->size() = 2 and self.atomicChanges->exists(oclIsTypeOf(AddedAssociationClass)) and self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation)) and self.atomicChanges->select(oclIsTypeOf(AddedAssociationClass)).affectedElement. oclAsType(AssociationClass).memberEnd.class -> includesAll(refinedAssoEndA and refinedAssoEndB) </pre>
<p>(a) Constraint on atomic changes</p> <pre> Context: AssoRefUsingAssociationClass let origAsso = self.atomicChanges->select(oclIsTypeOf(DeletedAssociation)). affectedElement.oclAsType(Association) let origClassA = origAsso.memberEnd.class->any(true) let origClassB = origAsso.memberEnd.class->excluding(origAssoEndA) let newAssociationClass = self.atomicChanges->select(oclIsTypeOf(AddedAssociationClass)) .affectedElement.oclAsType(AssociationClass) let refinedClassA = newAssociationClass.memberEnd.class->select(name=origClassA.name) let refinedClassB = newAssociationClass.memberEnd.class->excluding(refinedClassA) in self.traceabilityLinks->size() = 3 and self.traceabilityLink->exists(origin = origClassA and target = refinedClassA) and self.traceabilityLink->exists(origin = origClassB and target = refinedClassB) and self.traceabilityLink->exists(origin = origAsso and target = newAssociationClass) </pre>
<p>(b) Traceability links</p>

Figure 103 Refinement AssoRefUsingAssociationClass

E.5 Classes+Rels→Rel

This refinement refines several classes and relationships into a single relationship. Figure 104 provides a refined classification involving one type of refinements (Section E.5.1).

Figure 104 Taxonomy for Refinements of Type `Classes+Rels→Rel`

E.5.1 ReplaceAssociationClassWithAsso

Description: Replaces an association class with an association. The refinement is the opposite of the refinement `AssoRefUsingAssociationClass`.

Specification: As shown in Figure 105, the association class `OrigAssociationClass` is refined into the association `refinedAsso` which associates the classes `RefinedClassA` and `RefinedClassB`. The class `RefinedClassA` is refined from the class `OriginalClassA` and the class `RefinedClassB` is refined from the class `OriginalClassB`.

Figure 105 ReplaceAssociationClassWithAsso - Specification

User's Intention: An association class appears to be unnecessary (e.g., no attributes or attributes that are not specific to the association).

Atomic Changes: Two kinds of atomic changes are used to derive the refinement: DeletedAssociationClass and AddedAssociation. The specification is shown as the OCL invariant for class ReplaceAssociationClassWithAsso in Figure 106 (a).

Traceability Links: Three traceability links have to be established: one between the classes OriginalClassA (referred to as origClassA) and RefinedClassA (referred to as refinedClassA); one between the classes OriginalClassB (referred to as origClassB) and RefinedClassB (referred to as refinedClassB); one between the association class origAssociationClass (referred to as origAssoClass) and the association refinedAsso (referred to as newAsso). These traceability links are specified in the OCL expressions in Figure 106 (b).

User Help: none.

Context: ReplaceAssociationClassWithAsso

```

let deletedAssoClass = self.atomicChanges->select(oclIsTypeOf(DeletedAssociationClass)).
    affectedElement.oclAsType(AssociationClass)
let origClassA = deletedAssoClass.memberEnd.class->any(true)
let origClassB = deletedAssoClass.memberEnd.class->excluding(origClassA)
let newAsso = self.atomicChanges->select(oclIsTypeOf(AddedAssociation)).
    affectedElement.oclAsType(Association)
let refinedClassA = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name=origClassA.name)
let refinedClassB = self.refinedModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->select(name=origClassB.name)
in
self.atomicChanges->size() = 2
and self.atomicChanges->exists(oclIsTypeOf(DeletedAssociationClass))
and self.atomicChanges->exists(oclIsTypeOf(AddedAssociation))
and newAsso.memberEnd.class->includesAll(refinedClassA and refinedClassB)

```

(a) Constraint on atomic changes

Context: ReplaceAssociationClassWithAsso

```

let origAssoClass = self.atomicChanges->select(oclIsTypeOf(DeletedAssociationClass)).
    affectedElement.oclAsType(AssociationClass)
let origClassA = deletedAssoClass.memberEnd.class->any(true)
let origClassB = deletedAssoClass.memberEnd.class->excluding(origClassA)
let newAsso = self.atomicChanges->select(oclIsTypeOf(AddedAssociation)).
    affectedElement.oclAsType(Association)
let refinedClassA = newAsso.memberEnd.class->select(name=origClassA.name)
let refinedClassB = newAsso.memberEnd.class->excluding(refinedClassA)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origClassA and target = refinedClassA)
and self.traceabilityLink->exists(origin = origClassB and target = refinedClassB)
and self.traceabilityLink->exists(origin = origAssoClass and target = newAsso)

```

(b) Traceability links

Figure 106 Refinement ReplaceAssociationClassWithAsso

E.6 Rels→Rel

This refinement refines several relationships into a single relationship. This type of refinement is not common, as no class is included in the refinement. Figure 107 provides a refined classification involving one type of refinements (Section E.6.1).

Figure 107 Taxonomy for Refinements of Type Rels→Rel

E.6.1 RefAssoesIntoAssoSuperclassAndClient

Description: Refines two associations between two subclasses and a client class into a single association between the superclass of these two subclasses and the client class.

Specification: As shown in Figure 108, the associations origAsso1 and origAsso2 are refined into the association refinedAsso.

Figure 108 RefAssoesIntoAssoSuperclassAndClient - Specification

User's Intention: Two associations between a client class and two subclasses can be generalized to one association between the client class and the superclass of these two subclasses.

Atomic Changes: Two kinds of atomic changes are used to derive the refinement: RelocateAssociation and DeletedAssociation. Note that it is possible that the two original associations between the client class and the two subclasses are all deleted (through two DeletedAssociation atomic changes) and a new association between the client and superclasse is added. We assume the former situation. The specification is shown in Figure 109.

Traceability Links: Six traceability links have to be established:

- one between the classes OrigSuperClass (referred to as origSuper) and RefinedSuperClass (referred to as refinedSuper);
- one between the classes OrigSubclass1 (referred to as origSub1) and RefinedSubclass1 (referred to as refinedClass1);
- one between the classes OrigSubclass2 (referred to as origSub2) and RefinedSubclass2 (referred to as refinedSub2);
- one between the classes OrigClentClass (referred to as origClient) and RefinedClentClass (referred to as refinedClient);
- one between the association origAssol (referred to as origAssol) and the association refinedAsso (referred to as refinedAsso);
- one between the association origAsso2 (referred to as origAsso2) and the association refinedAsso.

These traceability links are specified in the OCL expressions in Figure 110.

User Help: none.

```

Context: RefAssoesIntoAssoSuperclassAndClient

let deletedAsso = self.atomicChanges ->
    select(oclIsTypeOf(DeletedAssociation)).affectedElement.oclAsType(Association)
let relocatedAsso = self.atomicChanges ->
    select(oclIsTypeOf(RelocatedAssociation)).affectedElement.oclAsType(Association)
let origClient = relocatedAsso.memberEnd.class->
    intersection(deletedAsso.memberEnd.class)
let origSub1 = relocatedAsso.memberEnd.class->excluding(origClient)
let origSub2 = deletedAsso.memberEnd.class->excluding(origClient)
let refinedSuper = self.atomicChanges -> select(oclIsTypeOf(RelocatedAssociation)).
    changeDescription.targetLocation.oclAsType(class)
let refinedSub1 = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origSub1.name)
let refinedSub2 = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origSub2.name)
let origSuper = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=refindSuper.name)

in
self.atomicChanges->size() = 2
and self.atomicChanges->exists(oclIsTypeOf(RelocateAssociation))
and self.atomicChanges->exists(oclIsTypeOf(DeletedAssociation))
and origSuper.generalization.specific -> includesAll(origSub1 and origSub2)
and refinedSuper.generalization.specific -> includesAll(refinedSub1 and refinedSub2)
and deletedAsso.memberEnd.class->excluding(origSub1)->
    equals(relocatedAsso.memberEnd.class->excluding(origSub2))

```

(a) Constraint on atomic changes

Figure 109 Refinement RefAssoesIntoAssoSuperclassAndClient (part A)

```

Context: RefAssoesIntoAssoSuperclassAndClient

let origAsso1 = self.atomicChanges ->
    select(oclIsTypeOf(RelocatedAssociation)).affectedElement.oclAsType(Association)
let origAsso2 = self.atomicChanges ->
    select(oclIsTypeOf(DeletedAssociation)).affectedElement.oclAsType(Association)
let origClient = relocatedAsso.memberEnd.class->intersection(origAsso2.memberEnd.class)
let origSub1 = origAsso1.memberEnd.class->excluding(origClient)
let origSub2 = origAsso2.memberEnd.class->excluding(origClient)
let refinedSuper = self.atomicChanges -> select(oclIsTypeOf(RelocatedAssociation)).
    changeDescription.targetLocation.oclAsType(class)
let refinedClient = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origClient.name)
let refinedSub1 = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origSub1.name)
let refinedSub2 = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origSub2.name)
let origSuper = origSub1.generalization.general
let refinedAsso = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Association))->Select(memberEnd.class->
        includesAll(refinedClient and refinedSuper))

in
self.traceabilityLinks->size() = 6
and self.traceabilityLink->exists(origin = origSuper and target = refinedSuper)
and self.traceabilityLink->exists(origin = origSub1 and target = refinedSub1)
and self.traceabilityLink->exists(origin = origSub2 and target = refinedSub2)
and self.traceabilityLink->exists(origin = origClient and target = refinedClient)
and self.traceabilityLink->exists(origin = origAsso1 and target = refinedAsso)
and self.traceabilityLink->exists(origin = origAsso2 and target = refinedAsso)

```

(b) Traceability links

Figure 110 Refinement RefAssoesIntoAssoSuperclassAndClient (part B)

E.7 Rel->Rels

This refinement refines a single relationship into several relationships. This type of refinement is not common, as no class is included into the refinement. Figure 111 provides a refined classification involving one type of refinements (Section E.7.1).

Figure 111 Taxonomy for Refinements of Type Rel->Rels

E.7.1 RefAssoIntoAssoesSubclassesAndClient

Description: Refines the association between a superclass and a client class into several associations between several subclasses of this superclass and the client class.

Specification: As shown in Figure 112, the association `origAsso` is refined into the associations `refinedAsso` and `newAsso`.

Figure 112 RefAssoIntoAssoesSubclassesAndClient – Specification

User's Intention: The association between a client class and a superclass can be specialized to the association between the client class and one of subclasses of this superclass.

Atomic Changes: Two kinds of atomic changes are used to derive the refinement: RelocateAssociation and AddedAssociation. Note that it is possible that the original association between the client class and the superclass is deleted (a DeletedAssociation atomic changes) and a new association between the client and a subclass is added. We assume the former situation. The specification is shown in Figure 113.

Traceability Links: Six traceability links have to be established:

- one between the classes OrigSuperClass (referred to as origSuper) and RefinedSuperClass (referred to as refinedSuper);
- one between the classes OrigSubclass1 (referred to as origSub1) and RefinedSubclass1 (referred to as refinedSub1);
- one between the classes OrigSubclass2 (referred to as origSub2) and RefinedSubclass2 (referred to as refinedSub2);
- one between the classes OrigClientClass (referred to as origClient) and RefinedClientClass (referred to as refinedClient);
- one between the association origAsso (referred to as origAsso) and the association refinedAsso (referred to as refinedAsso).
- one between the association origAsso and the association newAsso (referred to as newAsso).

These traceability links are specified in the OCL expressions in Figure 114.

User Help: none.

```

Context: RefAssoIntoAssoSubclassesAndClient

let addedAsso = self.atomicChanges ->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
let relocatedAsso = self.atomicChanges ->
    select(oclIsTypeOf(RelocatedAssociation)).affectedElement.oclAsType(Association)
let refinedSub1 = self.atomicChanges -> select(oclIsTypeOf(RelocatedAssociation)).
    changeDescription.targetLocation.oclAsType(Class)
let refinedAsso = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Association)) ->
        select(memberEnd.class->includes(refinedSub1) and memberEnd.class->
            intersection(addedAsso.memberEnd.class->size()==1)
let refinedClient = refinedAsso.memberEnd.class->excluding(refinedSub1)
let origClient = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(name=refinedClient.name)
let refinedSub2 = addedAsso.memberEnd.class->excluding(refinedClient)
let origSuper = relocatedAsso.memberEnd.class->excluding(origClient)
let refinedSuper = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=origSuper.name)
let origSub1 = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=refinedSub1.name)
let origSub2 = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=refinedSub2.name)

in
self.atomicChanges->size() = 2
and self.atomicChanges->exists(oclIsTypeOf(RelocateAssociation))
and self.atomicChanges->exists(oclIsTypeOf(AddedAssociation))
and origSuper.generalization.specific -> includesAll(origSub1 and origSub2)
and refinedSuper.generalization.specific -> includesAll(refinedSub1 and refinedSub2)
and refinedAsso.memberEnd.class->excluding(refinedSub1)->
    equals(addedAsso.memberEnd.class->excluding(refinedSub2))

```

(a) Constraint on atomic changes

Figure 113 Refinement RefAssoIntoAssoesSubclassesAndClient (part A)

```

Context: RefAssoIntoAssoesSubclassesAndClient

let addedAsso = self.atomicChanges ->
    select(oclIsTypeOf(AddedAssociation)).affectedElement.oclAsType(Association)
let relocatedAsso = self.atomicChanges ->
    select(oclIsTypeOf(RelocatedAssociation)).affectedElement.oclAsType(Association)
let refinedSub1 = self.atomicChanges -> select(oclIsTypeOf(RelocatedAssociation)).
    changeDescription.targetLocation.oclAsType(Class)
let refinedAsso = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Association)) ->
        select(memberEnd.class->includes(refinedSub1) and memberEnd.class->
            intersection(addedAsso.memberEnd.class->size())=1)
let refinedClient = refinedAsso.memberEnd.class->excluding(refinedSub1)
let origClient = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(name=refinedClient.name)
let refinedSub2 = addedAsso.memberEnd.class->excluding(refinedClient)
let origSuper = relocatedAsso.memberEnd.class->excluding(origClient)
let refinedSuper = self.refinedModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(name=origSuper.name)
let origSub1 = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(name=refinedSub1.name)
let origSub2 = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(name=refinedSub2.name)

in
self.traceabilityLinks->size() = 6
and self.traceabilityLink->exists(origin = origSuper and target = refinedSuper)
and self.traceabilityLink->exists(origin = origSub1 and target = refinedSub1)
and self.traceabilityLink->exists(origin = origSub2 and target = refinedSub2)
and self.traceabilityLink->exists(origin = origClient and target = refinedClient)
and self.traceabilityLink->exists(origin = origAsso and target = refinedAsso)
and self.traceabilityLink->exists(origin = origAsso and target = newAsso)

```

(b) Traceability links

Figure 114 Refinement RefAssoIntoAssoesSubclassesAndClient (part B)

E.8 InterfaceRefinement

Any refinements related to interfaces belong to this type of refinement. Figure 115 provides a refined classification involving three types of refinements.

Figure 115 Taxonomy for Refinements of Type InterfaceRefinement

`ExtractInterface` is to add an interface and let the class being refined to implement this interface (Section E.8.1). `ReplaceClassWithInterface` is to replaces the class being refined with an interface (Section E.8.2). `ReplaceInterfaceWithClass` is to replace the interface being refined with the superclass of a class which has implemented the interface (Section E.8.3).

E.8.1 ExtractInterface

Description: Adds an interface and lets the class being refined to implement this interface.

Specification: As shown in Figure 116, the class OriginalClass is refined into the class RefinedClass which implements the interface Interface.

Figure 116 ExtractInterface - Specification

User's Intention: A subset of a class's responsibilities can be extracted out from this class to an interface so that these responsibilities can be shared by other classes.

Atomic Changes: Two kinds of atomic changes are used to derive the refinement: AddedInterface, AddedDependency. The specification is given in Figure 117 (a).

Traceability Links: Three traceability links have to be established: one between the classes OriginalClass (referred to as origClass) and RefinedClass (referred to as refinedClass); one between the classes OriginalClass and the interface realization relationship (connecting the class RefinedClass and the interface Interface) (referred to as realizationRel); one between the classes OriginalClass and the new added interface Interface (referred to as interface). These traceability links are specified in the OCL expressions in Figure 117 (b).

User Help: none.

```

Context: ExtractInterface
self.atomicChanges->size() = 2
and self.atomicChanges->exists(oclIsTypeOf(AddedInterface))
and self.atomicChanges->exists(oclIsTypeOf(AddedDependency))
and self.atomicChanges->select(oclIsTypeOf(AddedDependency))
    .oclIsTypeOf(InterfaceRealization)
and self.atomicChanges->select(oclIsTypeOf(AddedDependency)).affectedElement.
    oclAsType(Dependency).supplier = self.atomicChanges->
        select(oclIsTypeOf(AddedInterface)).affectedElement.oclAsType(Interface))

```

(a) Constraint on atomic changes

```

Context: ExtractInterface
let interface = self.atomicChanges->select(oclIsTypeOf(AddedInterface))
    .affectedElement.oclAsType(Interface)
let realizationRel = self.atomicChanges->select(oclIsTypeOf(AddedDependency))
    .affectedElement.oclAsType(InterfaceRealization)
let refinedClass = realizationRel.client
let origClass = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> Select(name=refinedClass.name)
in
self.traceabilityLinks->size() = 3
and self.traceabilityLink->exists(origin = origClass and target = refinedClass)
and self.traceabilityLink->exists(origin = origClass and target = realizationRel)
and self.traceabilityLink->exists(origin = origClass and target = interface)

```

(b) Traceability links

Figure 117 Refinement ExtractInterface

E.8.2 ReplaceClassWithInterface

Description: Replaces the class being refined with an interface.

Specification: As shown in Figure 118, the class OriginalClass is replaced by the interface Interface. The operation Operation1() is moved into the interface.

Figure 118 ReplaceClassWithInterface - Specification

User's Intention: The modeling situation would be more appropriate for interface instead of class.

Atomic Changes: Three kinds of atomic changes are used to derive the refinement: AddedInterface, DeletedClass and MovedOperation. Note that the atomic change MovedOperation may appear more than once since this case is not shown in the specification given in Figure 119 (a).

Traceability Links: One traceability link has to be established: one between the class OriginalClass (referred to as origClass) and the interface Interface (referred to as interface). The traceability link is specified in the OCL expressions in Figure 119 (b).

User Help: none.

Context: ReplaceClassWithInterface

```

self.atomicChanges->size() = 3
and self.atomicChanges->exists(oclIsTypeOf(MovedOperation))
and self.atomicChanges->exists(oclIsTypeOf(AddedInterface))
and self.atomicChanges->exists(oclIsTypeOf(DeletedClass))
and self.atomicChanges->select(oclIsTypeOf(MovedOperation)).changeDescription
    .targetLocation.oclAsType(class)->equals(self.atomicChanges->
        select(oclIsTypeOf(AddedInterface)).affectedElement.oclAsType(Interface))
and self.atomicChanges->select(oclIsTypeOf(MovedOperation)).affectedElement.
    oclAsType(Operation).class->equals(self.atomicChanges->
        select(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class))

```

(a) Constraint on atomic changes

Context: ReplaceClassWithInterface

```

let interface = self.atomicChanges->select(oclIsTypeOf(AddedInterface)).
    affectedElement.oclAsType(Interface)
let origClass = self.originalModel.diagram->select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class))->Select(name= self.atomicChanges
        ->exists(oclIsTypeOf(DeletedClass)).affectedElement.oclAsType(Class).name)
in
self.traceabilityLinks->size() = 1
and self.traceabilityLink->exists(origin = origClass and target = interface)

```

(b) Traceability links

Figure 119 Refinement ReplaceClassWithInterface

E.8.3 ReplaceInterfaceWithSuperclass

Description: Replaces the interface being refined with the superclass of a class which has implemented the interface.

Specification: As shown in Figure 120, the interface `OrigInterface` is refined into the superclass `Superclass` which generalizes the class `RefinedClass`. The class `RefinedClass` is refined from the class `OrigClass` which implements the interface `OrigInterface`. The operation `Operation1()` is moved from the interface `OrigInterface` into the superclass.

Figure 120 ReplaceInterfaceWithSuperclass - Specification

User's Intention: The situation would be more appropriate for superclass instead of interface.

Atomic Changes: Five kinds of atomic changes are used to derive the refinement: DeletedInterface, AddedClass, DeletedDependency, AddedGeneralization and MovedOperation. Note that the atomic change MovedOperation may appear more than once since this case is not shown in the specification given in Figure 121 (a).

Traceability Links: Two traceability links have to be established: one between the classes `OrigClass` (referred to as `origClass`) and `RefinedClass` (referred to as `refinedClass`); one between the interface `OrigInterface` (referred to as `origInterface`) and the superclass `Superclass` (referred to as `superclass`). These traceability links are specified in the OCL expressions in Figure 121 (b).

User Help: none.

Context: ReplaceInterfaceWithSuperclass

```
let addedGen = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)).
    affectedElement.oclAsType(Generalization)
let deletedRel = self.atomicChanges->select(oclIsTypeOf(DeletedDependency)).
    affectedElement.oclAsType(Dependency)
in
self.atomicChanges->size() = 5
and self.atomicChanges->exists(oclIsTypeOf(MovedOperation))
and self.atomicChanges->exists(oclIsTypeOf(AddedClass))
and self.atomicChanges->exists(oclIsTypeOf(AddedGeneralization))
and self.atomicChanges->exists(oclIsTypeOf(DeletedInterface))
and self.atomicChanges->exists(oclIsTypeOf(DeletedDependency))
and self.atomicChanges->select(oclIsTypeOf(DeletedDependency))
    .oclIsTypeOf(InterfaceRealization)
and self.atomicChanges->select(oclIsTypeOf(MovedOperation)).changeDescription
    .targetLocation.oclAsType(class)= self.atomicChanges->
        select(oclIsTypeOf(AddedClass)).affectedElement.oclAsType(Class)
and addedGen.general = self.atomicChanges->
    select(oclIsTypeOf(AddedClass).affectedElement.oclAsType(Class))
and addedGen.specific = self.originalModel.diagram->
    select(oclIsTypeOf(ClassDiagram)).modelElements->
        select(oclIsTypeOf(Class)) -> select(name=deletedRel.client.name)
and deletedRel.supplier = self.atomicChanges->
    select(oclIsTypeOf(DeletedInterface).affectedElement.oclAsType(Interface))
```

(a) Constraint on atomic changes

Context: ReplaceInterfaceWithSuperclass

```
let superclass = self.atomicChanges->select(oclIsTypeOf(AddedClass)).
    affectedElement.oclAsType(Class)
let refinedClass = self.atomicChanges->select(oclIsTypeOf(AddedGeneralization)).
    affectedElement.oclAsType(Generalization).specific
let origClass = self.originalModel.diagram -> select(oclIsTypeOf(ClassDiagram)).
    modelElements->select(oclIsTypeOf(Class)) -> select(name=refinedClass.name)
let origInterface = self.atomicChanges->select(oclIsTypeOf(DeletedInterface)).
    affectedElement.oclAsType(Interface)
in
self.traceabilityLinks->size() = 2
and self.traceabilityLink->exists(origin = origClass and target = refinedClass)
and self.traceabilityLink->exists(origin = origInterface and target = superclass)
```

(b) Traceability links

Figure 121 Refinement ReplaceInterfaceWithSuperclass

Appendix F Formalization of Path

Class `Path` does not appear in our metamodel as it is only a helper class used to shorten our OCL expressions when we formalize refinement kind `Rel->Classes+Rels`. As shown in Figure 122, a `Path` instance is linked to a sequence of `Element` instances, i.e., a path is a sequence of UML class diagram model elements. Notice that a path is the aggregate of at least two model elements which indicate the start and end of the path.

Figure 122 The metamodel for `Path`

Since a `Path` instance is the aggregate of a sequence of UML model elements in the class diagram, these model elements should be associated together one by one. For example, if the start element is an instance of `Classifier`, then the next element should be an instance of `Relationship`. Otherwise, if the start element is an instance of `Relationship`, then the next element should be an instance of `Classifier`. In other words, in the context of class `Path`, we can write the following OCL constraints as its invariant.

```

context Path
inv: Sequence{1..self.pathModelElements->size()}->
  forAll(i,j:Integer|j=i+1 implies(
    if self.pathModelElements->at(i).oclIsTypeOf(Classifier)
    then self.pathModelElements->at(j).oclIsTypeOf(Relationship)
    else self.pathModelElements->at(j).oclIsTypeOf(Classifier)
    endif)
  )

```

Class `Path` has four static operations: `exists(endA, endB)`, `exists(endSetA, endSetB)`, `getPaths(endA, endB)`, and `getPaths(endSetA, endSetB)`, which are specified and formalized as follows.

1. exists(endA, endB)

- **Description:** this operation is used to check whether there exists a path between model elements endA and endB in the class diagram. It returns true if and only if there exists such a path.
- **Return type:** boolean.
- **Parameters:** endA and endB are instances of Element.
- **Formalization:**

```
context Path::exists(endA, endB):Boolean
pre: endA->notEmpty() and endB->notEmpty() and
    endA.ocliIsTypeOf(Element) and endB.ocliIsTypeOf(Element)
post: result = (self.getPaths(endA, endB)->size())>0)
```

2. exists(endSetA, endSetB)

- **Description:** this operation is used to check whether there exists a path between any pair of model elements, each element in the pair belonging to one of the two sets: endSetA and endSetB. Return true if and only if there exists a path between any pair of model elements.
- **Return type:** boolean.
- **Parameters:** endSetA and endSetB are sets.
- **Formalization:**

```
context Path::exists(endSetA, endSetB):Boolean
pre: endSetA->notEmpty() and endSetB->notEmpty()
    endSetA->forAll(t|t.ocliIsTypeOf(Element)) and
    endSetB->forAll(t|t.ocliIsTypeOf(Element))
post: result = (self.getPaths(endSetA, endSetB)->size())>0)
```

3. getPaths(endA, endB)

- **Description:** this operation returns all the paths between the model elements endA and endB.
- **Return type:** instances of class Path.

- **Parameters:** endA and endB are instances of Element.

- **Formalization:**

```

context Path::getPaths(endA, endB):Set(Path)
pre: endA->notEmpty() and endB->notEmpty() and
      endA.ocIsTypeOf(Element) and endB.ocIsTypeOf(Element)
post:
let interestingPaths = Path.allInstances->
  select (p:Path|p.pathModelElements->at(1)=endA and
    p.pathModelElements->at(p.pathModelElements
      ->size())=endB)
in
result = interestingPaths)

```

4. getPaths(endSetA, endSetB)

- **Description:** this operation returns all the paths between any pair of model elements, each element in the pair belonging to one of the two sets: endSetA and endSetB.

- **Return type:** paths which are composed of a sequence of model elements.

- **Parameters:** endEndA and endEndB are sets.

- **Formalization:**

```

context Path::getPaths(endSetA, endSetB):Set(Path)
pre: endSetA->notEmpty() and endSetB->notEmpty()
      endSetA->forAll(t|t.ocIsTypeOf(Element)) and
      endSetB->forAll(t|t.ocIsTypeOf(Element))
post:
let interestingPaths = Path.allInstances->
  select (p:Path| endSetA->includes(p.pathModelElements
    ->at(1)) and endSetB->includes(p.pathModelElements->
      at(p.pathModelElements->size()))
in
result = interestingPaths)

```

Table of Contents (complete)

ABSTRACT	3
ACKNOWLEDGMENTS.....	4
TABLE OF CONTENTS.....	5
LIST OF FIGURES	7
LIST OF TABLES	10
1 INTRODUCTION.....	11
2 DEFINITIONS AND CONCEPTS.....	14
2.1 VIEWS.....	14
2.2 IMPACT ANALYSIS.....	14
2.3 ATOMIC CHANGE	15
2.4 REFINEMENT.....	15
2.5 TRACEABILITY AND TRACEABILITY LINK.....	16
3 STATE OF THE ART	17
3.1 CLASSIFYING AND IDENTIFYING REFINEMENT.....	18
3.1.1 <i>Mens et al. – Automating Support for Software Evolution in UML.....</i>	<i>18</i>
3.1.2 <i>Engels et al. – Consistency-Preserving Model Evolution through Transformation.....</i>	<i>19</i>
3.1.3 <i>Shen et al. – Extending the UML Metamodel to Support Software Refinement.....</i>	<i>20</i>
3.1.4 <i>Hnatkowska et al. – Refinement relationship between collaborations.....</i>	<i>21</i>
3.1.5 <i>Pons and Kutsche – Traceability Across Refinement Steps in UML modeling.....</i>	<i>22</i>
3.1.6 <i>Discussion.....</i>	<i>23</i>
3.2 CAPTURING TRACEABILITY INFORMATION.....	23
3.2.1 <i>Letelier – A Framework for Requirements Traceability in UML-based Projects.....</i>	<i>23</i>
3.2.2 <i>Judson et al. – Supporting Design by Pattern-based Transformation.....</i>	<i>24</i>
3.2.3 <i>Discussion.....</i>	<i>24</i>
3.3 PERFORMING IMPACT ANALYSIS	25
3.3.1 <i>Briand et al. – Automated Impact Analysis of UML Models.....</i>	<i>25</i>
3.3.2 <i>Li and J. Offutt – Algorithmic Analysis of the Impact of Changes to Object-Oriented Software.....</i>	<i>26</i>
3.3.3 <i>Mens and D'Hondt – Automating Support for Software Evolution in UML.....</i>	<i>28</i>
3.3.4 <i>von Knethen et al. – QuaTrace: A Tool Environment for (Semi-)Automatic Impact Analysis Based on Traces.....</i>	<i>28</i>
3.3.5 <i>Comparison.....</i>	<i>29</i>
3.4 SUMMARY.....	33
4 APPROACH TAKEN.....	34
4.1 METAMODELS.....	35
4.1.1 <i>Conceptual metamodel.....</i>	<i>36</i>
4.1.2 <i>Metamodel for refinement.....</i>	<i>37</i>

4.1.3	<i>Metamodel for atomic change</i>	38
4.1.4	<i>Metamodel for traceability link</i>	40
4.1.5	<i>Metamodel for performing vertical impact analysis</i>	43
4.2	TAXONOMY OF ATOMIC CHANGES	44
4.3	TAXONOMY OF REFINEMENTS	45
4.4	REFINEMENT/TRACEABILITY LINK SPECIFICATION	46
4.4.1	<i>Atomic refinements derived from a single atomic change</i>	46
4.4.2	<i>Atomic refinements derived from several atomic changes</i>	48
5	AUTOMATION	51
5.1	THE ECLIPSE PLATFORM	52
5.1.1	<i>Eclipse Modeling Framework (EMF)</i>	53
5.1.2	<i>The OCL Engine</i>	54
5.2	RATIONAL SOFTWARE ARCHITECT	55
5.2.1	<i>Compare&merge engine</i>	55
5.3	EMF MODELS IN VIATool.....	56
6	CASE STUDY	59
6.1	DETAIL ASSOFUNCTIONALITY	60
6.2	TURN ATTR INTO CLASS	62
6.3	ASSO END MULTIPLICITY REF.....	64
6.4	ASSO END IS NAVIGABLE REF	66
6.5	ASSO END TYPE REF.....	67
7	CONCLUSION	69
	REFERENCES	72
	APPENDIX A METAMODEL	75
	APPENDIX B DICTIONARY FOR METAMODEL	76
B.1	ATOMICCHANGE.....	76
B.2	ATOMICCHANGETYPES	77
B.3	ATOMICREFINEMENT.....	77
B.4	CHANGE.....	78
B.5	CHANGEDescription	79
B.6	CLASSDIAGRAM	80
B.7	COMPOSITEREFINEMENT	80
B.8	DERIVEDTRACEABILITYLINK	81
B.9	ELEMENT	81
B.10	HORIZONTALIMPACT	82
B.11	IMPACT	82

B.12	REFINEMENT.....	83
B.13	TRACEABILITYLINK.....	84
B.14	UMLDIAGRAM.....	85
B.15	UMLMODEL.....	85
B.16	USERHELP	86
B.17	VERTICALIMPACT.....	87
APPENDIX C EXAMPLE ATOMIC CHANGES.....		88
C.1	ADDED.....	88
C.2	DELETED.....	88
C.3	CHANGED	89
C.4	MOVED	93
APPENDIX D TAXONOMY FOR ATOMIC CHANGES		95
APPENDIX E TAXONOMY AND FORMALIZATION FOR REFINEMENTS		101
E.1	CLASS->CLASSES+RELS.....	102
E.2	CLASSES+RELS->CLASS	125
E.3	CLASSES+RELS->CLASSES+RELS	137
E.4	REL->CLASSES+RELS	159
E.5	CLASSES+RELS->REL	173
E.6	RELS->REL.....	176
E.7	REL->RELS	180
E.8	INTERFACEREFINEMENT	184
APPENDIX F FORMALIZATION OF PATH.....		191